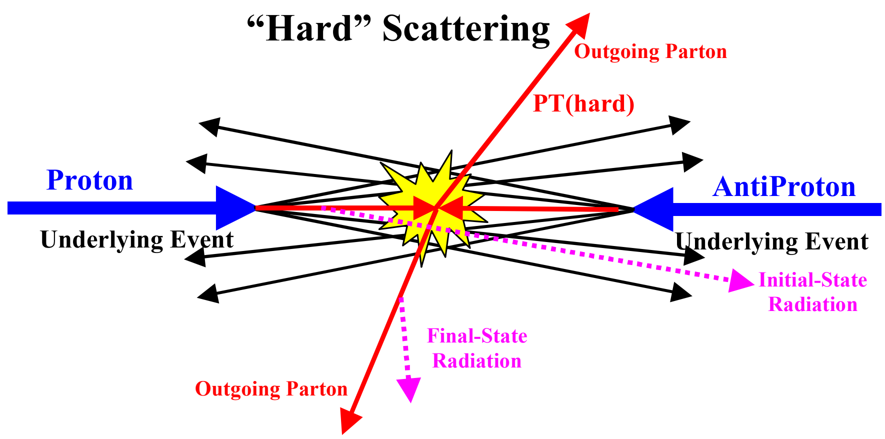
Elementary Particle Physics

Summer 2001



Books:

- *Introduction to Elementary Particles*, **David Griffiths**.
- *Modern Elementary Particle Physics*, **Gordon Kane**.
- *An Introduction to High Energy Physics*, Donald Perkins.
- *Quarks & Leptons: An Introductory Course in Modern Particle Physics*, **F. Halzen** and **A. D. Martin**.
- *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions*, **Chris Quigg**.
- *Applications of Perturbative QCD*, **R. D. Field**.

The Simple Structure of our Universe

Elementary Particle: Indivisible piece of matter without internal structure and without detectable size or shape .

Mass and chage located inside sphere of radius zero!

- **Four Forces:**
  - **Gravity** (**Solar Systems, Galaxies, Curved Space-Time , Black Holes**)
  - **Electromagnetism** (**Atoms & Molecules, Chemical Reactions**)
  - **Weak** (**Neutron Decay, Beta Radioactivity**)
  - **Strong** (**Atomic Nuclei, Fission & Fusion**)

- **Two Classes of Elementary Particles:**
  - **Leptons:** **Do not** interact with the **strong force** (but may interact with weak, EM and gravity).
  - **Quarks:** **Do** interact with the **strong force** (may also interact with weak, EM and gravity).

FERMIONS matter constituents spin = 1/2, 3/2, 5/2,...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c²	Electric charge	Flavor	Approx. Mass GeV/c²	Electric charge
ν_e electron neutrino	$< 7 \times 10^{-9}$	0	u up	0.005	2/3
e electron	0.000511	-1	d down	0.01	-1/3
ν_μ muon neutrino	< 0.0003	0	c charm	1.5	2/3
μ muon	0.106	-1	s strange	0.2	-1/3
ν_τ tau neutrino	< 0.03	0	t top (initial evidence)	170	2/3
τ tau	1.7771	-1	b bottom	4.7	-1/3

- **Quarks and Leptons have very different properties:**
  1. **Weak** and **EM** forces much weaker that strong force.
  2. **Quarks** have fractional electric charge.
  3. **Quarks** are found only as **constituents** of composite particles called **hadrons** (**baryons have B not 0, mesons have B = 0**). Leptons exist as free particles.

Baryon Number

- **Gauge Particles are the carriers (or mediators) of the forces:**
  - **Electromagnetism** – **Photon** γ (massless)
  - **Weak** – **Weak Vector Bosons** W^+, W^-, **Z** (massive)
  - **Gravity** – **Graviton**
  - **Strong** – **8 Gluons** (massless)

Labeling the Particles – Quantum Numbers

Elementary particles and hadrons are labeled by their **quantum numbers**. These labels characterize the properties of the particles.

Symbol	Name	Additive
M	Mass	
J	Spin Angular Momentum	
C	Charge Conjugation	
P	Parity	
G	G-Parity	
B	Baryon Number	Yes
Q_{em}	Electric Charge $Q = Y/2 + Iz$ $Q = Q_{weak} + Q_{U1}$	Yes
Q_{U1}	U1 Charge	Yes
Q_{weak}	Weak Charge	Yes
Q_{color}	Strong Charge	
Y	Hypercharge $Y = B + S + C_h + B_o + T_o$	Yes
S	Strangeness	Yes
C_h	Charmness	Yes
B_o	Bottomness	Yes
T_o	Topness	Yes
I	Isospin	Yes
I_z	3rd component of Isospin	Yes
L_e	Electron Lepton Number	Yes
L_μ	Muon Lepton Number	Yes
L_τ	Tau Lepton Number	Yes
L	Overall Lepton Number $L = L_e + L_\mu + L_\tau$	Yes

Not all particles carry every label. The particles are only labeled by the quantum numbers that are conserved for that particle.

- Particles with **integral spin** J (J = 0, 1, 2, …) are called **bosons**.
- Particles with **half-integral spin** J (J = ½, 3/2, …) are called **fermions**.
- Particles with spin-parity $J^P = 0^+$ **are refered to a scalars**, 0^- **are pseudo-scalars**, 1^- **are vectors**, 1^+ **are pseudo-vectors**, 2^+ **are tensors**, etc.
- **Hadrons** are labeled by $I^G J^{PC}$.

Leptons & Anti-Leptons

(J = ½ fermions, B = 0, Ch = 0, Bo = 0, To = 0)

Generation $Q_{em} = Q_{weak} + Q_{U1}$

Lepton		Mass MeV	Qem	L_e	L_μ	L_μ	Q_{U1}	Qweak
ν_e	1st	~ 0	0	1	0	0	-1/2	+1/2
e^-	1st	0.5	-1	1	0	0	-1/2	-1/2
ν_μ	2nd	~ 0	0	0	1	0	-1/2	+1/2
μ^-	2nd	106	-1	0	1	0	-1/2	-1/2
ν_τ	3rd	~ 0	0	0	0	1	-1/2	+1/2
τ^-	3rd	1777	-1	0	0	1	-1/2	-1/2

Generation **Q_{em} measured in units of the electron charge e**

Anti-Lepton		Mass MeV	Qem	L_e	L_μ	L_μ	Q_{U1}	Qweak
e^+	1st	0.5	+1	-1	0	0	+1/2	+1/2
$\bar{\nu}_e$	1st	~ 0	0	-1	0	0	+1/2	-1/2
μ^+	2nd	106	+1	0	-1	0	+1/2	+1/2
$\bar{\nu}_\mu$	2nd	~ 0	0	0	-1	0	+1/2	-1/2
τ^+	3rd	1777	+1	0	0	-1	+1/2	+1/2
$\bar{\nu}_\tau$	3rd	~ 0	0	0	0	-1	+1/2	-1/2

SU(2) Weak Lepton Doublets:

$$L_1 = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \mathrm{L}_2 = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \mathrm{L}_3 = \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

SU(2) Weak Anti-Lepton Doublets:

$$\bar{L}_1 = \begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix} \quad \bar{\mathrm{L}}_2 = \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix} \quad \bar{\mathrm{L}}_3 = \begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$$

Quarks & Anti-Quarks

(J = ½+ fermions, Le = 0, Lμ = 0, Lτ = 0)

Generation $Q_{em} = Q_{weak} + Q_{U1}$

Quarks		Mass MeV	B	Q_{em}	Y	I	I_z	S	C_h	B_o	T_o	Q_{U_1}	Q_{weak}	Q_{color}
u, u, u	1st	5	1/3	2/3	1/3	1/2	1/2	0	0	0	0	+1/6	+1/2	R, B, G
d, d, d	1st	10	1/3	-1/3	1/3	1/2	-1/2	0	0	0	0	+1/6	-1/2	R, B, G
c, c, c	2nd	1,500	1/3	2/3	4/3	0	0	0	1	0	0	+1/6	+1/2	R, B, G
s, s, s	2nd	200	1/3	-1/3	-2/3	0	0	-1	0	0	0	+1/6	-1/2	R, B, G
t, t, t	3rd	175,000	1/3	2/3	4/3	0	0	0	0	0	1	+1/6	+1/2	R, B, G
b, b, b	3rd	4,700	1/3	-1/3	-2/3	0	0	0	0	-1	0	+1/6	-1/2	R, B, G

Anti-Quarks		Mass MeV	B	Q_{em}	Y	I	Iz	S	Ch	Bo	To	Q_{U1}	Qw	Qcolor
dbar, dbar, dbar	1st	10	-1/3	1/3	-1/3	1/2	1/2	0	0	0	0	-1/6	+1/2	Rbar, Bbar, Gbar
ubar, ubar, ubar	1st	5	-1/3	-2/3	-1/3	1/2	-1/2	0	0	0	0	-1/6	-1/2	Rbar, Bbar, Gbar
sbar, sbar, sbar	2nd	200	-1/3	1/3	2/3	0	0	1	0	0	0	-1/6	+1/2	Rbar, Bbar, Gbar
cbar, cbar, cbar	2nd	150	-1/3	-2/3	-4/3	0	0	0	-1	0	0	-1/6	-1/2	Rbar, Bbar, Gbar
bbar, bbar, bbar	3rd	4,700	-1/3	1/3	2/3	0	0	0	0	1	0	-1/6	+1/2	Rbar, Bbar, Gbar
tbar, tbar, tbar	3rd	175,000	-1/3	-2/3	-4/3	0	0	0	0	0	-1	-1/6	-1/2	Rbar, Bbar, Gbar

SU(2) Weak Quark and Anti-Quark Doublets:

$$Q_1^{R,B,G} = \begin{pmatrix} u_{R,B,G} \\ d'_{R,B,G} \end{pmatrix} \quad Q_2^{R,B,G} = \begin{pmatrix} c_{R,B,G} \\ s'_{R,B,G} \end{pmatrix} \quad Q_3^{R,B,G} = \begin{pmatrix} t^{R,B,G} \\ b'_{R,B,G} \end{pmatrix}$$

$$\overline{Q}_1^{R,B,G} = \begin{pmatrix} \overline{d}'_{R,B,G} \\ \overline{u}_{R,B,G} \end{pmatrix} \quad \overline{Q}_2^{R,B,G} = \begin{pmatrix} \overline{s}'_{R,B,G} \\ \overline{c}_{R,B,G} \end{pmatrix} \quad \overline{Q}_3^{R,B,G} = \begin{pmatrix} \overline{b}'^{R,B,G} \\ \overline{t}_{R,B,G} \end{pmatrix}$$

Vector Bosons

$(J = 1^-, B = 0, C_h = 0, B_o = 0, T_o = 0, L_e = 0, L_\mu = 0, L_\tau = 0)$

$Q_{em} = Q_{weak} + Q_{U1}$

Boson	Name	Mass GeV	Q_{em}	Q_{U_1}	Q_{weak}	Q_{color}
γ	Photon	0	0	0	0	none
W^+	W-Boson	81	+1	0	+1	none
W^-	W-Boson	81	-1	0	-1	none
Z	W-Boson	92	0	0	0	none
G_1	Gluon	0	0	0	0	RBbar
G_2	Gluon	0	0	0	0	RGbar
G_3	Gluon	0	0	0	0	BRbar
G_4	Gluon	0	0	0	0	BGbar
G_5	Gluon	0	0	0	0	GRbar
G_6	Gluon	0	0	0	0	GBbar
G_7	Gluon	0	0	0	0	RRbar BBbar GGbar
G_8	Gluon	0	0	0	0	RRbar BBbar GGbar

BOSONS force carriers spin = 0, 1, 2,...

Unified Electroweak spin = 1	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.22	−1
W^+	80.22	+1
Z^0	91.187	0

Strong or color spin = 1	Mass GeV/c²	Electric charge
g gluon	0	0

Classifying the Forces

- **Notation**

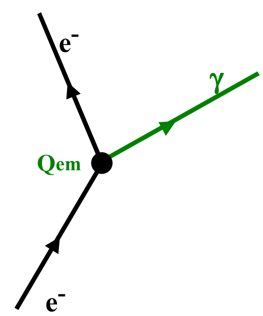
$$\begin{array}{c|cc} & a & b \\ \hline a & A & B \\ b & C & D \end{array}$$

implies the transisitions

$$\begin{array}{|cc} \hline a \to a+A & a \to b+B \\ b \to a+C & b \to b+D \end{array}$$

- **U(1) of Electromagnitism (1 x 1 transisition matrix)**

$$\begin{array}{c|cc} & \nu_e & e^- \\ \hline \nu_e & 0 & 0 \\ e^- & 0 & \gamma \end{array} \longrightarrow \begin{array}{c|c} & e- \\ \hline e- & \gamma \end{array}$$

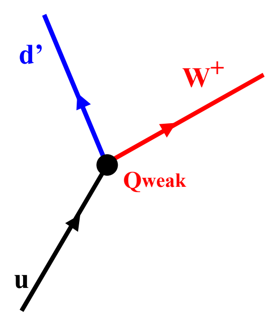


also

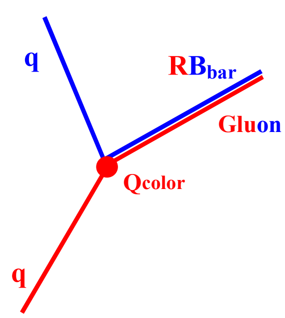
$$\begin{array}{c|cc} & u & d \\ \hline u & \gamma & 0 \\ d & 0 & \gamma \end{array} \longrightarrow \begin{array}{c|c} & u \\ \hline u & \gamma \end{array}$$ **and** $$\begin{array}{c|c} & d \\ \hline d & \gamma \end{array}$$

- **SU(2) Weak (2 x 2 transisition matrix)**

$$\begin{array}{c|cc} & \nu_e & e^- \\ \hline \nu_e & Z & W^+ \\ e^- & W^- & Z \end{array} \qquad \begin{array}{c|cc} & u & d' \\ \hline u & Z & W^+ \\ d' & W^- & Z \end{array}$$



- **SU(3) Color (3 x 3 transisition matrix)**



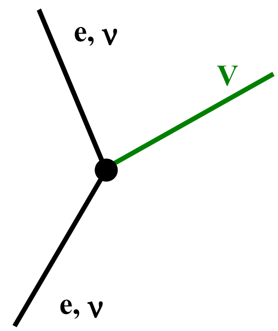
$$\begin{array}{c|ccc} & q_R & q_B & q_G \\ \hline q_R & R\bar{R} & R\bar{B} & R\bar{G} \\ q_B & B\bar{R} & B\bar{B} & B\bar{G} \\ q_G & G\bar{R} & G\bar{B} & G\bar{G} \end{array}$$

q = u, d, s, c, b, t

ElectroWeak Force
(Unification of Weak and Electromagnetic Forces)

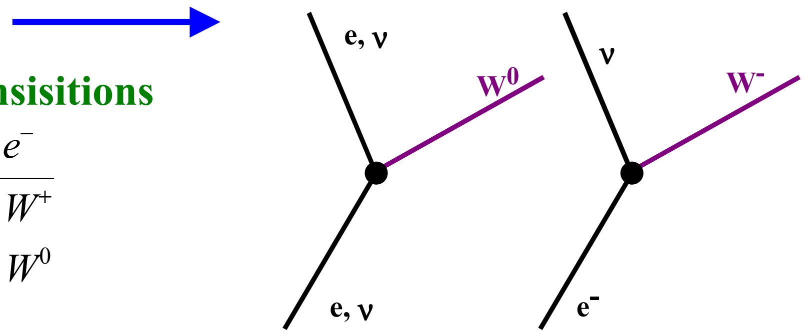
- **U(1) Transisitions**

$$\begin{array}{c|cc} & \nu_e & e^- \\ \hline \nu_e & V^0 & 0 \\ e^- & 0 & V^0 \end{array}$$



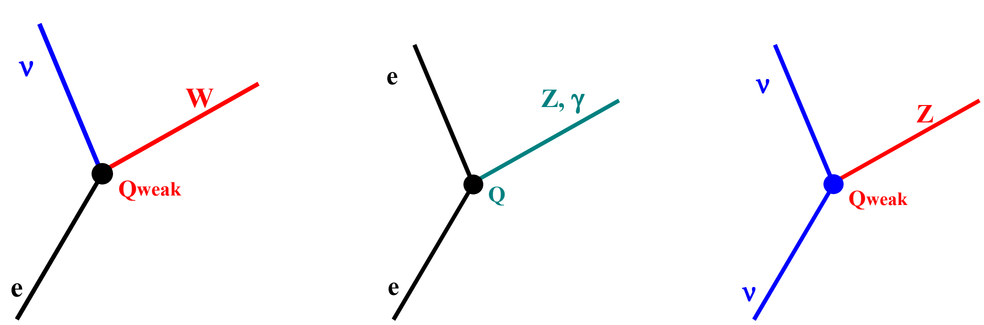
- **SU(2) Transisitions**

$$\begin{array}{c|cc} & \nu_e & e^- \\ \hline \nu_e & W^0 & W^+ \\ e^- & W^- & W^0 \end{array}$$



- **SU(2) x U(1) ElectroWeak (contains both electromagnetic and weak force)**

$$\begin{array}{c|cc} & \nu_e & e^- \\ \hline \nu_e & W^0+V^0 \rightarrow Z & W^+ \\ e^- & W^- & W^0+V^0 \rightarrow Z+\gamma \end{array}$$



Flavor Mixing – Generation Hopping
(Kobayashi-Maskawa Matrix)

The Weak Interactions are **not diagonal** in quark flavor and hence,

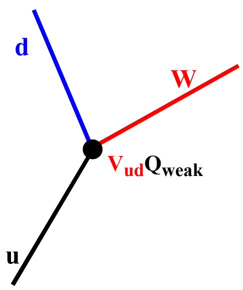
$$u \rightarrow d' + W^+ \quad c \rightarrow s' + W^+ \quad t \rightarrow b' + W^+$$

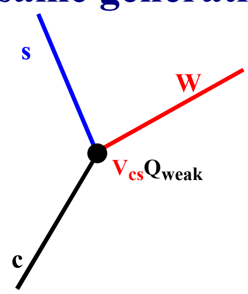
where

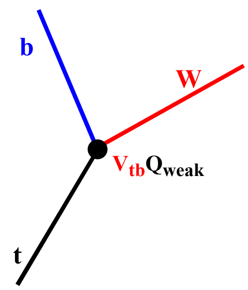
CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

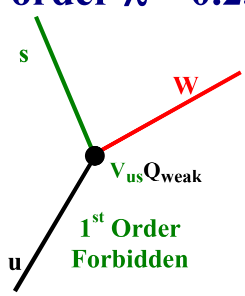
- **Tranisitions within the same generation are of order one**

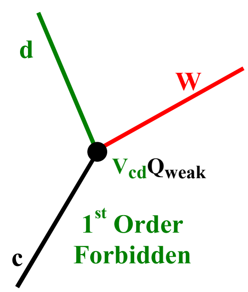




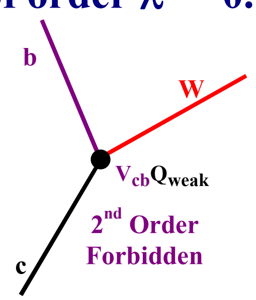


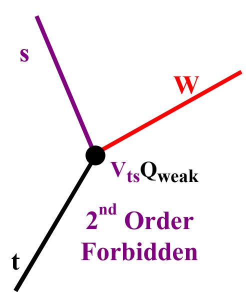
- **$1^{st} - 2^{nd}$ generation transisitions are "1^{st} order" forbidden and are of order $\lambda \sim 0.23$.**





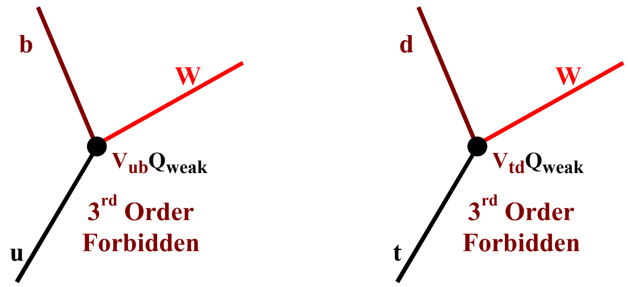
- **$2^{nd} - 3^{rd}$ generation transisitions are "2^{nd} order" forbidden and are of order $\lambda^2 \sim 0.05$.**



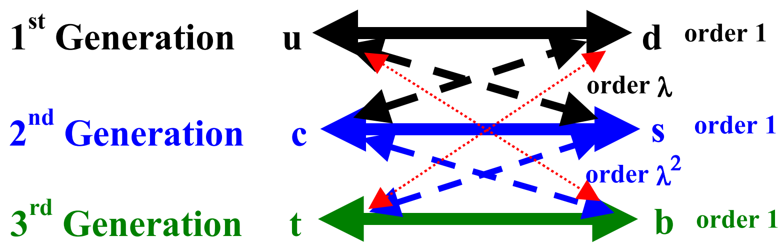


Flavor Mixing – Generation Hopping (continued)

- $1^{st} - 3^{rd}$ generation transisitions ar "3^{rd} order" forbidden and are of order $\lambda^3 \sim 0.001$



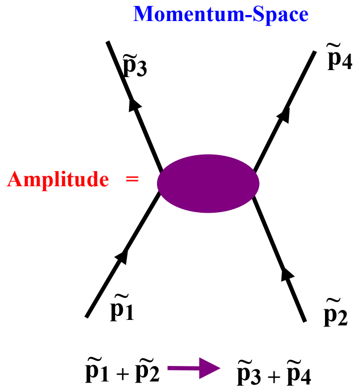
- Transisition Pattern:



- Experimental Summary (magnitude of the matrix elements):

$$\begin{pmatrix} [0.9745 \leftrightarrow 0.9760] & [0.217 \leftrightarrow 0.224] & [0.0018 \leftrightarrow 0.0045] \\ [0.217 \leftrightarrow 0.224] & [0.9737 \leftrightarrow 0.9753] & [0.036 \leftrightarrow 0.042] \\ [0.004 \leftrightarrow 0.013] & [0.036 \leftrightarrow 0.042] & [0.9991 \leftrightarrow 0.9994] \end{pmatrix}$$

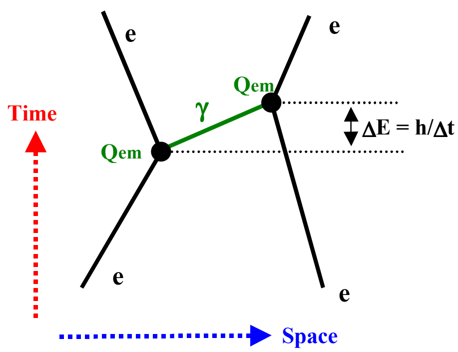
Feynman Diagrams – Quantum Field Theory (Pictures)

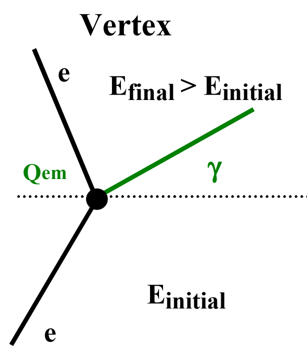


Feynman diagrams are a way to organize and summerize the **rules of perturbation theory**. They represent the Quantum Mechanical amplitude for the process.

Probability = |Amplitude|^2

- **Space-Time Diagrams (constructed from vertices)**





- **Momemtum-Space Diagrams**

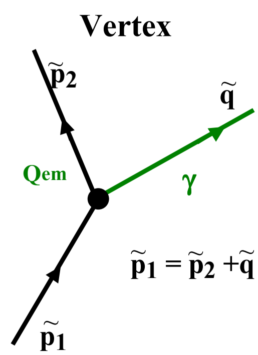
At a vertex quantum additive numbers are conseerved and the **4-momentum is conserved**, but particles may or may not be on **their mass shell**.

$$\tilde{p}^2 = E^2 - \vec{p}\cdot\vec{p} = m^2$$

"on shell" "real" particle

$$\tilde{p}^2 = E^2 - \vec{p}\cdot\vec{p} \neq m^2$$

"off shell" "virtual" particle

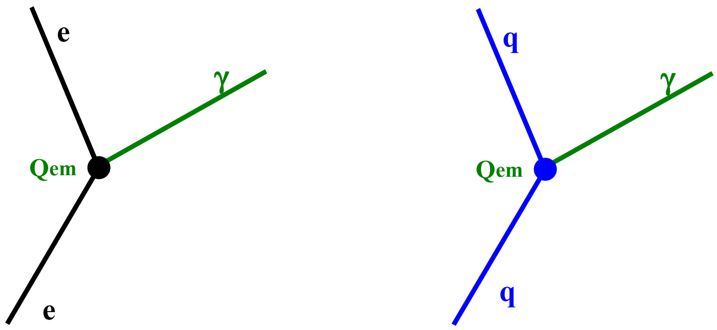


- **Particle-Antiparticle Relation**

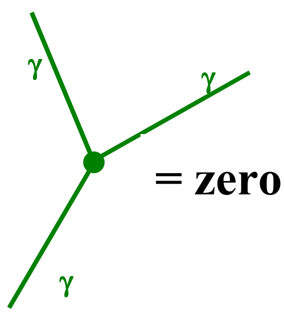
A **particle of 4-momentum p corresponds** to **an antiparticle of 4-momentum –p** and vice-versa.

Electromagnetic Intractions - QED
(Photons Couple to Electric Charge)

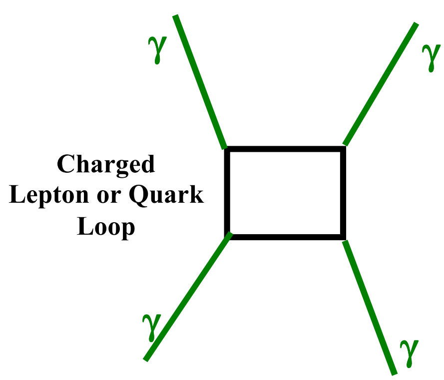
- **Charged Lepton or Quark - Photon Vertex**



- **Photons do not carry electric charge and hence do not directly couple to each other.**

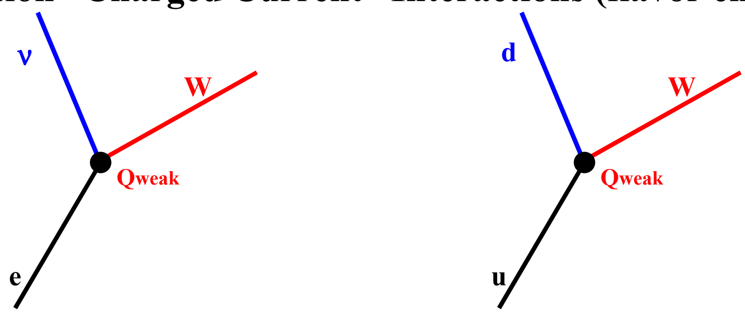


- **However photons can interact with each other indirectly.**

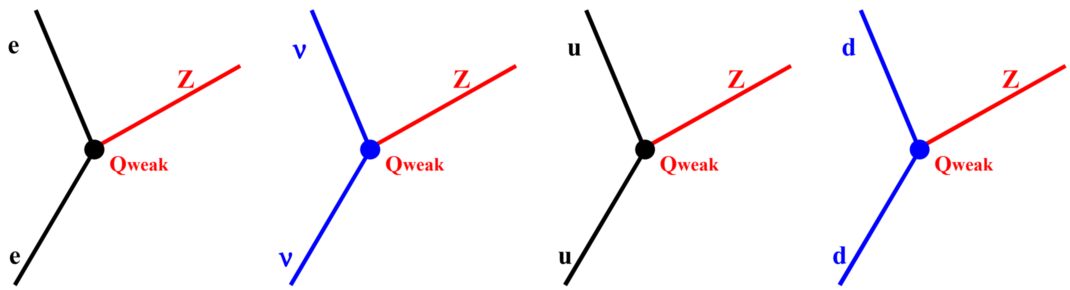


Weak Intractions – SU(2)xU(1)
(W & Z Couple to Weak Charge)

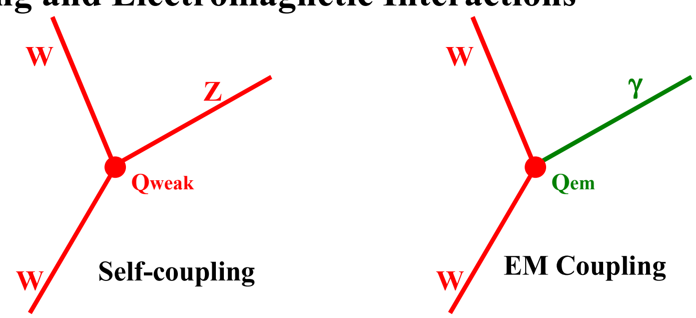
- **1st Generation "Charged Current" Interactions (flavor changing)**



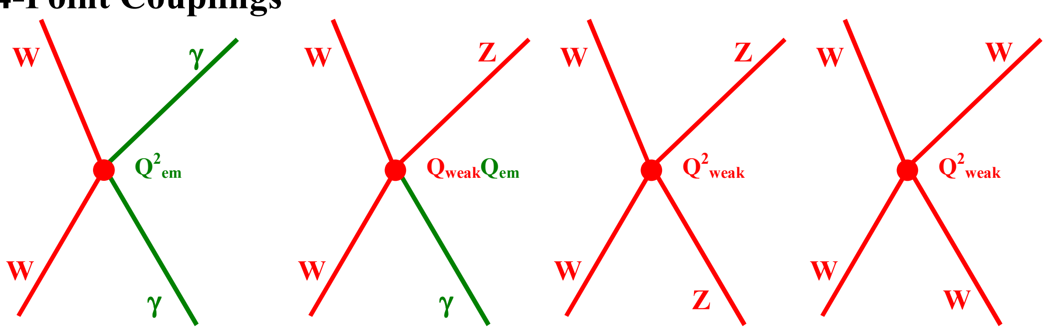
- **1st Generation "Neutral Current" Interactions**



- **Self-Coupling and Electromagnetic Interactions**

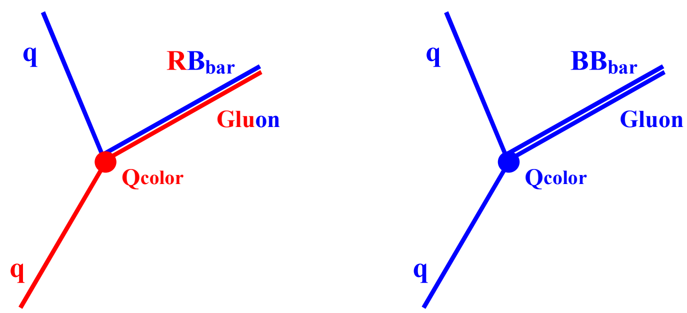


- **4-Point Couplings**

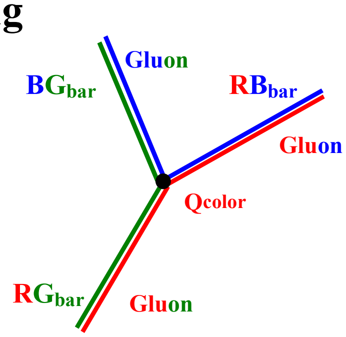


Strong Intractions - QCD
(Gluons Couple to Color Charge)

- **Quark (q = u, d, s, b, t) Color Changing and Non-Color Changing Interactions**

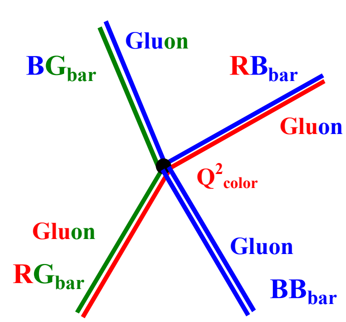


- **Gluon Self-Coupling**



Gluons carry color and couple to each other!

- **4-Point Coupling**

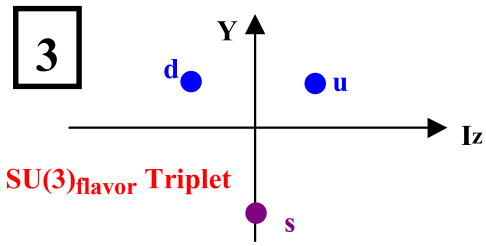


Hadrons – PseudoScalar Meson Nonet

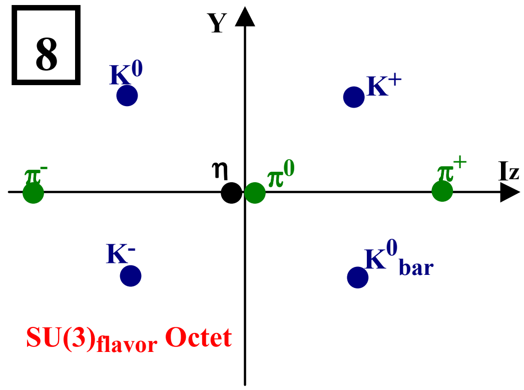
($J^P = 0^-$ bosons, B = 0, Ch = 0, Bo = 0, To = 0)

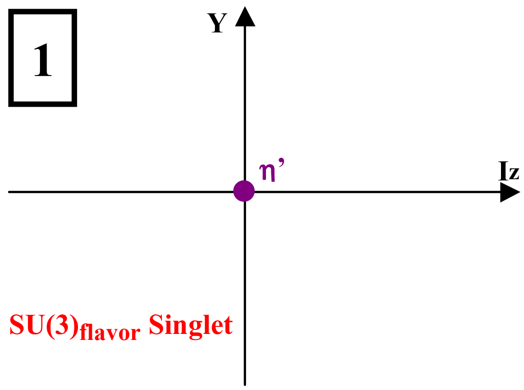
Y = B + S +Ch +Bo + To Qem = Y/2 + Iz

Symbol	Name	Mass MeV	Qem	Net Quarks	I	Iz	Y	S	Qcolor
π^+	pion	140	+1	udbar	1	+1	0	0	singlet
π^0	pion	135	0	uubar, ddbar	1	0	0	0	singlet
π^-	pion	140	-1	dubar	1	-1	0	0	singlet
K^+	kaon	494	+1	usbar	½	+1/2	+1	+1	singlet
K^0	kaon	478	0	dsbar	½	-1/2	+1	+1	singlet
K^0_{bar}	kaon	478	0	sdbar	½	+1/2	-1	-1	singlet
K^-	kaon	494	-1	subar	½	-1/2	-1	-1	singlet
η	eta	549	0	uubar, ddbar, ssbar	0	0	0	0	singlet
η'	eta-prime	958	0	uubar, ddbar, ssbar	0	0	0	0	singlet



$$3 \times \bar{3} = 8 + 1$$



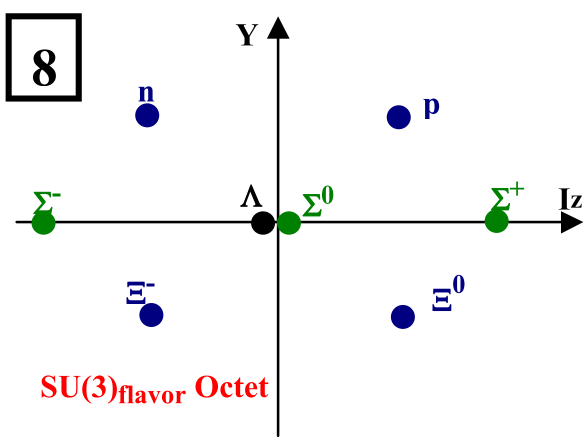


Hadrons – ½⁺ Baryon Octet

($J^P = \frac{1}{2}^+$ fermions, B = 1, Ch = 0, Bo = 0, To = 0)

Symbol	Name	Mass MeV	Qem/e	Net Quarks	I	Iz	Y	S	Qcolor
Σ^+	Sigma	1189	+1	uus	1	+1	0	-1	singlet
Σ^0	Sigma	1193	0	uds	1	0	0	-1	singlet
Σ^-	Sigma	1189	-1	dds	1	-1	0	-1	singlet
p	Proton	938	+1	uud	½	+1/2	+1	0	singlet
n	Neutron	940	0	udd	½	-1/2	+1	0	singlet
Ξ^0	Cascade	1315	0	ssu	½	+1/2	-1	-2	singlet
Ξ^-	Cascade	1321	-1	ssd	½	-1/2	-1	-2	singlet
Λ	Lambda	1116	0	uds	0	0	0	-1	singlet

Y = B + S +Ch +Bo + To **Qem = Y/2 + Iz**



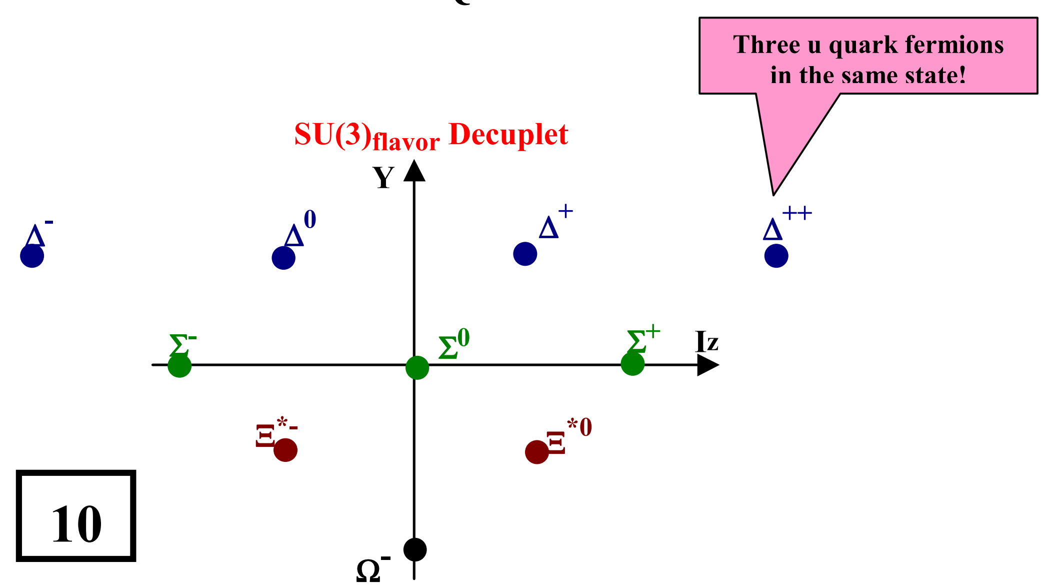
3 x 3 x 3 = 10 + 8 + 8 + 1

Hadrons – $3/2^+$ Baryon Decuplet

($J^P = 3/2^+$ fermions, B = 1, Ch = 0, Bo = 0, To = 0)

Symbol	Name	Mass MeV	Qem	Net Quarks	I	Iz	Y	S	Qcolor
Δ^{++}	Delta	1232	+2	uuu	3/2	+3/2	1	0	singlet
Δ^{+}	Delta	1232	+1	uud	3/2	+1/2	1	0	singlet
Δ^{0}	Delta	1232	0	ddu	3/2	-1/2	1	0	singlet
Δ^{-}	Delta	1232	-1	ddd	3/2	+3/2	1	0	singlet
Σ^{*+}	SigmaStar	1385	+1	uus	1	+1	0	-1	singlet
Σ^{*0}	SigmaStar	1385	0	uds	1	0	0	-1	singlet
Σ^{*-}	SigmaStar	1385	-1	dds	1	-1	0	-1	singlet
Ξ^{*0}	CascadeStar	1530	0	ssu	½	+1/2	-1	-2	singlet
Ξ^{*-}	CascadeStar	1530	-1	ssd	½	-1/2	-1	-2	singlet
Ω^{-}	Lambda	1672	-1	sss	0	0	-2	-3	singlet

$Y = B + S + Ch + Bo + To$ $\qquad$ $Qem = Y/2 + Iz$



$$3 \times 3 \times 3 = 10 + 8 + 8 + 1$$

Units

It is convenient to set $\mathbf{h_{bar} = h/2\pi = 1}$ and to set the speed of light $\mathbf{c = 1}$.

Units of h = [M][L^2]/[T] = 1 (1)
Units of c = [L]/[T] = 1 (2)

where

[M] = mass
[L] = length
[T] = time

We have but one free unit left or alternatively we can **measure mass, length, and time all in the same units**.

(1)/(2) implies [M][L] = 1
(2) implies [L] = [T]

thus

[Mass] = [Energy] = [momentum] = 1/[Length] = 1/[Time]

- **Express everyting in energy units:**

1 MeV = 10^6 ev
1 GeV = 1,000 MeV
1 TeV = 1,000 GeV

$\mathbf{h_{bar}c = 1.973 \times 10^{-11}}$ **MeV-cm = 0.1973 GeV-fm = 1**
1 fm = 10^{-13}cm 1 GeV^{-1} = 0.1973 fm

Fermi

$\mathbf{h_{bar} = 6.58 \times 10^{-22}}$ **MeV-sec = 0.0658 GeV-ss = 1**
1 ss = 10^{-23}sec 1 GeV^{-1} = 0.0658ss

Strong Second

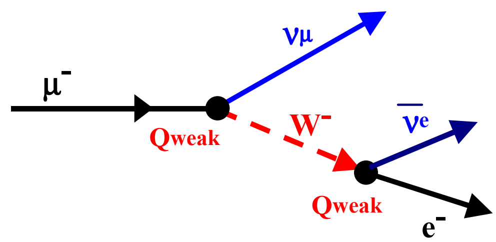
Particle Decay

Stable Particles: At present it seems that **photons**, **neutrinos**, **protons**, and **electrons** are **stable** and hence everything eventually decaus into these **four** particles.

Baryon Number Conservation: At present it seems that **baryon number is conserved** so that everything with B = 1 eventually decays into a **proton** (**plus B = 0 stuff**).

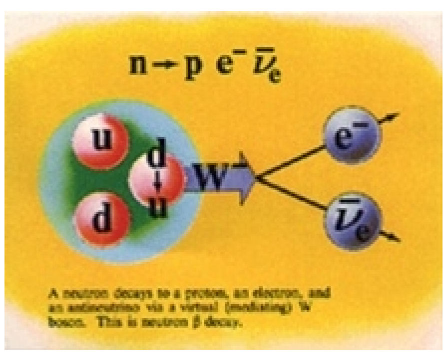
Muon Decay (weak process):

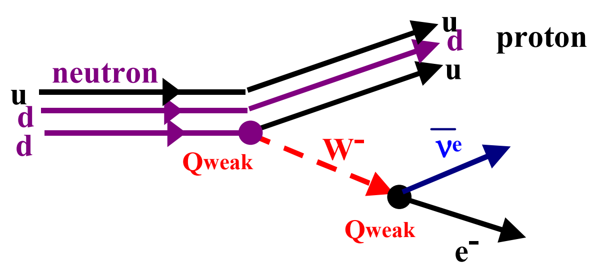
$$\mu^- \to e^- + \bar{\upsilon}_e + \upsilon_\mu \quad \tau = 2.2\times 10^{-6}\,s \quad c\tau = 660\,m$$



Neutron Decay (weak process):

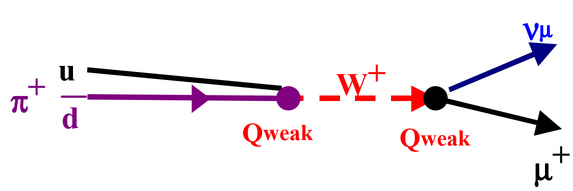
$$n \to p + e^- + \bar{\upsilon}_e \quad \tau = 896\,s \quad c\tau = 2.7\times 10^{11}\,m$$





Charged Pion Decay (weak process):

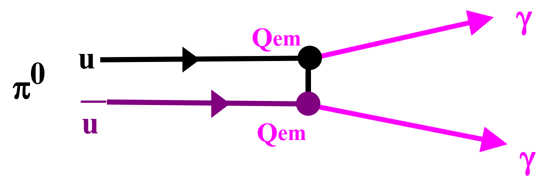
$$\pi^+ \to \mu^+ + \nu_\mu \quad \tau = 2.6\times 10^{-8}\,s \quad c\tau = 780\,cm$$



Particle Decay

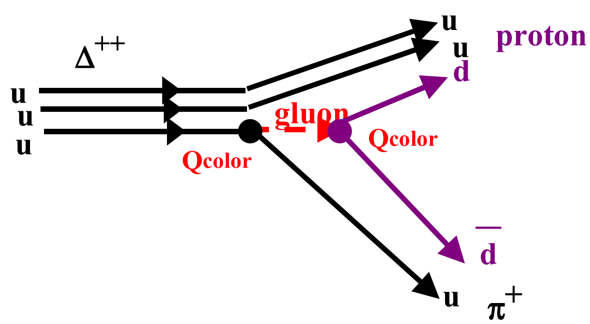
Neutral Pion Decay (electromatnetic process):

$$\pi^0 \rightarrow \gamma + \gamma \quad \tau = 0.8\times10^{-16}s \quad c\tau = 2.5\times10^{-6}cm$$



Delta Decay (strong process):

$$\Delta^{++} \rightarrow p + \pi^+ \quad \tau \approx 10^{-23}s \quad c\tau = 3\times10^{-15}cm$$



- **What is meant by an particle?**

  Single coherent object with definite identity (definite mass, electric charge, angular momentum)

- **Does a particle have to be absolutely stable to be a particle?**

  Look at the **uncertainty principle** ($\Delta E\Delta t \sim h$). If system has a finite **lifetime τ** then the uncertainty in its mass (**Δm = Γ called "width"**) is given by $\Delta m \sim h/\tau$. We consider an unstable object a particle provided,

  $$\Delta m/m = \Gamma/m << 1 \quad \text{(called a particle)}.$$

  Remember that,

  $$1\ GeV^{-1} = 0.0658 \times 10^{-23}\ sec$$

  which implies that a 1 GeV particle should live longe than $\sim10^{-23}$ sec. For the Δ^{++} $\Gamma \sim 100$ MeV so that $\Gamma/m \sim 1/10$ which satisfies the criterion.

The Top Quark

Top Decay:

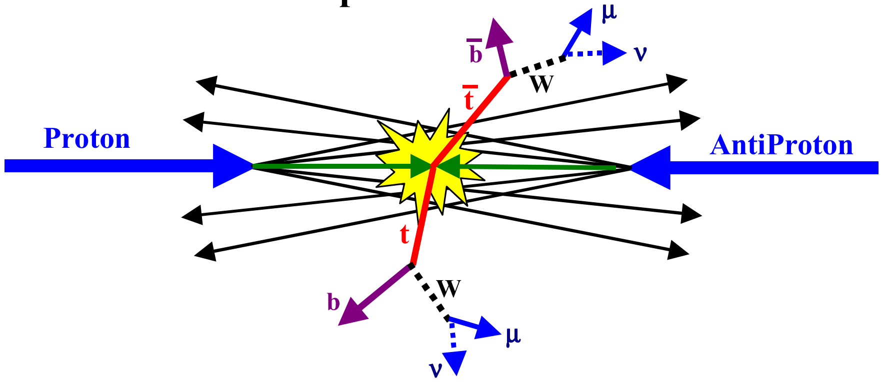
$$t \to bW \to b \begin{pmatrix} e\upsilon_e(1) \\ \mu\upsilon_\mu(1) \\ \tau\upsilon_\tau(1) \\ u\bar{d}'(3) \\ c\bar{s}'(3) \end{pmatrix}$$

$\mu\upsilon_\mu$: 1/9

$u\bar{d}'$, $c\bar{s}'$: 6/9

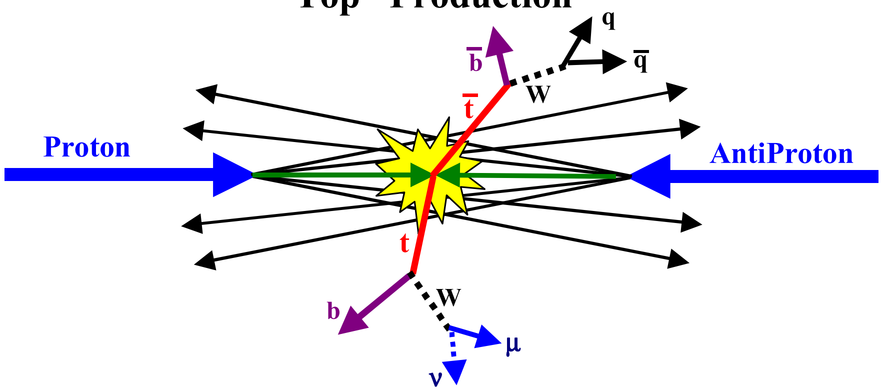
Discovery Mode (μμννjj): Rate = $(1/9)^2$ = 1/81 = 1.2%

"Top" Production



Analysis Mode (μνjjjj): Rate = 2(1/9)(6/9) = 12/81 = 14.8%

"Top" Production



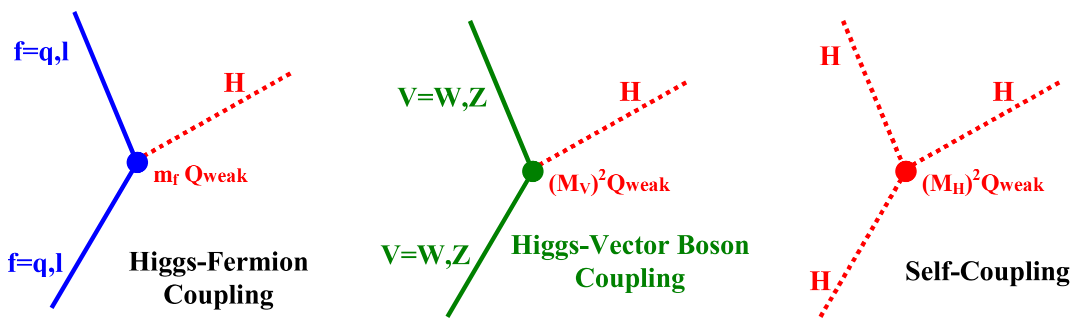
The Standard Model Higgs Boson

Holy Grail of the Standard Model!

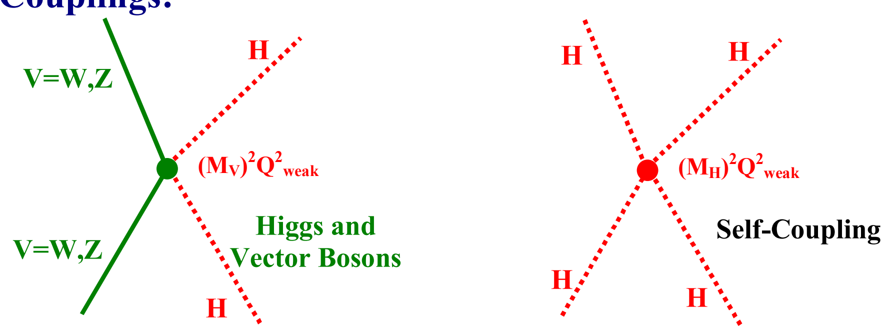
Why do particles have mass?

The standard model gives a partial answer to this question. All particles are massless and their mass is genereated by spontaneous symmetry breaking. The scalar Higgs ($J^P=0^+$) is a consequence of this symmetry breaking mechanism.

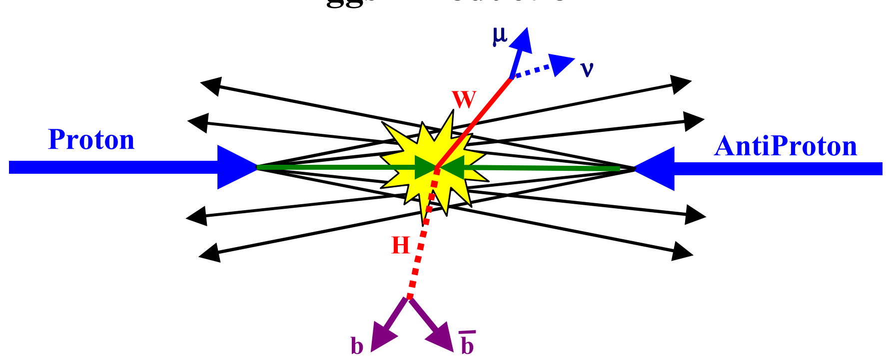
3-Point Veticies:



4-Point Couplings:

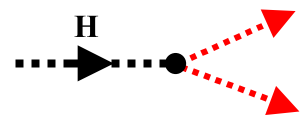
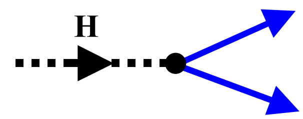
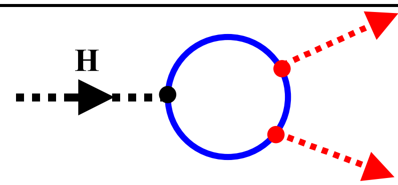


"Higgs" Production



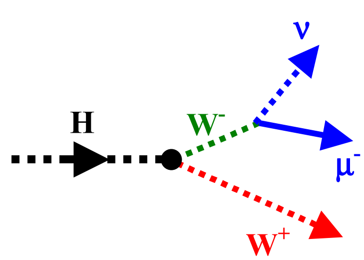
Standard Model **Higgs** Decay

The decay modes and branching fractions of the Higgs depend on its mass. In the limit of large Higgs mass ($M_H >> m_i$) then the branching fractions are as follows:

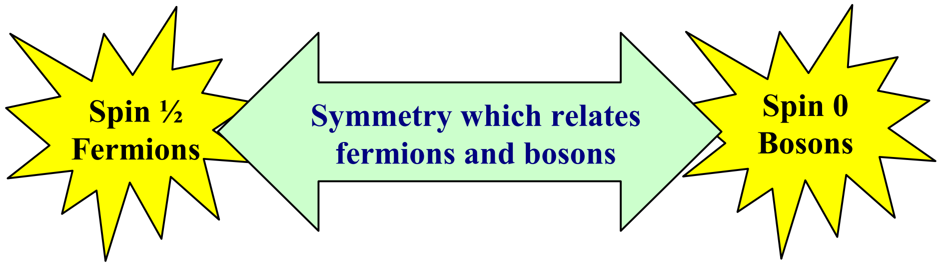
Decay	Γ/Γ_{WW}	Diagram
$H \rightarrow W^+W^-$	1	
$H \rightarrow ZZ$	½	
$H \rightarrow t\bar{t}$	$6m_t^2 / M_H^2$	
$H \rightarrow b\bar{b}$	$6m_b^2 / M_H^2$	
$H \rightarrow \tau^+\tau^-$	$2m_\tau^2 / M_H^2$	
$H \rightarrow gg$	$\alpha_s /(16\pi^2)$	
$H \rightarrow \gamma\gamma$	$\alpha_s /(16\pi^2)$	

The **Higgs Mass**

Precision fits to the LEP data indicate that **M_H < 180 GeV** which means that above table is not accurate and that the Higgs cannot decay to on-shell top-antitop and maybe not to on-shell ZZ or WW. However, even if the Higgs mass is below $2M_W$ it can decay into, for example, **$\mu\nu W$**, through a virtual W as follows:



Supersymmetry



For every "normal" spin ½ lepton there corresponds a spin 0 "slepton" (supersymmetric partner):

$$\begin{pmatrix}\upsilon_e\\ e^-\end{pmatrix}\xrightarrow{SusyPartner}\begin{pmatrix}\tilde{\upsilon}_e\\ \tilde{e}^-\end{pmatrix}$$

$$\begin{pmatrix}\upsilon_\mu\\ \mu^-\end{pmatrix}\xrightarrow{SusyPartner}\begin{pmatrix}\tilde{\upsilon}_\mu\\ \tilde{\mu}^-\end{pmatrix}$$

$$\begin{pmatrix}\upsilon_\tau\\ \tau^-\end{pmatrix}\xrightarrow{SusyPartner}\begin{pmatrix}\tilde{\upsilon}_\tau\\ \tilde{\tau}^-\end{pmatrix}$$

Scalar neutrino: "snutrino"

For every "normal" spin ½ quark there corresponds a spin 0 "squark" (supersymmetric partner):

Carry color charge: RBG

$$\begin{pmatrix}u\\ d\end{pmatrix}\xrightarrow{SusyPartner}\begin{pmatrix}\tilde{u}\\ \tilde{d}\end{pmatrix}$$

$$\begin{pmatrix}c\\ s\end{pmatrix}\xrightarrow{SusyPartner}\begin{pmatrix}\tilde{c}\\ \tilde{s}\end{pmatrix}$$

$$\begin{pmatrix}t\\ b\end{pmatrix}\xrightarrow{SusyPartner}\begin{pmatrix}\tilde{t}\\ \tilde{b}\end{pmatrix}$$

Scalar quark: "stop" quark

For every "normal" spin 1 gauge boson there corresponds a spin ½ "gaugino" (supersymmetric partner):

Gluons (spin 1) $g_1, g_2, \ldots, g_8 \xrightarrow[SusyPartners]{} \tilde{g}_1, \tilde{g}_2, \ldots, \tilde{g}_8$ **Gluinos (spin ½)**

W/Z Bosons (spin 1) $W^+, W^-, Z \xrightarrow[SusyPartners]{} \tilde{W}^+, \tilde{W}^-, \tilde{Z}$ **Wino/Zino (spin ½)**

Photon (spin 1) $\gamma \xrightarrow[SusyPartner]{} \tilde{\gamma}$ **Photino (spin ½)**

For every "normal" spin 0 Higgs there corresponds a spin ½ "fermionic" Higgs (supersymmetric partner):

Higgs (spin 0) $H_1, H_2 \xrightarrow[SusyPartners]{} \tilde{H}_1, \tilde{H}_2$ **Higgsino (spin ½)**

2 Higgs doublets

Supersymmetry

Super-Summary (MSSM):

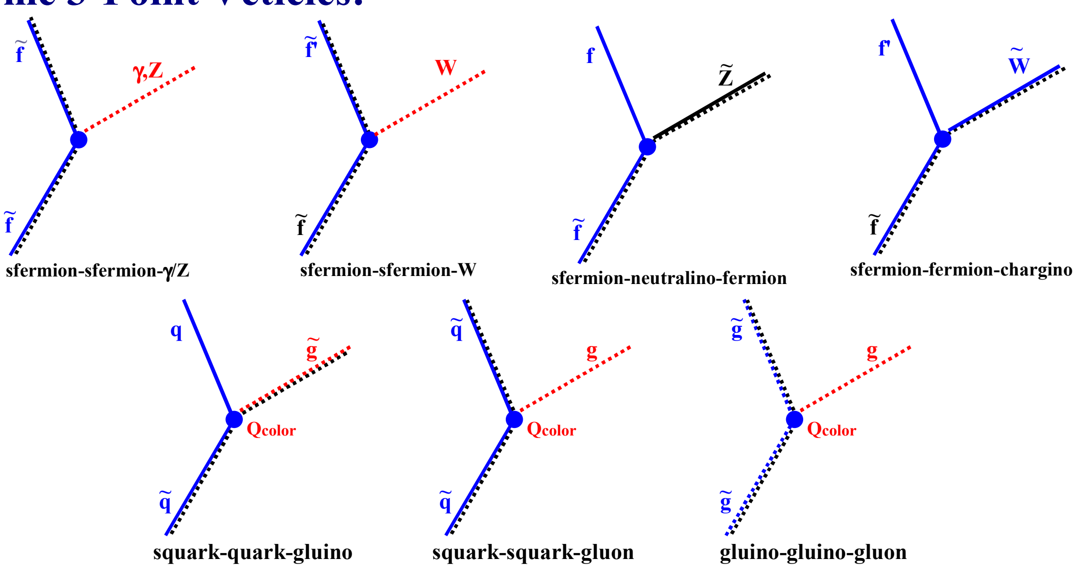
Fermions (24 particles)	Spin ½ fermions	quarks, leptons	$f = (u,d,s,c,b,t,\upsilon_e,e^-,\upsilon_\mu,\mu^-,\upsilon_\tau,\tau^-)$
Sfermions (24 particles)	Scalar Fermions	squarks, sleptons	$\tilde f = (\tilde u,\tilde d,\tilde s,\tilde c,\tilde b,\tilde t,\tilde\upsilon_e,\tilde e^-,\tilde\upsilon_\mu,\tilde\mu^-,\tilde\upsilon_\tau,\tilde\tau^-)$
Gluinos	Spin ½ fermions		$\tilde g = (\tilde g_1,\tilde g_2,\tilde g_3,\tilde g_4,\tilde g_5,\tilde g_6,\tilde g_7,\tilde g_8)$
Charginos (4 particles)	Spin ½ fermions	winos, Higgsinos	$\tilde W^\pm,\tilde H^\pm \xrightarrow[Mix]{} \tilde W_1^\pm,\tilde W_2^\pm$
Neutralinos (4 particles)	Spin ½ fermions	photino, zino, Higgsinos	$\tilde\gamma,\tilde Z,\tilde H_1^0,\tilde H_2^0 \xrightarrow[Mix]{} \tilde Z_1,\tilde Z_2,\tilde Z_3,\tilde Z_4$
Higgs Bosons (5 particles)	Spin 0 Bosons		$H_l^0,H_h^0,H_P^0,H^\pm$

Lightest Neutralino

All the three point verticies involve supersymmetric particles in pairs which implies the following.

- Supersymmetric partners are produced in pairs starting from normal particles.
- The decay of supersymmetric particles will contain a supersymmetric particle.
- The lightest supersymmetric particle (called the **LSP**) is stable.

Some 3-Point Veticies:



Supersymmetry

The Decay of Superpartners:

$$\tilde{f} \rightarrow f + \tilde{Z}_i$$
$$\tilde{f} \rightarrow f' + \tilde{W}_i$$
$$\tilde{g} \rightarrow \tilde{q} + q$$
$$\tilde{q} \rightarrow q + \tilde{g}$$
$$\tilde{g} \rightarrow g + \tilde{Z}_i$$

$M_{gluino} > M_{squark}$ (for $\tilde{g} \rightarrow \tilde{q} + q$)

$M_{squark} > M_{gluino}$ (for $\tilde{q} \rightarrow q + \tilde{g}$)

The LSP is a new stable particle which is either the lightest neutralino, $\tilde{Z}_1$, or a sneutrino, $\tilde{\upsilon}$ (not favored based on LEP constraints and cosmological arguments).

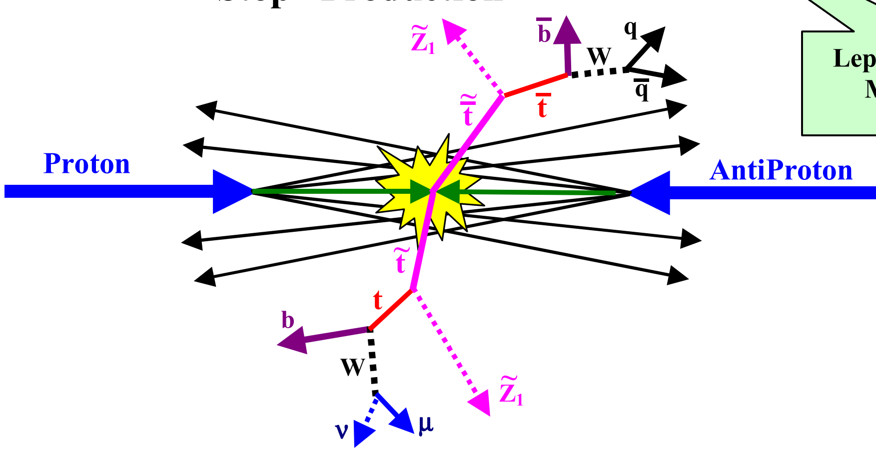
$$\boxed{\gamma, \upsilon, p, \tilde{Z}_1}$$

Stable?

Stop Production at the Collider: $\mu \upsilon b \bar{b} q \bar{q} \tilde{Z}_1 \tilde{Z}_1$

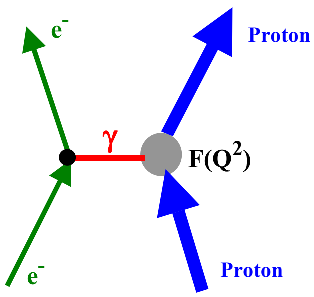
Leptons + MultiJets + Missing Energy!

"Stop" Production



Electron-Proton Elastic Scattering: Form Factors

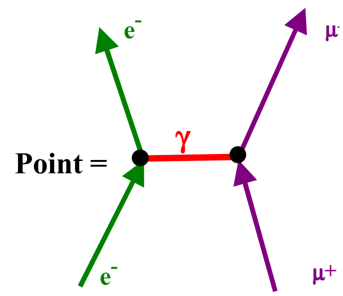
Electron-Proton Elastic Scattering: $e^- + p \to e^- + p$



Compare elastic **electron-proton** scattering with elastic **electron-muon** scattering (**point interaction**),

$$\frac{d\sigma}{d\Omega}(e + p \to e + p) = \left(\frac{d\sigma}{d\Omega}\right)_{po\,\mathrm{int}} \left|F(Q^2)\right|^2$$

The **form factor $F(Q^2)$** measures the distribution of charge within the proton. If **$F(Q^2) = 1$** then the proton is a "point-like" object (**with no substructure**). (Actually the proton (spin ½) has two form factors the magnetic form factor and the electric form factor, but I will ignor this complication.)

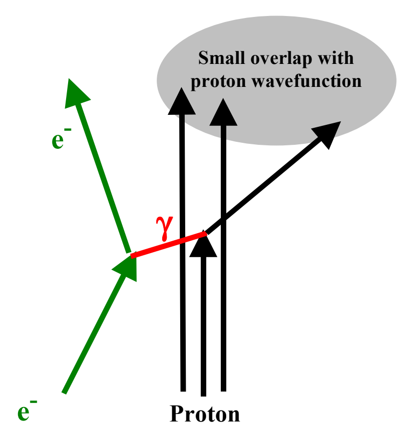


Experimental Results:

Experiments show that the proton form factor behaves like,

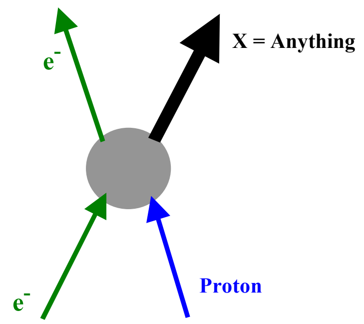
$$F(Q^2) \sim 1/Q^4.$$

Thus, the **proton is not a point like object** (its charge is distributed over space).



Deep Inelastic Scattering: Structure Functions

Inelastic Electron-Proton Scattering: $e^- + p \rightarrow e^- + X$

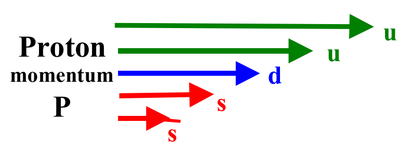


In the **laboratory frame** (proton initially at rest) measure the energy loss of the electron **ν = E – E'** and the **4-momentun transfer Q^2**. The differential cross section can be written in the form,

$$\frac{d^2\sigma}{d\Omega' dE'} = \frac{4\alpha^2 E'^2}{Q^4}\left(2W_1(x,Q^2)\sin^2\frac{\theta}{2} + W_2(x,Q^2)\cos^2\frac{\theta}{2}\right)$$

where $\mathbf{x = Q^2/(2M\nu)}$.

Parton Model: A **fast moving proton** is a collection of **partons** (constituents of the proton) each carrying a certain fraction ξ of the proton momentum.



$G_{A\rightarrow i}(\xi)$ is the **number of partons** of **type i** within a fast moving **hadron of type A** with fraction of momentum ξ ($\mathbf{p_i = \xi P}$) between ξ and ξ + dξ.

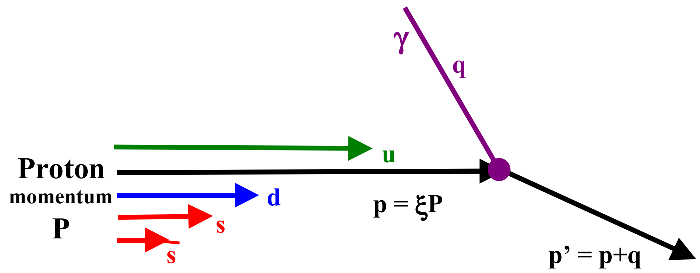
Momentum Sum Rule: The sum of the momentum of all the constituents must equal one.

$$\sum_{\substack{All\\Partons}} \int_0^1 \xi\, G_{A\rightarrow i}(\xi)\, d\xi = 1$$

Net Number of Quarks: The net number of **u quarks in a proton is 2** and the **net number of d quarks is 1**.

$$\int_0^1 \left(G_{p\rightarrow u}(\xi) - G_{p\rightarrow \bar{u}}(\xi)\right)d\xi = 2 \qquad \int_0^1 \left(G_{p\rightarrow d}(\xi) - G_{p\rightarrow \bar{d}}(\xi)\right)d\xi = 1$$

DIS Electron-Proton: Parton Model



$$(p')^2 = (p+q)^2 = (\xi p + q)^2 = m^2$$

implies that

$$\xi = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{2M\nu} = x$$

when **Q^2 = -q^2** is large.

Scaling: Predict that

$$\nu W_2(x,Q^2) = F_2(x,Q^2) \to F_2(x)$$

where

$$F_2^{ep}(x) = \frac{4}{9} x\left(G_{p\to u}(x) + G_{p\to\bar{u}}(x)\right) + \frac{1}{9} x\left(G_{p\to d}(x) + G_{p\to\bar{d}}(x)\right)$$

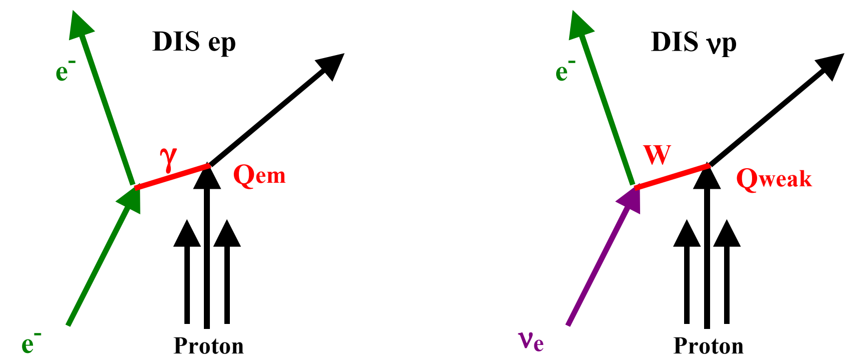
$$+ \frac{1}{9} x\left(G_{p\to s}(x) + G_{p\to\bar{s}}(x)\right) + \ldots$$

DIS Experiments (1972-1975): Observe approximate scaling and **measure quark distributions**. Find that only about one-half of the proton momentum is carried by the charged quarks:

$$\sum_{i=1}^{n_f} \int_0^1 x\left(G_{p\to q_i}(x) + G_{p\to\bar{q}_i}(x)\right)dx \approx 0.5$$

The remaining momentum must be carried by electricrically neutral partons (i.e. **gluons**).

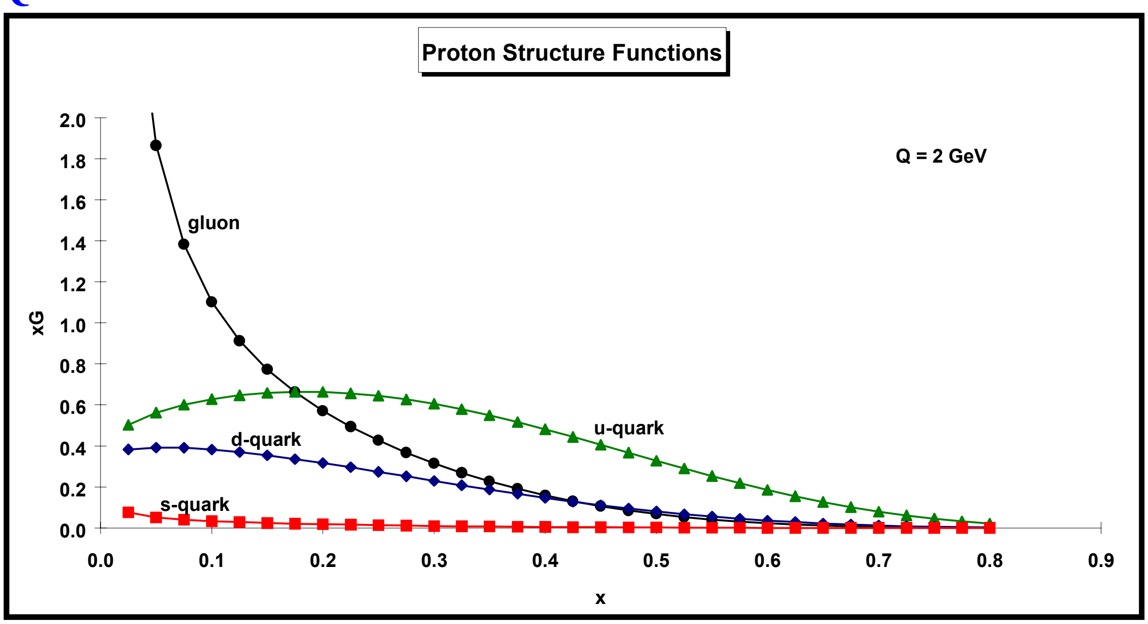
Neutrino-Proton vs Electron-Proton



Quarks have fractional electric charge: By comparing deep inelastic electron-proton scattering with deep inelastic neutrino-proton scattering one can determine the electric charge of the quarks.

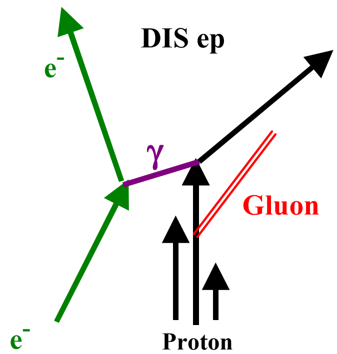
$$F_2^{\nu p}(x) = 2x\left(G_{p\to u}(x) + G_{p\to \bar{u}}(x)\right) + 2x\left(G_{p\to d}(x) + G_{p\to \bar{d}}(x)\right)$$
$$+\, 2x\left(G_{p\to s}(x) + G_{p\to \bar{s}}(x)\right) + \ldots$$

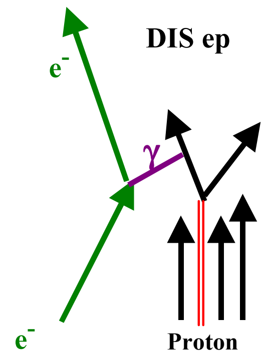
Quark and Gluon Distributions:



DIS Electron-Proton: QCD

Perturbative QCD – Scale Breaking: QCD tells us that quarks can radiate gluons before or after the interact with the virtual photon in DIS ep scattering. **Also, gluons within the proton can produce quark-antiquark pairs** that then interact with the virtual photon.





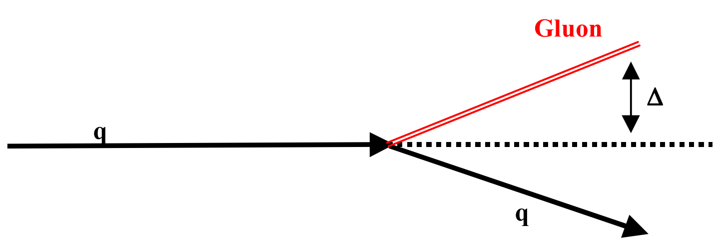
This causes a breaking of scaling and the quark (and gluon) distributions become a function of the scale, Q2, of the probing virtual photon:

$$G_{A\to i}(x,Q^2)$$

Probability of Emitting a "Hard" Gluon: QCD tells us that the probability of emitting a gluon with transverse momentum (relative to the quark direction) greater than Δ is

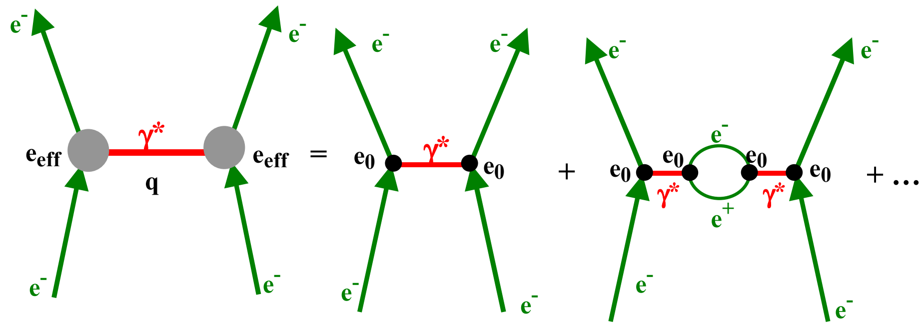
$$P_\Delta \propto \alpha_s(Q^2)\log^2(Q^2/\Delta^2) \sim \log(Q^2)$$

and hence more and more hard gluons are emitted as Q2 increases producing a logarithmtic scale breaking. However, given $G_{A\to i}(x,Q_0^{\;2})$ one can compute (via QCD perturbation theory) $G_{A\to i}(x,Q^2)$, provided $\mathbf{Q_0^2}$ and $\mathbf{Q^2}$ are both large ($\mathbf{Q_0^2} < \mathbf{Q^2}$).



QED Effective Coupling: Renormalization

Elastic Electron-Electron Scattering:



In QED the strength of the coupling must be determined experimentally; for example, by measuring the rate of electron-electron elastic scattering. However, one immediately runs into trouble since the vacuum polarization correction to the virtual photon propagator diverges like **log(λ)**, where **λ** is some **ultraviolet cutoff** that can be arbitrarily large. In particular, the leading order bubble contribution is,

$$\alpha_0 B(Q^2) = -\frac{\alpha_0}{3\pi}\left(\log(\lambda^2/Q^2) + \frac{5}{3}\right) \quad Q^2/m_e^2 >> 1$$

and

$$\alpha_0 B(Q^2) = -\frac{\alpha_0}{3\pi}\left(\log(\lambda^2/m_e^2) - \frac{Q^2}{5m_e^2}\right) \quad Q^2/m_e^2 << 1$$

where $\mathbf{q^2 = - Q^2}$ is the 4-momentum of the virtual (**spacelike**) photon and $\boldsymbol{\alpha_0 = e_0^2/4\pi}$ is the **bare coupling**.

Effective Coupling: It is convenient to define an effective coupling that includes the vacuum polarization bubbles as follows:

$$\alpha_{eff}(Q^2) = \alpha_0\left(1 + \alpha_0 B(Q^2) + \alpha_0 B(Q^2)\alpha_0 B(Q^2) + \cdots\right)$$

yielding

$$\alpha_{eff}(Q^2) = \frac{\alpha_0}{1 - \alpha_0 B(Q^2)}$$

QED Effective Coupling: Renormalization

Renormalization: We see that the effective coupling is given by

$$\frac{1}{\alpha_{eff}(Q^2)} = \frac{1}{\alpha_0} - B(Q^2)$$

where $\mathbf{B(Q^2)}$ is **infinite** (**diverges as the cutoff λ becomes large**) and α_0 is the **unmeasurable bare coupling**. We must **express all experimental observables in terms of other experimental observables** and so we define the **fine structure constant** $\alpha = e^2/4\pi$ to be the effective charge at $\mathbf{Q^2 = 0}$ (**this is called the Thompson limit and corresponds a large distance limit**),

$$\alpha = \frac{e^2}{4\pi} \equiv \alpha_{eff}(Q^2 = 0) \approx \frac{1}{137}$$

Now writing the effective coupling in terms of α gives

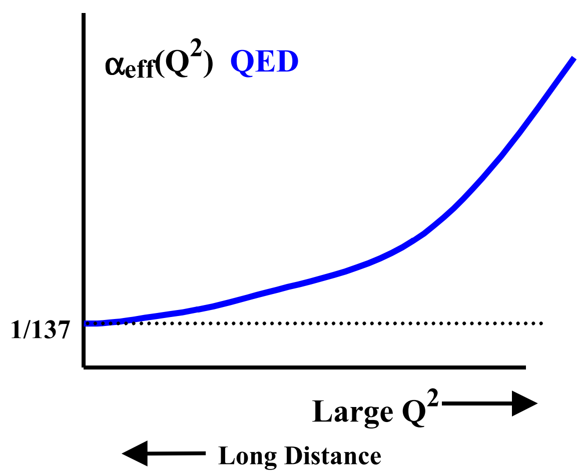
$$\frac{1}{\alpha_{eff}(Q^2)} = \frac{1}{\alpha} - \left(B(Q^2) - B(0)\right) = \frac{1}{\alpha} - \frac{1}{3\pi}\log(Q^2/m_e^2)$$

Finite and independent of cut-off λ.

or

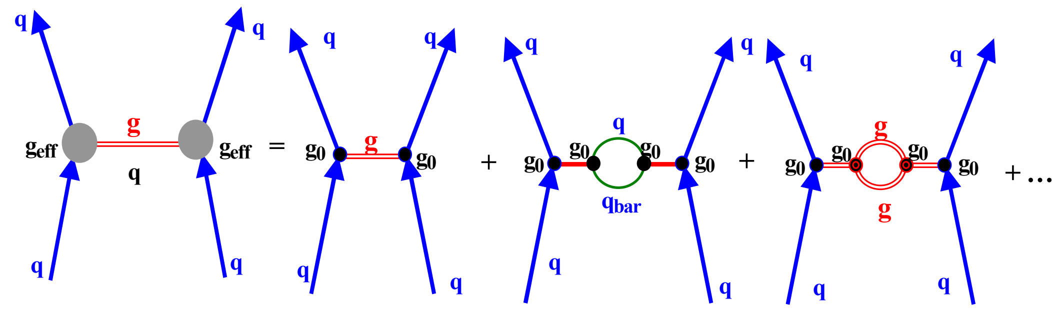
$$\alpha_{QED}(Q^2) = \alpha_{eff}(Q^2) = \frac{\alpha}{1 - (\alpha/3\pi)\log(Q^2/m_e^2)}$$

The QED effective coupling strength is equal to **1/137** at small $\mathbf{Q^2}$ and then increases as $\mathbf{Q^2}$ increases!



QCD Effective Coupling: Asymptotic Freedom

Elastic Quark-Quark Scattering:



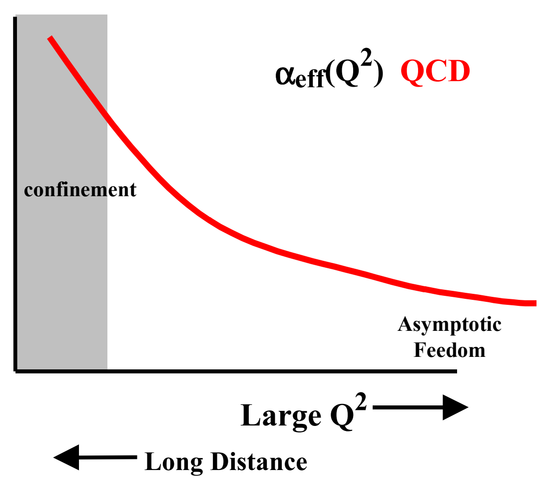
In QCD there are two types of bubbles quark loops and gluon loops and the leading order bubble contribution is,

$$\alpha_0 B_{QCD}(Q^2) = -\alpha_0 a \log(\lambda^2/Q^2)$$

where λ is the ultraviolet cutoff and $\alpha_0 = g_0^2/4\pi$ is the **bare strong coupling** and

$$a = -\frac{\beta_0}{4\pi} \qquad \beta_0 = 11 - 2n_f/3\,.$$

The **11 comes from the gluon loop** bubbles and the **$-2n_f/3$ comes from the quark** loop bubbles (**nf is the number of quark flavors**).



Renormalization (or Subtraction Point): In this case we cannot define the "experimental charge" to be at $Q^2 = 0$ (**long distance limit**). Instead we choose some Q^2, say $Q^2 = \mu^2$ to define the coupling and **express all observables in terms of the coupling at this point** (**called the renormalization point**) and

$$\frac{1}{\alpha_{eff}(Q^2)} = \frac{1}{\alpha(\mu^2)} - \left(B(Q^2) - B(\mu^2)\right)$$

Finite and independent of cut-off λ

Thus,

$$\alpha_s(Q^2) = \alpha_{eff}(Q^2) = \frac{\alpha(\mu^2)}{1 + \alpha(\mu^2)(\beta_0/4\pi)\log(Q^2/\mu^2)}$$

which approaches zero as Q^2 becomes large (**asymptotic freedom**).

QCD Effective Coupling: The Λ Parameter

The behavior of the **QCD coupling constant** as takes a bit of getting used to. In QED it is easy to define the **charge of an electron e**. It is related to the long distance behavior of the effective QED coupling. We cannot do this for QCD since the effective coupling cannot be calculated (**by perturbation theory**) at low $\mathbf{Q^2}$. Instead we define an arbitrary point μ and define α_s to be the effective coupling at that point:

$$\alpha_s \equiv \alpha_s(\mu^2)\ .$$

However, it does not matter which point μ one chooses (physical observables are independent of the choice of μ). If instead one chooses the point μ_2 then the two couplings are related (**to lowest order**) by

$$\frac{1}{\alpha_s(\mu_2^2)} - a\log(Q^2/\mu_2^2) = \frac{1}{\alpha(\mu^2)} - a\log(Q^2/\mu^2)$$

which means that there are not two parameters $\alpha_s(\mu^2)$ and μ^2 but rather one **scale Λ** that is independent of the point μ^2,

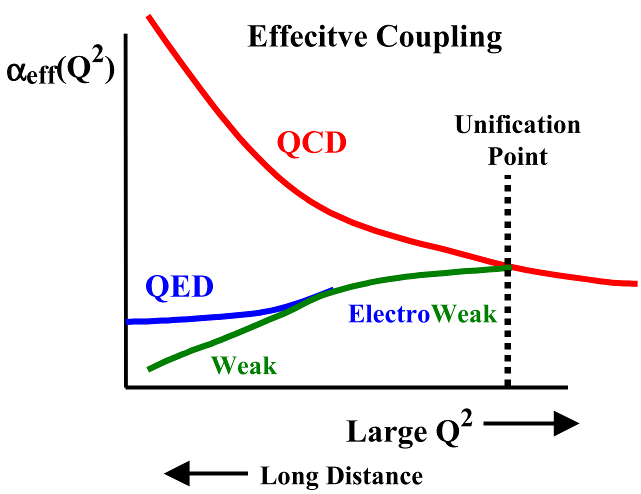
$$\frac{1}{a\alpha_s(\mu_2^2)} + \log(\mu_2^2) = \frac{1}{a\alpha(\mu^2)} + \log(\mu^2) \equiv \log(\Lambda^2)$$

In terms of Λ the effective QCD coupling is given by

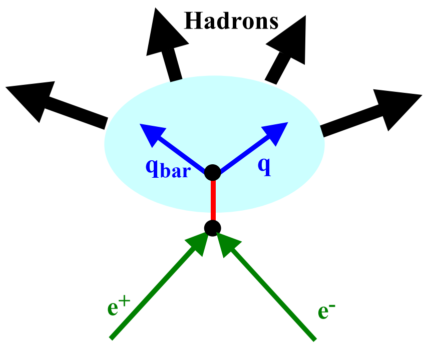
$$\alpha_s(Q^2) = \alpha_{eff}(Q^2) = \frac{4\pi}{\beta_0\log(Q^2/\Lambda^2)}\ .$$

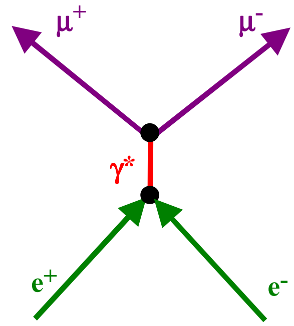
Experiments indicate that Λ is around **200 MeV**.

Unification:



Electron-Positron Annihilations

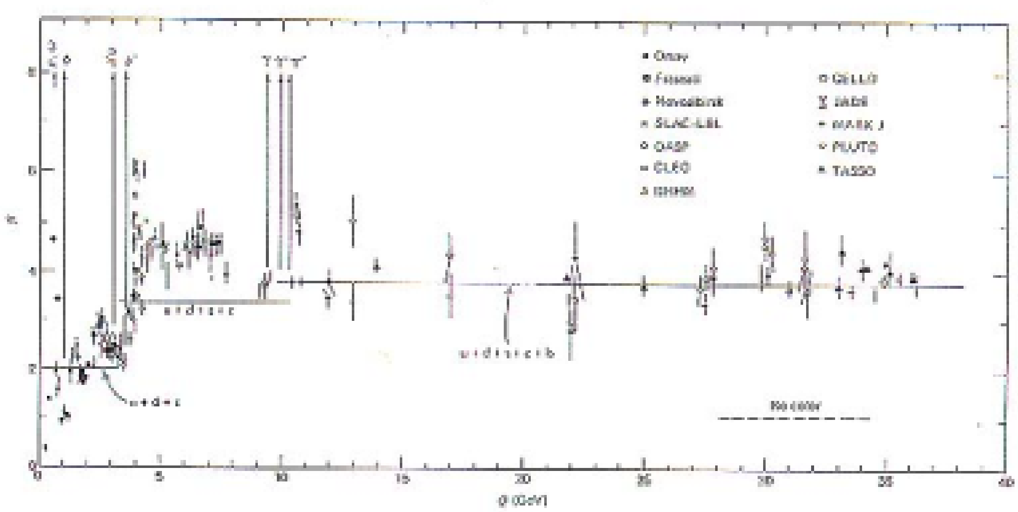




Count the Number of Quark Flavors: Measure the ratio

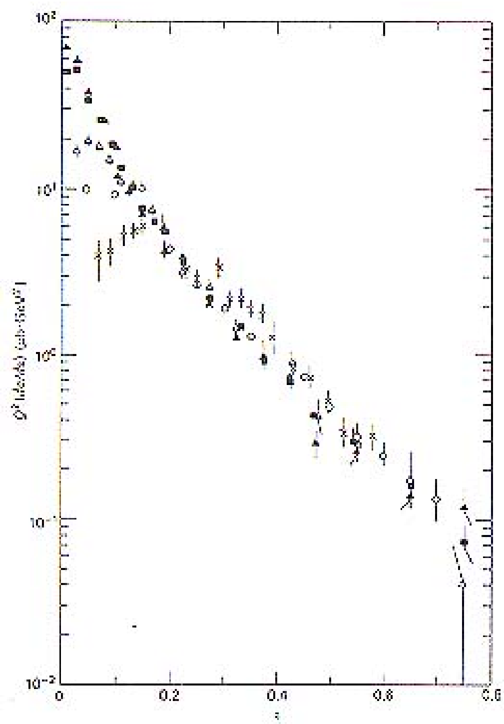
$$R_{e^+e^-} = \frac{\sigma(e^+e^- \to Hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_{i=1}^{nf} e_{q_i}^2$$

and verify that there are indeed three colors of quarks.

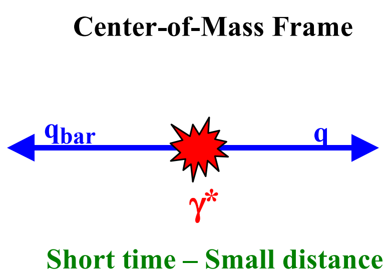


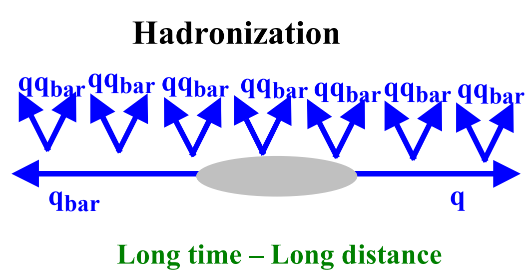
Electron-Positron Annihilations

Quark Fragmentation Functions: Measure the probability of finding a hadron of type h carrying the fraction z of the parent quarks momentum: $D_q^h(x,Q^2)$.



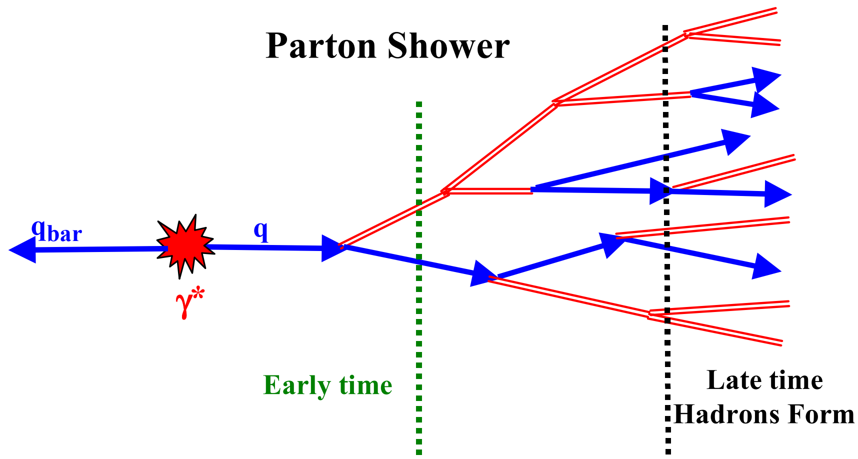
Hadronization:



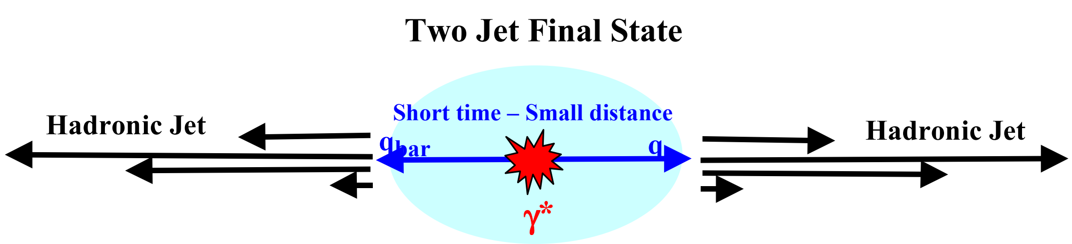


Electron-Positron Annihilations

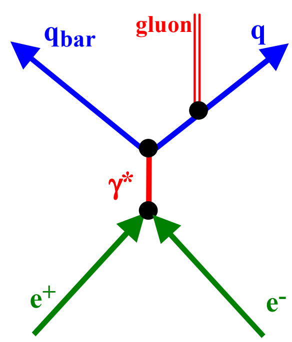
Parton Showers:



Quark Jets:



QCD Perturbative Corrections:



R(e^+e^-) is slightly larger due to **"final state interactions"**.

$$R_{e^+e^-} = \left(1 + \frac{\alpha_s(Q^2)}{\pi}\right) 3\sum_{i=1}^{nf} e_{q_i}^2$$

Electron-Positron Annihilations

Three-Jet Final State: