

Title: Graduate Course on Standard Model & Quantum Field Theory - 5A

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Abstract: Graduate Course on Standard Model & Quantum Field Theory

particle	Mass	$J^P$	B	L	$L_c$	$L_s$	$L_b$
graviton	0	2	0	0	0	0	0
photon	0	1	0	0	0	0	0
$\nu_e$	} < 1 eV? $\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0	0
$\nu_\mu$			0	0	0	0	0
$\nu_\tau$			0	0	0	0	0
$e^\pm$	0.51 MeV	$\frac{1}{2}$	$\pm 1$	0	$\pm 1$	0	0
$\mu^\pm$	105 MeV	$\frac{1}{2}$	$\pm 1$	0	$\pm 1$	0	0
$\pi^0$	140 MeV	0	$\pm 0$	0	$\pm 1$	0	0
$\pi^\pm$			$\pm 1$	0	$\pm 1$	0	0

$K^0, K^+, K^-$  } ~ 500 MeV    0     $\pm 1$   
 ( $\bar{u}s, u\bar{s}, \bar{d}s, \dots$ )

$p, \eta, \dots$  ... strongly-interacting bound states of quarks.  
 starting just above 1 GeV.  
 proton 938 MeV

$\eta$	$\eta'$	$\eta(549)$	$\eta(766)$	$\eta(958)$	$\eta(1300)$	$\eta(1405)$	$\eta(1450)$	$\eta(1700)$	$\eta(1760)$
$\pi^0$	$\pi^\pm$	$\pi(137)$	$\pi(167)$	$\pi(1300)$	$\pi(1670)$	$\pi(1700)$	$\pi(1760)$	$\pi(1900)$	$\pi(2160)$
$\rho^0$	$\rho^\pm$	$\rho(770)$	$\rho(1450)$	$\rho(1700)$	$\rho(1700)$	$\rho(1700)$	$\rho(1700)$	$\rho(1700)$	$\rho(1700)$
$\omega$	$\omega$	$\omega(782)$	$\omega(1420)$	$\omega(1640)$	$\omega(1640)$	$\omega(1640)$	$\omega(1640)$	$\omega(1640)$	$\omega(1640)$
$\phi$	$\phi$	$\phi(1020)$	$\phi(1680)$	$\phi(1680)$	$\phi(1680)$	$\phi(1680)$	$\phi(1680)$	$\phi(1680)$	$\phi(1680)$
$\eta'$	$\eta'$	$\eta'(958)$	$\eta'(1640)$	$\eta'(1640)$	$\eta'(1640)$	$\eta'(1640)$	$\eta'(1640)$	$\eta'(1640)$	$\eta'(1640)$
$\eta$	$\eta$	$\eta(549)$	$\eta(766)$	$\eta(958)$	$\eta(1300)$	$\eta(1405)$	$\eta(1450)$	$\eta(1700)$	$\eta(1760)$
$\pi$	$\pi$	$\pi(137)$	$\pi(167)$	$\pi(1300)$	$\pi(1670)$	$\pi(1700)$	$\pi(1760)$	$\pi(1900)$	$\pi(2160)$
$\rho$	$\rho$	$\rho(770)$	$\rho(1450)$	$\rho(1700)$	$\rho(1700)$	$\rho(1700)$	$\rho(1700)$	$\rho(1700)$	$\rho(1700)$
$\omega$	$\omega$	$\omega(782)$	$\omega(1420)$	$\omega(1640)$	$\omega(1640)$	$\omega(1640)$	$\omega(1640)$	$\omega(1640)$	$\omega(1640)$
$\phi$	$\phi$	$\phi(1020)$	$\phi(1680)$	$\phi(1680)$	$\phi(1680)$	$\phi(1680)$	$\phi(1680)$	$\phi(1680)$	$\phi(1680)$
$\eta'$	$\eta'$	$\eta'(958)$	$\eta'(1640)$	$\eta'(1640)$	$\eta'(1640)$	$\eta'(1640)$	$\eta'(1640)$	$\eta'(1640)$	$\eta'(1640)$
$\eta$	$\eta$	$\eta(549)$	$\eta(766)$	$\eta(958)$	$\eta(1300)$	$\eta(1405)$	$\eta(1450)$	$\eta(1700)$	$\eta(1760)$

$K^\pm, K_L^0, K_S^0$  { ~50 MeV 0  $\pm 1$  0 0 0 0 0 }  
 (us, us,  $\bar{u}d, \dots$ )  
 $\rho, \eta, \dots$  strongly-interacting bound states of quarks.  
 starting just less than 1 GeV.  
 $\rho(770)$   $\eta(549)$   $\eta(766)$   $\eta(958)$   $\eta(1300)$   $\eta(1405)$   $\eta(1450)$   $\eta(1700)$   $\eta(1760)$

$K^{\pm}$   
 $K_L^0, K_S^0$  }  $\sim 50 \text{ MeV}$    0    $\pm 1$    0   0   0   0   0  
 (us, us, ~~ud~~, ...)

$\pi, \eta, \dots$  strongly-interacting bound states of quarks.  
 starting just less than 1 GeV.

meson  
 (udd) (bound state)   438 MeV  
 baryon (udd)   710 MeV

$K$	1	1	0	0	0	0
$\frac{1}{2}$	0	1	0	0	0	0



$\left. \begin{matrix} K^+ \\ K^0 \\ K^- \end{matrix} \right\} \sim 50 \text{ MeV} \quad 0 \quad \pm 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0$   
 (is, us, ~~us~~, ...)

$\pi, \eta, \dots$  strongly-interacting bound states of quarks.  
 starting just less than 1 GeV.

proton (udd) (bound state)	938 MeV	$\frac{1}{2}$	1	1	0	0	0	0
neutron (udd)	940 MeV	$\frac{1}{2}$	0	1	0	0	0	0
u	$\sim 5 \text{ MeV}$							

$K^{\pm}$   
 $K_L^0, K_S^0$   $\left\{ \begin{array}{l} \sim 500 \text{ MeV} \\ 0 \end{array} \right.$   $\begin{array}{l} 0 \\ \pm 1 \\ 0 \end{array}$   $\begin{array}{l} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array}$   
 (us, us, sd, ...)

$\pi, \eta, \dots$  strongly-interacting bound states of quarks.  
 starting just less than 1 GeV.

proton (uud) (ground state) 938 MeV	$\frac{1}{2}$	1	1	0	0	0	0
neutron (udd) 940 MeV	$\frac{1}{2}$	0	1	0	0	0	0
u ~ 5 MeV	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
d ~ 10 MeV	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{2}{3}$	0	0	0	0

particle	mass	$J$	$C$	$B$	$L$	$L_e$	$L_\mu$	$L_\tau$
graviton	0	2		0	0	0	0	0
photon	0	1	0	0	0	0	0	0
$\nu_e$	} < 1eV? $\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0	0	0
$\nu_\mu$								
$\nu_\tau$								
$e^\pm$	0.511 MeV	$\frac{1}{2}$	$\pm 1$	0	$\pm 1$	$\pm 1$	0	0
$\mu^\pm$	105 MeV	$\frac{1}{2}$	$\pm 1$	0	$\pm 1$	0	0	0
$\pi^0$	140 MeV	0	0	0	$\pm 1$	0	$\pm 1$	0
$\pi^\pm$			$\pm 1$	0	0	0	0	0

$u$	$\sim 5$ MeV	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
$d$	$\sim 10$ MeV	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
$s$	$\sim 150$ MeV	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0

$s$	$\sim 150 \text{ MeV}$	$1/2$	$-1/3$	$1/3$	$0$	$0$	$0$	$0$
$c$	$\sim 1 \text{ GeV}$	$1/2$	$2/3$	$1/2$	$0$	$0$	$0$	$0$
$b$	$\sim 5 \text{ GeV}$	$1/2$	$-1/3$	$1/3$	$0$	$0$	$0$	$0$
$t$	$\sim 180 \text{ GeV}$	$1/2$	$2/3$	$1/3$	$0$	$0$	$0$	$0$
$\tau$	$\sim 1 \text{ GeV}$	$1/2$	$-1$	$0$	$1$	$0$	$0$	$1$

S	~ 150 MeV	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
		$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0

c	~ 1 GeV	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{6}$	0	0	0	0
b	~ 5 GeV	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
t	~ 180 GeV	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
$\tau$	~ 1 GeV	$\frac{1}{2}$	-1	0	1	0	0	-1
$W^+$	~ 80 GeV	1	$\pm 1$	0	0	0	0	0
$Z^0$	~ 90 GeV	1	0	0	0	0	0	0



$\nu_e$								
$\nu_\mu$								
$\nu_\tau$								
$e$								
$\mu$								
$\tau$								
$\pi^0$								
$\pi^\pm$								

$\left. \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \right\} < 1 \text{ eV? } \frac{1}{2}$   
 0.51 MeV  $\frac{1}{2}$   
 105 MeV  $\frac{1}{2}$   
 140 MeV 0  
 $\left. \begin{matrix} e \\ \mu \\ \tau \end{matrix} \right\} \begin{matrix} \frac{1}{2} \\ \frac{1}{2} \\ 0 \end{matrix}$   
 $\left. \begin{matrix} \pi^0 \\ \pi^\pm \end{matrix} \right\} \begin{matrix} 0 \\ \pm 1 \end{matrix}$   
 $\left. \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \right\} \begin{matrix} 0 \\ 0 \\ 0 \end{matrix}$   
 $\left. \begin{matrix} e \\ \mu \\ \tau \end{matrix} \right\} \begin{matrix} 0 \\ \pm 1 \\ \pm 1 \end{matrix}$   
 $\left. \begin{matrix} \pi^0 \\ \pi^\pm \end{matrix} \right\} \begin{matrix} 0 \\ \pm 1 \end{matrix}$   
 $\left. \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \right\} \begin{matrix} 0 \\ 0 \\ 0 \end{matrix}$   
 $\left. \begin{matrix} e \\ \mu \\ \tau \end{matrix} \right\} \begin{matrix} 0 \\ 0 \\ 0 \end{matrix}$   
 $\left. \begin{matrix} \pi^0 \\ \pi^\pm \end{matrix} \right\} \begin{matrix} 0 \\ 0 \end{matrix}$

$u$	$\sim 5 \text{ MeV}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
$d$	$\sim 10 \text{ MeV}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
$s$	$\sim 150 \text{ MeV}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0

$c$	$\sim 1 \text{ GeV}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
$b$	$\sim 5 \text{ GeV}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
$t$	$\sim 180 \text{ GeV}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
$\tau$	$\sim 1 \text{ GeV}$	$\frac{1}{2}$	-1	0	-1	0	0	-1
$W^\pm$	$\sim 80 \text{ GeV}$	1	$\pm 1$	0	0	0	0	-
$Z^0$	$\sim 90 \text{ GeV}$	1	0	0	0	0	0	0

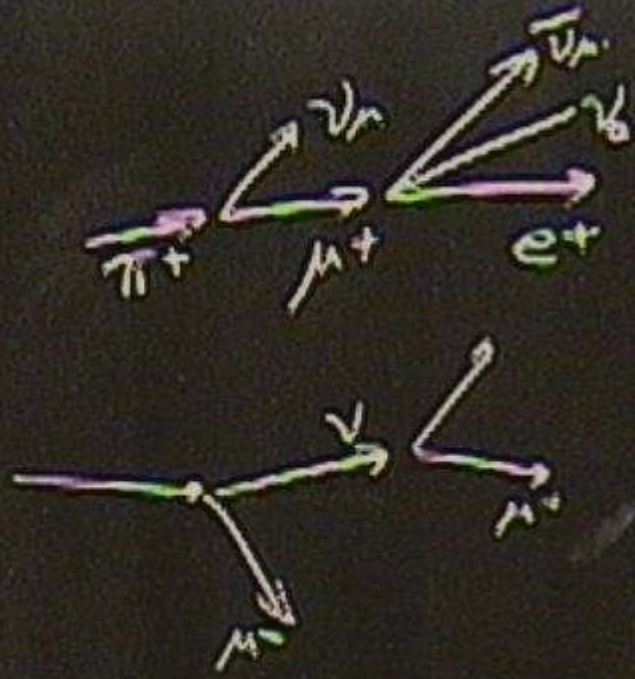
$e^+$	0.51 MeV	$1/2$	$1/2$	0	$\pm 1$	0	0	0	0
$\mu^+$	105 MeV	$1/2$	$1/2$	0	$\pm 1$	$\pm 1$	0	0	0
$\pi^0$	140 MeV	0	0	0	$\pm 1$	0	0	$\pm 1$	0
$\pi^\pm$		0	$\pm 1$	0	0	0	0	0	0

starting just less than 1 GeV.

proton (udd) (ground state)	938 MeV	$1/2$	1	1	0	0	0	0	0
neutron (udd)	940 MeV	$1/2$	0	1	0	0	0	0	0
u	$\sim 5$ MeV	$1/2$	$2/3$	$1/3$	0	0	0	0	0
d	$\sim 10$ MeV	$1/2$	$-1/3$	$2/3$	0	0	0	0	0
s	$\sim 150$ MeV	$1/2$	$-1/3$	$1/3$	0	0	0	0	0

$Z^0$	$\sim 1$ GeV	$1/2$	-1	0	1	0	0	0	0
$Z^0$	$\sim 80$ GeV	1	$\pm 1$	0	0	0	0	0	0
8 gluons	$\sim 90$ GeV	1	0	0	0	0	0	0	0

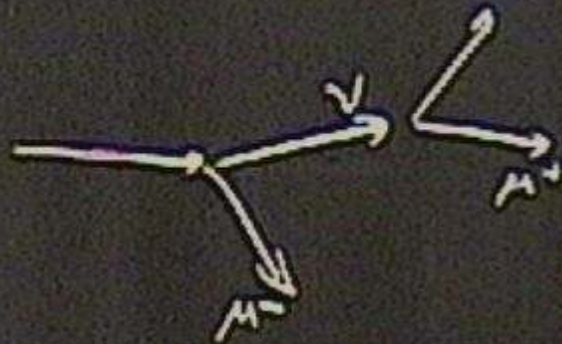
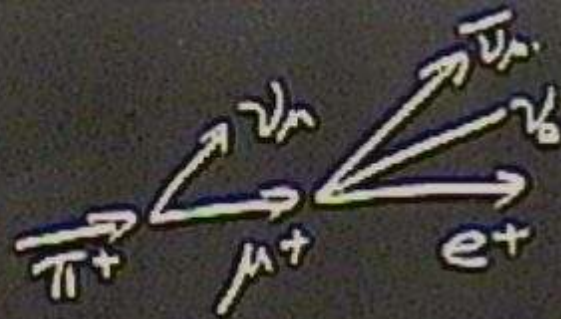
0  
0  
0  
0  
0



$$q \nu / fm \sim 10^{-15} m$$

$$p \sim \hbar / \lambda \sim 100 \text{ MeV}/c$$

$$\sim 1 m^{-1}$$

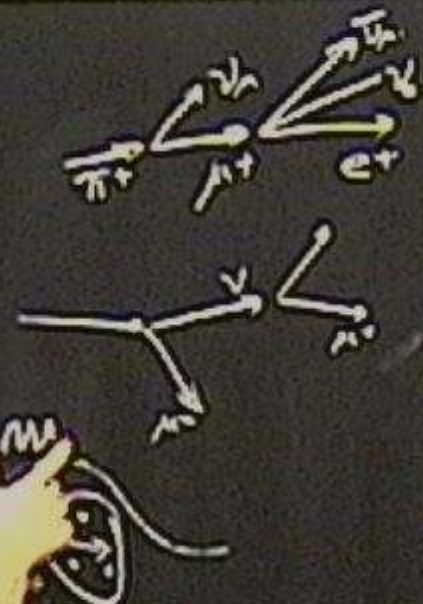


$$q\nu / fm \sim 10^{-15} m$$

$$p\nu \frac{h\nu}{q} = 100 \text{ MeV}/c$$

$$E = \sqrt{p^2 + m^2} \approx p$$

0 0 0  
0 0 0  
0 0 0  
0 0 0  
0 0 0



$$r \sim 1 \text{ fm} \sim 10^{-15} \text{ m}$$
$$E_{\text{cm}} = 100 \text{ MeV}/c$$
$$E = \sqrt{p^2 + m^2} \approx p$$

proton (uud) (ground state) 150 MeV	$\frac{1}{2}$	1	1	0	0	0	0
neutron (udd) 740 MeV	$\frac{1}{2}$	0	1	0	0	0	0
u ~ 5 MeV	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
d ~ 10 MeV	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{2}{3}$	0	0	0	0
s ~ 100 MeV	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0

$T^+$ 1 GeV	$\frac{1}{2}$	-1	0	1	0	0	1
90 GeV	1	$\pm 1$	0	0	0	0	0
GeV	1	0	0	0	0	0	0

proton	938 MeV	$\frac{1}{2}$	1	1	0	0	0	0
(uud) bound state								
neutron	939 MeV	$\frac{1}{2}$	0	1	0	0	0	0
(udd)								
u	$\sim 5$ MeV	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0	0	0
d	$\sim 10$ MeV	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
s	$\sim 150$ MeV	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0

$\tau^-$	$\sim 1$ GeV	$\frac{1}{2}$	-1	0	1	0	0	1
$W^-$	$\sim 80$ GeV	1	$\pm 1$	0	0	0	0	1
$Z^0$	$\sim 90$ GeV	1	0	0	0	0	0	0
$\gamma$	0	1	0	0	0	0	0	0

proton 938 MeV  
 (udd) (planned stable)  
 neutron (udd) 940 MeV

	$\frac{1}{2}$	1	1	0	0	0	0
u	$\frac{1}{2}$	0	1	0	0	0	0
d	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
s	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0

$\tau^-$  ~ 1 GeV  
 $W^\pm$  ~ 80 GeV  
 $Z^0$  ~ 90 GeV  
 $\gamma$  ~ 0

	$\frac{1}{2}$	-1	0	1	0	0	1
	1	1	0	0	0	0	0
	1	0	0	0	0	0	0
	1	0	0	0	0	0	0

proton  $938 \text{ MeV}$   
 (udd) ground state  
 neutron (udd)  $940 \text{ MeV}$

$u$	$\sim 5 \text{ MeV}$	$\frac{1}{2}$	$0$	$1$	$0$	$0$	$0$	$0$	$0$
$d$	$\sim 10 \text{ MeV}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	$0$	$0$	$0$	$0$	$0$
$s$	$\sim 150 \text{ MeV}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	$0$	$0$	$0$	$0$	$0$

$\tau^-$	$\sim 1 \text{ GeV}$	$\frac{1}{2}$	$-1$	$0$	$1$	$0$	$0$	$0$	$1$
$\nu_\tau$	$\sim 80 \text{ GeV}$	$1$	$\pm 1$	$0$	$0$	$0$	$0$	$0$	$0$
$Z^0$	$\sim 90 \text{ GeV}$	$1$	$0$	$0$	$0$	$0$	$0$	$0$	$0$
$\gamma$	$\sim 0$	$1$	$0$	$0$	$0$	$0$	$0$	$0$	$0$

proton  $938 \text{ MeV}$   
 (used ground state)  
 neutron (udd)  $940 \text{ MeV}$

		$\frac{1}{2}$	1	1	0	0	0	0
u	$\sim 5 \text{ MeV}$	$\frac{1}{2}$	0	1	0	0	0	0
d	$\sim 10 \text{ MeV}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
s	$\sim 150 \text{ MeV}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0

$\tau^-$	$\sim 1 \text{ GeV}$	$\frac{1}{2}$	-1	0	1	0	0	1
$W^\pm$	$\sim 80 \text{ GeV}$	1	$\pm 1$	0	0	0	0	0
$Z^0$	$\sim 90 \text{ GeV}$	1	0	0	0	0	0	0
$\delta$ gluons	$\sim 0$	1	0	0	0	0	0	0

$\nu_e$	$< 1\text{eV? } \frac{1}{2}$	0	0	$\frac{2}{3}$	0	0	0	0
$\nu_\mu$	0.51 MeV	$\frac{1}{2}$	0	0	0	0	0	0
$\nu_\tau$	1.05 MeV	$\frac{1}{2}$	0	0	0	0	0	0
$\pi^0$	140 MeV	0	0	0	0	0	0	0
$\pi^\pm$			$\pm 1$	0	0	0	0	0

(quark flavor table)  
neutrons (udd)

	700 MeV	$\frac{1}{2}$	0	1	0	0	0	0
u	$\sim 5\text{ MeV}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
d	$\sim 10\text{ MeV}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{2}{3}$	0	0	0	0
s	$\sim 150\text{ MeV}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0

$t$	$\sim 180\text{ GeV}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	0
$b$	$\sim 1\text{ GeV}$	$\frac{1}{2}$	-1	0	0	0	0	0
$W^\pm$	$\sim 80\text{ GeV}$	1	$\pm 1$	0	0	0	0	-
$Z$	$\sim 90\text{ GeV}$	1	0	0	0	0	0	0
8 gluons	$\sim 0$	1	0	0	0	0	0	0

Spin-1 particles:

photon ( $\gamma$ )

$W^\pm$

$Z$

8 gluons.

Spin=1 particles:

- [ photon ( $\gamma$ )
- [  $W^+$
- [  $Z$
- [ 8 gluons.

$$G = SU_c(3)$$

Spin=1 particles:

[ photon ( $\gamma$ )  
[  $W^+$   
[  $Z$   
[ 8 gluons.

$$G = \underbrace{SU(3)}_{\substack{\text{gluons} \\ \text{colour}}} \times \underbrace{SU_L(2) \times U_Y(1)}_{\gamma, W, Z}$$

Spin=1 particles:

photon ( $\gamma$ )

$W^\pm$   
 $Z$

8 gluons.

$$G = SU(3) \times SU_2(2) \times U_Y(1)$$

gluons

colour

$\gamma, W, Z$

Hyper charge

$U(1)$  electromagnetism

spin 1 particles.

$\left[ \begin{array}{l} \text{photon } (\gamma) \\ W^\pm \\ Z \\ 8 \text{ gluons.} \end{array} \right.$

$$G = SU(3) \times SU_L(2) \times U_Y(1)$$

gluons  
 colour  
 $\gamma, W, Z$   
 Hyper charge

$SU(N)$   
 $N \times N$   
 unitary  
 determinant 1

$U(1)$  electromagnetism

$\pi^0$	$\pi^\pm$	$\rho^0$	$\rho^\pm$	$\omega$	$\eta$	$\eta'$	$\phi$	$\omega$	$\rho^0$	$\rho^\pm$	$\omega$	$\eta$	$\eta'$	$\phi$
$< 140 \text{ MeV}$	$135 \text{ MeV}$	$770 \text{ MeV}$	$770 \text{ MeV}$	$770 \text{ MeV}$	$548 \text{ MeV}$	$958 \text{ MeV}$	$1020 \text{ MeV}$	$770 \text{ MeV}$	$770 \text{ MeV}$	$770 \text{ MeV}$	$770 \text{ MeV}$	$548 \text{ MeV}$	$958 \text{ MeV}$	$1020 \text{ MeV}$
$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$
$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$
$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$
$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$
$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$

$u$	$d$	$s$	$c$	$b$	$t$	$\nu_e$	$\nu_\mu$	$\nu_\tau$
$\sim 5 \text{ MeV}$	$\sim 10 \text{ MeV}$	$\sim 150 \text{ MeV}$	$\sim 1.3 \text{ GeV}$	$\sim 4.2 \text{ GeV}$	$\sim 170 \text{ GeV}$	$0$	$0$	$0$
$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$	$1/2$
$2/3$	$1/3$	$1/3$	$2/3$	$2/3$	$2/3$	$0$	$0$	$0$
$1/3$	$2/3$	$2/3$	$1/3$	$1/3$	$1/3$	$0$	$0$	$0$
$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$
$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$
$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$

$t$	$\tau$	$W^\pm$	$Z$	$\gamma$	$g$	$g$	$g$	$g$
$\sim 170 \text{ GeV}$	$\sim 1.8 \text{ GeV}$	$\sim 80 \text{ GeV}$	$\sim 90 \text{ GeV}$	$0$	$0$	$0$	$0$	$0$
$1/2$	$1/2$	$1$	$1$	$1$	$1$	$1$	$1$	$1$
$2/3$	$-1$	$2/3$	$1/3$	$0$	$0$	$0$	$0$	$0$
$1/3$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$
$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$
$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$
$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$	$0$

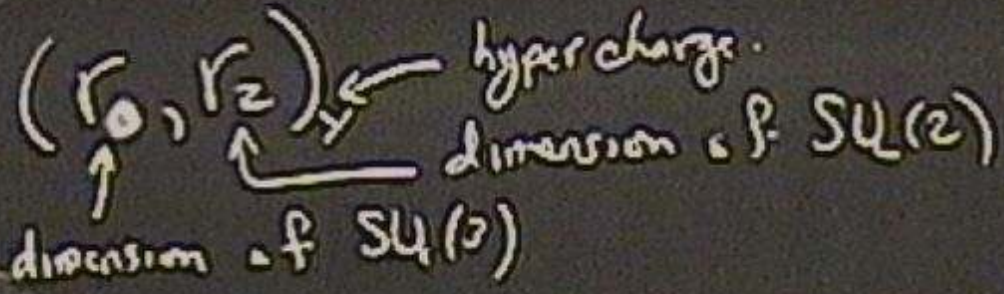


Unit 1

How the fermions transform under  $G$ :

unit 1

How the fermions transform under G:



How the fermions transform under  $G$ :

$(r_1, r_2)$  ← hypercharge.  
 ↑ dimension of  $SU(3)$   
 ↑ dimension of  $SU(2)$

For leptons we have:

$\nu_i \quad i=1,2,3$

$\ell_i \quad i=1,2,3 \leftarrow \text{LH: } \bar{e}_L, \bar{\mu}_L, \bar{\tau}_L$

$E_i \quad i=1,2,3 \leftarrow \text{RH: } e_R, \mu_R, \tau_R$

How the fermions transform under  $G$ :

$$\begin{array}{c}
 (r_0, r_2) \leftarrow \text{hypercharge} \\
 \uparrow \quad \quad \quad \uparrow \\
 \text{dimension of } SU(3) \quad \quad \text{dimension of } SU(2)
 \end{array}$$

For leptons we have:

$$\begin{array}{l}
 \psi_i \quad i=1,2,3 \\
 e_L, \mu_L \rightarrow \psi_i \quad i=1,2,3 \\
 e_R, \mu_R \rightarrow E_i \quad i=1,2,3
 \end{array}$$



How the fermions transform under  $G$ :

$$\begin{array}{c}
 (r_0, r_2) \leftarrow \text{hypercharge} \\
 \uparrow \quad \quad \quad \uparrow \\
 \text{dimension of } SU(3) \quad \quad \text{dimension of } SU(2)
 \end{array}$$

For leptons we have:

$$\begin{array}{l}
 \psi_i \quad i=1,2,3 \\
 e_{i,\mu} \rightarrow \ell_i \quad i=1,2,3 \\
 \bar{e}_{i,\mu} \rightarrow E_i \quad i=1,2,3
 \end{array}$$



How the fermions transform under G:

$(r_1, r_2)$  ← hypercharge.  
 $\uparrow$  ← dimension of  $SU(2)$   
 $\uparrow$  ← dimension of  $SU(3)$

For leptons we have:

$\nu_i$   $i=1,2,3$

$e_L, \mu_L \rightarrow \ell_i$   $i=1,2,3$

$e_R, \mu_R \rightarrow E_i$   $i=1,2,3$

'family'

$(1, 2)_{-1/2}$   
 $(1, 1)_{+1}$

Majorana spinors:  $E_i$

$$\delta\psi_L \equiv \underbrace{\frac{1}{2}(1+\gamma_5)}_{\gamma_L} \delta\psi = \gamma_L \left[ \underbrace{i\omega_2^a(t_A)}_{SU_2(1)} \psi + \underbrace{i\omega_2^a(t_A)}_{SU_2(2)} \psi + \underbrace{i\omega_1 y}_{U_1(1)} \psi \right]$$



Majorana spinors:  $E_i$

$$\delta\psi_L \equiv \underbrace{\frac{1}{2}(1+\gamma_5)}_{\gamma_L} \delta\psi = \gamma_L \left[ \underbrace{i\omega_2^a(t_a)}_{SU_2(1)} \psi + \underbrace{i\omega_3^a(t_a)}_{SU_2(2)} \psi + \underbrace{i\omega_1 y}_{U_1(1)} \psi \right]$$

$$\Rightarrow \delta\psi_R = \frac{1}{2}(1-\gamma_5) \delta\psi = \gamma_R \left[ -i\omega_2^a(t_a)^* \psi - i\omega_3^a(t_a)^* \psi - i\omega_1 y \psi \right]$$

Majorana spinors:  $E_i$

$$\delta\psi_L \equiv \underbrace{\frac{1}{2}(1+\gamma_5)}_{\gamma_L} \delta\psi = \gamma_L \left[ \underbrace{i\omega_2^a(t_a)}_{SU_2(1)} \psi + \underbrace{i\omega_2^a(t_a)}_{SU_2(2)} \psi + \underbrace{i\omega_1 y}_{U_1(1)} \psi \right]$$

$$\Rightarrow \delta\psi_R = \frac{1}{2}(1-\gamma_5)\delta\psi = \gamma_R \left[ -i\omega_2^a(t_a)^* \psi - i\omega_2^a(t_a)^* \psi - i\omega_1 y \psi \right]$$

$\psi_R = M\psi_L^*$  if  $\psi$  is Majorana



$$Y_L \delta E_1 = Y_L \left[ \underset{\omega_1^*}{0} + \underset{\omega_2^*}{0} + i\omega_1 E_1 \right]$$



How the fermions transform under G:

$$\begin{array}{c}
 (\nu_1, \nu_2)_{\frac{1}{2}} \leftarrow \text{hypercharge} \\
 \uparrow \quad \quad \quad \uparrow \\
 \text{dimension of } SU(2) \quad \text{dimension of } SU(2)
 \end{array}$$

For leptons we have:

- $\nu_i \quad i=1,2,3$
- $e_L, \mu_L \rightarrow e_i \quad i=1,2,3$
- $e_R, \mu_R \rightarrow E_i \quad i=1,2,3$

"family"

$$\left. \begin{array}{l}
 (1, 2)_{-\frac{1}{2}} \\
 (1, 1)_{+1}
 \end{array} \right\}$$

$$\gamma_L \delta E_i = \gamma_L \left[ \underset{\omega_1}{0} + \underset{\omega_2}{0} + i\omega_1 E_i \right]$$

$$l_i = \begin{pmatrix} v_i \\ e_i \end{pmatrix}$$



$$\gamma_L \delta E_i = \gamma_L \left[ \underset{\omega_1}{0} + \underset{\omega_2}{0} + i\omega_1 E_i \right]$$

$$l_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix} \quad \gamma_L \delta l_i = \gamma_L \left[ \underset{\omega_1}{0} + i\omega_2 \left( \frac{\tau_1}{2} \right) l_i + i\omega_1 \left( -\frac{1}{2} \right) l_i \right]$$

$t_a = \frac{1}{2} \tau_a$   
 $\uparrow$   
 Pauli matrix

$$l_i = \begin{pmatrix} v_i \\ e_i \end{pmatrix} \quad \gamma_L \delta l_i = \gamma_L \left[ \underset{\omega_3}{0} + i \omega_2 \left( \frac{\tau_1}{2} \right) l_i + i \omega_1 \left( -\frac{1}{2} \right) l_i \right]$$

↑ Pauli matrix

Rule  $\tau_3 = \frac{1}{2} \tau_3 = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$$\gamma_L \delta E_i = \gamma_L \left[ \underset{\omega_3^*}{0} + \underset{\omega_2^*}{0} + i\omega_1 E_i \right]$$

$$l_i = \begin{pmatrix} v_i \\ e_i \end{pmatrix} \quad \gamma_L \delta l_i = \gamma_L \left[ \underset{\omega_3^*}{0} + i\omega_2^* \left( \frac{\tau_1}{2} \right) l_i + i\omega_1 \left( -\frac{1}{2} \right) l_i \right]$$

$t_a = \frac{1}{2} \tau_1$   
 ↑  
 Pauli  
 matrix

Rule     Rule      $t_3 = \frac{1}{2} \tau_3 = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$Q = t_3 + \gamma$  for the particle destroyed by the LH field.

How the fermions transform under G:

$(T_0, T_2) \leftarrow$  hypercharge  
 $\uparrow \quad \quad \quad \uparrow$   
 dimension of  $SU(2)$   
 dimension of  $SU(3)$

leptons we have:

- $\nu_i \quad i=1,2,3$
- $e_L, \mu_L \rightarrow \ell_i \quad i=1,2,3$
- $e_R, \mu_R \rightarrow E_i \quad i=1,2,3$

'family'

$\left. \begin{array}{l} \\ \\ \end{array} \right\} \begin{array}{l} (1, 2)_{-1/2} \\ (1, 1)_{+1} \end{array}$

$$\gamma_L \delta E_i = \gamma_L \left[ \underset{\omega_1}{0} + \underset{\omega_2}{0} + i \omega_1 E_i \right]$$

$t_a = \frac{1}{2} \tau_a$   
 ↑  
 Pauli matrix

$\begin{pmatrix} v_i \\ e_i \end{pmatrix}$

$$\gamma_L \delta l_i = \gamma_L \left[ \underset{\omega_1}{0} + i \omega_2 \left( \frac{\tau_1}{2} \right) l_i + i \omega_1 \left( -\frac{1}{2} \right) l_i \right]$$

Rule     Rule      $t_3 = \frac{1}{2} \tau_3 = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$Q = t_3 + \gamma$  for the particle destroyed by the LH field.

$$\gamma_L \delta E_i = \gamma_L \left[ \underset{\omega_1}{0} + \underset{\omega_2}{0} + i\omega_1 E_i \right]$$

$$l_i = \begin{pmatrix} v_i \\ e_i \end{pmatrix} \quad \gamma_L \delta l_i = \gamma_L \left[ \underset{\omega_2}{0} + i\omega_2 \left( \frac{\tau_1}{2} \right) l_i + i\omega_1 \left( -\frac{1}{2} \right) l_i \right]$$

$t_a = \frac{1}{2} \tau_a$   
 ↑  
 Pauli matrix

Rule     Rule      $t_3 = \frac{1}{2} \tau_3 = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$Q = t_3 + Y$  for the particle destroyed by the LH field.

How the fermions transform under  $G$ :

$(r_0, r_2) \leftarrow$  hypercharge.  
 $\uparrow$  dimension of  $SU(2)$   
 $\uparrow$  dimension of  $SU(3)$

For leptons we have:

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

$\nu_i \quad i=1,2,3$   
 $e_L, \mu_L \rightarrow \bar{e}_i \quad i=1,2,3$   
 $\bar{\nu}_i, \bar{\mu}_i \rightarrow E_i \quad i=1,2,3$   
 'family'

$\left. \begin{matrix} (1, 2)_{-1/2} \\ (1, 1)_{+1} \end{matrix} \right\}$