1 Interazioni

Interazione	Gravità	Electromagnetic	Forte	Debole
Between	tutte	tutte	quark	lep, quark, l-q
Teoria	Newton	QED	QCD	
Bosone	gravitone	fotone γ	8 gluoni g	W^+, Z^0
Massa bos		0	0	100 GeV
Source	massa	electric ch.	colore	weak ch.
CC	KM^2	$\alpha = e^2/4\pi$ $= 1/137$	$\alpha_s \leq 1$	$M^2 G_F$ $= 1/29$
Potenziale	$-GMm/r$	$-\alpha/r$	$-4\alpha_s/3r + kr$	$-f\alpha_s/r$
Lifetime (s)		10^{-19}	10^{-23}	10^{-10}
σ (cm^{-3})			10^{-26}	10^{-38}

2 Simmetrie

Parità	P	C	CP	G
Espressione	$P\Phi(\mathbf{r}) = \Phi(-\mathbf{r})$	$C\Phi(\pi^+) = \Phi(\pi^-)$ $C\Phi(\pi^0) = \pm\Phi(\pi^0)$	$H = \frac{\mathbf{s}\cdot\mathbf{p}}{sp}$	$G = CR$ $= Ce^{i\pi I_2}$
Conservazione	forte, e.m.	forte, e.m.	debole	

3 Leptoni

Leptone		Massa (MeV)	Carica (e)	L_e	L_μ	L_τ
Elettrone	e^-	0.5	-1	1	0	0
Neutrino	ν_e	<3 eV	0	1	0	0
Muone	μ^-	105	-1	0	1	0
Neutrino	ν_μ	<0.19	0	0	1	0
Tau	τ^-	1777	-1	0	0	1
Neutrino	ν_τ	<18.2	0	0	0	1

Particella	I	II	III	Q (e)	Isospin	Ipercarica	Colore
Leptoni LH	ν_e	ν_μ	ν_τ	0	1/2	-1	–
	e	μ	τ	-1	1/2	-1	–
Leptoni RH	e	μ	τ	-1	0	-2	–

4 Quarks

$$\text{Ipercarica: } Y = B^* + S \qquad \text{Numero barionico: } B^* = \frac{1}{3}$$

$$Q = I_3 + \frac{Y}{2}$$

Quark		m_q (GeV)	m'_q (MeV)	Q (e)	S	C	B	T	I_3	Y
Up	u	0.33	1.5 – 3.3	2/3	0	0	0	0	1/2	1/3
Down	d	0.33	3.5 – 6.0	−1/3	0	0	0	0	−1/2	1/3
Charme	c	1.58	1270	2/3	0	1	0	0	1/2	1/3
Strange	s	0.47	104	−1/3	−1	0	0	0	0	−2/3
Top	t	174	171 200	2/3	0	0	0	1	1/2	1/3
Bottom	b	4.58	4200	−1/3	0	0	−1	0	−1/2	1/3

Particella	I	II	III	Q (e)	Isospin	Ipercarica	Colore
Quarks LH	u	c	t	+2/3	1/2	+1/3	r, b, g
	d	s	b	−1/3	1/2	+1/3	r, b, g
Quarks RH	u	c	t	+2/3	0	+4/3	r, b, g
	d	s	b	−1/3	0	−2/3	r, b, g

4.1 Quark top

$$p + \bar{p} \to t + \bar{t} + any$$
$$t \to W + b \to l + \nu_l + b \qquad t \to W + b \to \bar{q} + q' + b$$
$$t + \bar{t} \to W^+ + B + W^- + \bar{b} \to \bar{l} + \nu_l + b + l + \bar{\nu}_l + \bar{b} \to l + \bar{l} + \mathbf{p_T} + (\leq 2 \text{ jets})$$
$$t + \bar{t} \to W^+ + B + W^- + \bar{b} \to \tau^+ + \nu_\tau + b + \tau^- + \bar{\nu}_\tau + \bar{b} \to \tau^+ + \tau^- + \mathbf{p_T} + (\leq 2 \text{ jets})$$
$$t + \bar{t} \to W^+ + B + W^- + \bar{b} \to \tau + \nu_\tau + b + l + \bar{\nu}_l + \bar{b} \to \tau + l + \mathbf{p_T} + (\leq 2 \text{ jets})$$
$$t + \bar{t} \to W^+ + B + W^- + \bar{b} \to \bar{l} + \nu_l + b + q' + \bar{q} + \bar{b} \to l + \mathbf{p_T} + (\leq 4 \text{ jets})$$
$$t + \bar{t} \to W^+ + B + W^- + \bar{b} \to \tau + \nu_\tau + b + q' + \bar{q} + \bar{b} \to \tau + \mathbf{p_T} + (\leq 4 \text{ jets})$$
$$t + \bar{t} \to W^+ + B + W^- + \bar{b} \to \bar{q}' + q + b + q' + \bar{q} + \bar{b} \to (\leq 6 \text{ jets})$$

5 Mesoni

$$\Delta E_{hf}(qq) = \frac{4\pi\alpha_s}{9} |\Psi(0)| \sigma_\mathbf{i}\sigma_\mathbf{j} = \frac{\Delta E_{hf}(q\bar{q})}{2}$$
$$J^{PC} : \begin{cases} 0 & \text{pseudoscalari} \\ 1 & \text{vettori} \end{cases}$$

Mesone	Composizione	Carica (e)	Massa (MeV)	Decadimento	J^{PC}
π^+	$u\bar{d}$	$+1$	140	$\mu^+\nu_\mu$	0^-
π^0	$\frac{d\bar{d}-u\bar{u}}{\sqrt{2}}$	0	135	$\gamma\gamma$	0^{-+}
π^-	$d\bar{u}$	-1	140	$\mu^-\bar{\nu}_\mu$	0^-
η_8	$\frac{d\bar{d}+u\bar{u}-2s\bar{s}}{\sqrt{6}}$	0	549	$\gamma\gamma$	0^{-+}
η_0	$\frac{d\bar{d}+u\bar{u}+s\bar{s}}{\sqrt{3}}$	0	958	2γ, $\eta+2\pi$	0^{-+}
B^+	$u\bar{b}$	$+1$	5279		0^-
B^0	$d\bar{b}$	0	5279.4		0^-
B^-	$s\bar{b}$	-1	5369.6		0^-
B_c^+	$c\bar{b}$	$+1$	6400		0^-
D^+	$c\bar{d}$	$+1$	1869		0^-
D^0	$c\bar{u}$	0	1864		0^-
D^-	$s\bar{c}$	-1	1968		0^-
K^+	$u\bar{s}$	$+1$	494	$\mu^+\nu_\mu$	0^-
K^0	$d\bar{s}$	0	498	$\pi^+\pi^-$	0^-
K^-	$s\bar{u}$	-1	494	$\mu^-\bar{\nu}_\mu$	0^-
$\bar{K}^0$	$s\bar{d}$	0	498	$\pi^+\pi^-$	
K^{*+}	$u\bar{s}$	$+1$	892	$K\pi$	1^{--}
K^{*0}	$d\bar{s}$	0	892	$K\pi$	1^{--}
K^{*-}	$s\bar{u}$	-1	892	$K\pi$	1^{--}
ρ^+	$d\bar{u}$	$+1$	776	2π	1^-
ρ^0	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	0	776	2π	1^{--}
ρ^-	$u\bar{d}$	-1	776	2π	1^-
ω	$\frac{d\bar{d}+u\bar{u}}{\sqrt{2}}$	0	783	3π	1^{--}
Φ	$s\bar{s}$	0	1019	$K\bar{K}$	1^{--}
J/Ψ	$c\bar{c}$	0	3097		1^{--}
Υ	$b\bar{b}$	0	9460.3	$B^0\bar{B}^0$	1^{--}
θ	$t\bar{t}$	0		2π	$1^-, 0^+$

5.1 Mesone K

$$|K_1\rangle = \frac{|K^0\rangle + |\bar{K}^0\rangle}{\sqrt{2}} \qquad |K_2\rangle = \frac{|K^0\rangle - |\bar{K}^0\rangle}{\sqrt{2}}$$

$$CP\,|K_1\rangle = +1\,|K_1\rangle \qquad CP\,|K_2\rangle = -1\,|K_2\rangle$$

Produzione		Decadimento		Lifetime (s)
K^0	$S=+1$	$K_1 = K_S \to 2\pi$	$CP=+1$	$\tau_1 = 0.9\cdot 10^{-10}$
$\bar{K}^0$	$S=-1$	$K_2 = K_L \to 3\pi$	$CP=-1$	$\tau_2 = 0.5\cdot 10^{-7}$

$$\pi^- + p \to \Lambda + K^0 \qquad \pi^- + p \to \bar{K}^0 + K^+ + p \qquad \pi^- + p \to \bar{K}^0 + \bar{\Lambda} + n + n$$

S: $0; 0; -1; +1$ S: $0; 0; -1; +1; 0$ S: $0; 0; -1; +1; 0; 0$

$$\left|K_S^0\right\rangle = \frac{\left|K_1\right\rangle + \epsilon\left|K_2\right\rangle}{\sqrt{1+\epsilon^2}} \qquad \left|K_L^0\right\rangle = \frac{\left|K_2\right\rangle + \epsilon\left|K_1\right\rangle}{\sqrt{1+\epsilon^2}} \qquad |\epsilon| = 2.3 \cdot 10^{-3}$$

6 Barioni

$$M = M_0 + M_1 Y + M_2 \left[I\left(I+1\right) - \frac{Y^2}{4}\right]$$

$$K = \frac{4\pi\alpha_s}{9}\left|\Psi\left(0\right)\right|^2$$

$$\Delta E_{fs} = -\alpha^4 m \left(\frac{1}{4n^2}\right)\left(\frac{4n}{2J+1} - \frac{3}{2}\right)$$

$$\Delta E_{hf} = \alpha^4 m \left(\frac{m}{m_p}\right)\left(\frac{\gamma_p}{2n^3}\right)\left(\frac{\pm 4}{\left(2F+1\right)\left(2I+1\right)}\right)$$

Barione		Quark	Carica (e)	Massa (MeV)	$\Delta E_{hf}/K$	J^P
N		qqq		~ 939	$-3/m_n^2$	
	p	uud	$+1$			$1/2^+$
	n	udd	0			$1/2^+$
Δ		qqq		~ 1232		
	Δ^{++}	uuu	$+2$			$3/2^+$
	Δ^+	duu	$+1$			$3/2^+$
	Δ^0	ddu	0			$3/2^+$
	Δ^-	ddd	-1			$3/2^+$
Σ		qqs		~ 1193	$1/m_n^2 - 4/\left(m_n m_s\right)$	
Σ		qqs		~ 1384	$1/m_n^2 + 2/\left(m_n m_s\right)$	
	Σ^+	uus	$+1$			$1/2^+$
	Σ^0	dus	0			$1/2^+$
	Σ^-	dds	-1			$1/2^+$
	Σ_c^{++}	uuc	$+2$	2455		$1/2^+$
Ξ		qss		~ 1318	$1/m_n^2 - 4/\left(m_n m_s\right)$	
Ξ		qss		~ 1533	$1/m_n^2 + 2/\left(m_n m_s\right)$	
	Ξ^0	uss	0			$1/2^+$
	Ξ^-	dss	-1			$1/2^+$
	Λ	uds	0	1116	$-3/m_n^2$	$1/2^+$
	Λ_b^0	udb	0	5624		$1/2^+$
	Λ_c^+	udc	$+1$	2285		$1/2^+$
	Ω^-	sss	-1	1672	$3/m_n^2$	$3/2^+$

7 Reazioni e decadimenti

$N\left(t\right) = N\left(0\right)e^{-\Gamma t} = \sigma L_{int}$ Cross section: $\sigma = \frac{W_{if}}{\Phi}$ Decay rate: $\Gamma = W_{if}$

$$\text{Event rate: } R = \frac{dN}{dt} = \sigma L \qquad \text{Luminosity: } L_{\text{int}} = \int L dt$$

$$\text{Flux: } \Phi = n_a v_i \qquad \frac{dN}{dt} = \Phi n_b \sigma = n_a v_i n_b \sigma$$

$$\text{Transition rate: } W_{if} = \Phi\sigma = v_i \sigma \qquad M_{if} = \int \Psi L_{int} dV \qquad \rho_f = \frac{dN}{dE_0}$$

$$\text{Fermi golden rule: } W_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 \rho_f$$

Decadimento	$a \to b + c$	$a + b \to c + d$
Diff decay rate	$\frac{1}{8\pi m_a} \int |M_{if}|^2 \frac{|\mathbf{p}|}{E^*} dE^* \delta(m_a - E^*)$	
Decay rate	$\frac{|\mathbf{p}||M_{if}|^2}{8\pi m_a^2}$	$\sigma\Phi$
Diff cross section	$\frac{\Gamma}{\Phi}$	$\frac{1}{(8\pi)^2} \frac{|M_{if}|^2}{(E_a+E_b)^2} \frac{\mathbf{p}_f}{\mathbf{p}_i}$

$$\text{Breit-Wigner formula relativistica: } P(m) \propto \frac{1}{(m - m_0)^2 + \frac{\Gamma}{4}}$$

8 QED

$$\text{Schrödinger: } \left(-\frac{1}{2m}\right) \nabla^2 \Psi = i \frac{\partial \Phi}{\partial t}$$

$$\text{Klein-Gordon spin 0: } -\frac{\partial^2 \Psi}{\partial t^2} + \nabla^2 \Psi = m^2 \Psi \qquad \text{Dirac spin } \frac{1}{2}\text{: } i\gamma^\mu \partial_\mu \Psi = m\Psi$$

$$(\gamma^\mu p_\mu \pm m) u = 0 \qquad E = \pm\sqrt{\mathbf{p}^2 + m^2} \qquad g_e = \sqrt{4\pi e^2} = \sqrt{4\pi\alpha}$$

$$\text{Vertice: } i\gamma_\mu g_e (2\pi)^4 \delta^4 (k_1 + k_2 + k_3)$$

$$\text{Leptoni, quarks: } \frac{i(\gamma^\mu q_\mu + m)}{q^2 - m^2} \frac{d^4 q}{(2\pi)^4} \qquad \text{Fotoni: } \frac{ig^{\mu\nu}}{q^2} \frac{d^4 q}{(2\pi)^4}$$

$$M_{if} = -\frac{g_e^2}{(p_1 - p_3)^2} [\bar{u}_{s_3}(p_3) \gamma^\mu u_{s_1}(p_1)] [\bar{u}_{s_4}(p_4) \gamma_\mu u_{s_2}(p_2)]$$

Scattering	Nome
$e^- + \mu^- \to e^- + \mu^-$	elastic scattering (particelle di Dirac)
$e^- + e^- \to e^- + e^-$	scattering
$e^- + e^+ \to e^- + e^+$	scattering
$e^- + \gamma \to e^- + \gamma$	Compton scattering
$e^- + p \to e^- + p$	elastic scattering (esclusiva)
$e^- + p \to e^- + X$	inelastic scattering (inclusiva)
$e^- + e^+ \to \gamma, Z^0 \to q + \bar{q} \to adroni$	annihilation into hadrons

$$g_R = g_e \sqrt{1 - \frac{g_e^2}{12\pi^2}\left[\ln\left(\frac{M_{\text{cutoff}}^2}{m^2}\right)\right]} = \sqrt{4\pi\alpha\left(q^2\right)}$$

$$\alpha\left(q^2\right) \equiv \alpha\left(q_0^2\right)\left[1 + \frac{\alpha\left(q_0^2\right)}{3\pi} f\left(-\frac{q^2}{m^2}\right)\right]$$

$$M_{if} = -g_R^2\left[\bar{u}\left(3\right)\gamma^\mu u\left(1\right)\right]\frac{g_{\mu\nu}}{q^2}\left[1 + \frac{g_R^2}{12\pi^2} f\left(-\frac{q^2}{m^2}\right)\right]\left[\bar{u}\left(4\right)\gamma^\nu u\left(2\right)\right]$$

9 Interazione elettromagnetica

9.1 $e^- + \mu^- \to e^- + \mu^-$

$$M_{if} = -\frac{g_e^2}{\left(p_1 - p_3\right)^2}\left[\bar{u}_{s_3}\left(p_3\right)\gamma^\mu u_{s_1}\left(p_1\right)\right]\left[\bar{u}_{s_4}\left(p_4\right)\gamma_\mu u_{s_2}\left(p_2\right)\right] = -\frac{g_e^2}{\left(p_1 - p_3\right)^2} J_e^\lambda J_{\mu,\lambda}$$

$$\left\langle\left|M_{if}\right|^2\right\rangle = \frac{8g_e^4}{\left(p_1 - p_3\right)^4}\left[\left(p_1 \cdot p_2\right)\left(p_3 \cdot p_4\right) + \left(p_1 \cdot p_4\right)\left(p_3 \cdot p_2\right) - \left(p_1 \cdot p_3\right) m_2^2\right]$$

$$\text{Formula di Dirac: } \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)}\frac{E'}{E}\left[\cos^2\left(\frac{\theta}{2}\right) - \frac{q^2}{2m_\mu^2}\sin^2\left(\frac{\theta}{2}\right)\right]$$

9.2 $e^- + p \to e^- + p$

$$J_{p,\lambda} \equiv \bar{u}\left(4\right)\left[F_1\left(q^2\right)\gamma_\lambda + \frac{k}{2M_p} F_2\left(q^2\right) i\sigma_{\lambda\nu} q^\nu\right] u\left(2\right) \qquad k = 1.79$$

Fattore di forma elettrico: F_1 Fattore di forma magnetico: F_2

$$G_E = F_1 + \frac{kq^2}{4M^2} F_2 \qquad G_M = F_1 + kF_2$$

$$\text{Rosenbluth: } \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)}\frac{E'}{E}\left\{\left[F_1^2 - \frac{kq^2}{4M_p^2} F_2^2\right]\cos^2\frac{\theta}{2} - \frac{q^2}{2M_p^2}\left[F_1 + kF_2\right]^2 \sin^2\left(\frac{\theta}{2}\right)\right\}$$

9.3 $e^- + p \to e^- + X$

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

$$\text{Fattori di struttura: } W_1 = \frac{\left[F_1 + kF_2\right]^2}{2M_p}\delta\left(x - 1\right) \qquad W_2 = -\frac{2M}{q^2}\left[F_1^2 - \frac{kq^2}{4M_p^2} F_2^2\right]\delta\left(x - 1\right)$$

9.4 Deep inelastic scattering

$$\text{Relazione Callan-Gross: } 2xF_1(x) = F_2(x)$$

Funzione di struttura: $F_1 = W_1 M_p$ Funzione di struttura: $F_2 = -\frac{q^2}{2M_p x} W_2$

$$W_1^i = \frac{Q_i^2}{2M_p}\delta(x - z_i) \qquad W_2^i = -\frac{2x^2 M_p Q_i^2}{q^2}\delta(x - z_i)$$

Considerando il protone come uud:

$$F_1(x) = \frac{1}{2}\left[2\left(\frac{2}{3}\right)^2 \delta\left(\frac{m_u}{M_p} - x\right) + \left(-\frac{1}{3}\right)^2 \delta\left(\frac{m_d}{M_p} - x\right)\right] = \frac{1}{2}\delta\left(\frac{m_u}{M_p} - x\right)$$

$$F_2(x) = x\delta\left(\frac{m_u}{M_p} - x\right)$$

9.5 $e^- + e^+ \to \gamma, Z^0 \to q + \bar{q} \to adroni$

$$M_{if} = -\frac{Qg_e^2}{(p_1 + p_2)^2}\left[\bar{v}(2)\gamma_\mu u(1)\right]\left[\bar{u}(3)\gamma^\mu v(4)\right]$$

$$\sigma = \frac{\pi}{3}\left(\frac{Q\alpha}{E}\right)^2 \sqrt{1 - \frac{M^2}{E^2}}\sqrt{1 - \frac{m^2}{E^2}}\left(1 + \frac{M^2}{2E^2}\right)\left(1 + \frac{m^2}{2E^2}\right)$$

10 Interazione debole

Corrente	Carica CC	Neutra NC
Mediatore	$W^\pm$	Z^0
ΔQ	$\neq 0$	$= 0$

$W^\pm$ propagatore: $-\frac{i\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{M_W^2}\right)}{q^2 - M_W^2}$ Z^0 propagatore: $-\frac{i\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{M_Z^2}\right)}{q^2 - M_Z^2}$

$$\text{Se } q^2 \ll M_{W,Z}^2 \Longrightarrow \frac{ig_{\mu\nu}}{M_{W,Z}^2}$$

Vertice CC: $-\frac{ig_W}{\sqrt{8}}\left[\gamma^\mu\left(1 - \gamma^5\right)\right]$ Vertice NC: $-\frac{ig_Z}{2}\left[\gamma^\mu\left(C_V - C_A\gamma^5\right)\right]$

$$C_V = \left(T_f^3\right) - 2\sin^2(\theta_W)Q_f \qquad \sin^2(\theta_W) = 0.231\,53 \pm 0.000\,16$$

$$M_W = 80.419 \pm 0.056\,\mathrm{GeV} \qquad M_Z = 91.1882 \pm 0.0022\,\mathrm{GeV}$$

	Q_f (e)	$\left(T_f^3\right)_{LH}$	$\left(T_f^3\right)_{RH}$	$C_{V,f}$	$C_{A,f}$
ν_e, ν_μ, ν_τ	0	$+1/2$		$+1/2$	$+1/2$
e, μ, τ	-1	$-1/2$	0	$-1/2 + 2\sin^2\theta_W$	$-1/2$
u, c, t	$+2/3$	$+1/2$	0	$+1/2 - 4/3\sin^2\theta_W$	$+1/2$
d, s, b	$-1/3$	$-1/2$	0	$-1/2 + 2/3\sin^2\theta_W$	$-1/2$

Mediatore	Decadimento
W^- W^+ $W^\pm$	$e^-\bar{\nu}_e, \mu^-\bar{\nu}_\mu, \tau^-\bar{\nu}_\tau$ $e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau$ $q'\bar{q}$
Z^0	$e^+e^-, \mu^+\mu^-, \tau^+\tau-, \nu\bar{\nu}, q\bar{q}$

Scattering	Nome
$\nu_\mu + e^- \to \mu^- + \nu_e$	quasi-elastic scattering
$\mu^- \to \bar{\nu}_e + \nu_\mu + e^-$	muon decay
$n \to \bar{\nu}_e + p + e^-$	neutron β decay
$\pi \to l + \nu_l$	π meson decay
$\nu_\mu + e^- \to \nu_\mu + e^-$	elastic scattering
$e^- + e^+ \to \gamma, Z^0 \to f + \bar{f}$	electron-positron annihilation at Z^0 pole
$\nu_e + e^- \to e^- + \nu_e$	elastic scattering
$\bar{\nu}_e + e^- \to e^- + \bar{\nu}_e$	elastic scatterin
$\nu_\mu + q \to \mu^- + q'$	scattering

10.1 $\nu_\mu + e^- \to \mu^- + \nu_e$

$$M_{if} = \frac{g_W^2}{8M_W^2}\left[\bar{u}(3)\gamma^\mu\left(1-\gamma^5\right)u(1)\right]\left[\bar{u}(4)\gamma_\mu\left(1-\gamma^5\right)u(2)\right]$$

$$\left\langle |M_{if}|^2\right\rangle = 2\left(\frac{g_W}{M_W}\right)^4 (p_1\cdot p_2)(p_3\cdot p_4) \qquad \sigma = \frac{1}{8\pi}\left[\left(\frac{g_W}{M_W}\right)^2 E\right]^2\left[1-\left(\frac{m_\mu}{2E}\right)^2\right]^2$$

10.2 $\mu^- \to \bar{\nu}_e + \nu_\mu + e^-$

$$M_{if} = \frac{g_W^2}{8M_W^2}\left[\bar{u}(3)\gamma^\mu\left(1-\gamma^5\right)u(1)\right]\left[\bar{u}(4)\gamma_\mu\left(1-\gamma^5\right)u(2)\right]$$

$$\left\langle |M_{if}|^2\right\rangle = 2\left(\frac{g_W}{M_W}\right)^4 (p_1\cdot p_2)(p_3\cdot p_4) \qquad \Gamma = \left(\frac{g_W}{M_W}\right)^4 \frac{m_\mu^5}{12\,(8\pi)^3} = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

$$\text{Fermi CC: } G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2 = 1.166\cdot 10^{-5}\,\text{GeV}^{-2}$$

10.3 Decadimento β: $n \to p + e^- + \bar{\nu}_e$

$$M_{if} = \frac{g_W^2}{8M_W^2}\left[\bar{u}(3)\gamma^\mu\left(C_V - C_A\gamma^5\right)u(1)\right]\left[\bar{u}(4)\gamma_\mu\left(1-\gamma^5\right)v(2)\right]$$

$$\left\langle |M_{if}|^2\right\rangle = \left(\frac{g_W}{M_W}\right)^4 M_n E_\nu\left(M_n^2 - M_p^2 - m_e^2 - 2M_nE_\nu\right)$$

$$C_V = 1.0 \pm 0.003 \qquad C_A = 1.26 \pm 0.02$$

10.4 $\pi \to l + \nu_l$

$$M_{if} = \frac{g_W^2}{8M_W^2}\left[\bar{u}\left(3\right)\gamma_\mu\left(1-\gamma_5\right)v\left(2\right)\right]f_\pi p^\mu \qquad f_\pi = m_\pi\cos\left(\theta_C\right)$$

$$\left\langle \left|M_{if}\right|^2\right\rangle = \left(\frac{g_W}{2M_W}\right)^4 f_\pi^2 m_l^2\left(m_\pi^2 - m_l^2\right) \qquad \Gamma = \left(\frac{g_W}{4M_W}\right)^4\frac{f_\pi^2}{\pi m_\pi}m_l^2\left(m_\pi^2 - m_l^2\right)^2$$

$$\theta_C = 13.1^\circ$$

10.5 $\nu_\mu + e^- \to \nu_\mu + e^-$

$$M_{if} = \frac{g_Z^2}{8M_Z^2}\left[\bar{u}\left(3\right)\gamma_\mu\left(1-\gamma_5\right)u\left(1\right)\right]\left[\bar{u}\left(4\right)\gamma^\mu\left(C_V - C_A\gamma_5\right)u\left(2\right)\right]$$

$$\sigma = \frac{2}{3\pi}\left[\left(\frac{g_Z}{2M_Z}\right)^2 E_\nu\right]^2\left(C_V^2 + C_A^2 + C_V C_A\right)$$

10.6 $e^- + e^+ \to \gamma, Z^0 \to f + \bar{f}$

$$\sigma_\gamma = \frac{g_e^4 Q_f^2}{48\pi E^2} \qquad \sigma_Z = \frac{\left(g_Z^2 E\right)^2}{48\pi}\left\{\frac{\left[\left(C_V^f\right)^2 + \left(C_A^f\right)^2\right]\left[\left(C_V^e\right)^2 + \left(C_A^e\right)^2\right]}{\left(4E^2 - M_Z^2\right)^2 + M_Z^2\Gamma_Z^2}\right\}$$

$$M_{if} = -\frac{g_Z^2}{4\left(q^2 - M_Z^2\right)}\left[\bar{u}\left(4\right)\gamma^\mu\left(C_V^f - C_A^f\gamma_5\right)v\left(3\right)\right]\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{M_Z^2}\right)\left[\bar{v}\left(2\right)\gamma^\mu\left(C_V^f - C_A^f\gamma_5\right)u\left(1\right)\right]$$

10.7 $\nu_e + e^- \to e^- + \nu_e$

$$\left\langle \left|M_{if}\right|^2\right\rangle = 2\left(\frac{g_W}{M_W}\right)^4\left(p_1\cdot p_2\right)\left(p_3\cdot p_4\right) \qquad \sigma = \frac{G_F^2}{\pi}s \qquad G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2$$

10.8 $\bar{\nu}_e + e^- \to e^- + \bar{\nu}_e$

$$\left\langle \left|M_{if}\right|^2\right\rangle = 2\left(\frac{g_W}{M_W}\right)^4\left(p_1\cdot p_2\right)\left(p_3\cdot p_4\right) \qquad \sigma = \frac{G_F^2}{3\pi}s \qquad G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2$$

10.9 Neutrino-nucleon deep inelastic scattering. $\nu_\mu\left(\bar{\nu}_\mu\right)+N\rightarrow\mu^-\left(\mu^+\right)+X$

$$q^2=-4EE'\sin^2\left(\frac{\theta}{2}\right)\qquad x=-\frac{q^2}{2M\left(E-E'\right)}\qquad y=\frac{\left(E-E'\right)}{E}$$

$$\frac{d\sigma^{eN}}{dq^2dx}=\frac{4\pi\alpha^2}{q^4}\left[\frac{y^2}{2}\frac{2xF_1^{eN}\left(x\right)}{x}+\left(1-y\right)\frac{F_2^{eN}\left(x\right)}{x}\right]$$

$$\frac{4\pi\alpha^2}{q^4}=\frac{G_F^2}{2\pi}\qquad dq^2=2M_NExdy$$

$$\frac{d\sigma^{\nu N}}{dxdy}=\frac{G_F^2M_NE}{2\pi}\left[\left(F_2^{\nu N}\left(x\right)+xF_3^{\nu N}\left(x\right)\right)\left(F_2^{\nu N}\left(x\right)-xF_3^{\nu N}\left(x\right)\right)\left(1-y\right)^2\right]$$

$$F_2^{\nu N}=2x\left[Q\left(x\right)+\bar{Q}\left(x\right)\right]\qquad F_2^{\nu N}=\frac{18}{5}F_2^{eN}\qquad xF_3^{\nu N}=2x\left[Q\left(x\right)-\bar{Q}\left(x\right)\right]$$

$$Q\left(x\right)=d^p\left(x\right)+d^n\left(x\right)=d\left(x\right)+u\left(x\right)\qquad\bar{Q}\left(x\right)=\bar{u}^p\left(x\right)+\bar{u}^n\left(x\right)=\bar{u}\left(x\right)+\bar{d}\left(x\right)$$

$$\text{Gross-Llewellyn-Smith:}\ \int_0^1F_3^{\nu N}dx=3$$

11 QCD

$$g_s=\sqrt{4\pi\alpha_s}$$

$$\langle1|=r\bar{b}\qquad\langle2|=r\bar{g}\qquad\langle3|=b\bar{r}\qquad\langle4|=b\bar{g}\qquad\langle5|=g\bar{r}\qquad\langle6|=g\bar{b}$$

$$\langle7|=\frac{r\bar{r}-g\bar{g}}{\sqrt{2}}\qquad\langle8|=\frac{r\bar{r}+g\bar{g}-2b\bar{b}}{\sqrt{6}}\qquad\langle9|=\frac{r\bar{r}+g\bar{g}+b\bar{b}}{\sqrt{3}}$$

$$f=\frac{1}{4}\left[c_3^+\lambda^\alpha c_1\right]\left[c_2^+\lambda^\alpha c_4\right]\qquad\text{Vertice quark-gluone:}\ \frac{-ig_s\lambda^\alpha\gamma^\mu}{2}$$

$$\text{Propagatore quark:}\ \frac{i\left(\gamma^\mu q_\mu+m\right)}{q^2-m^2}\qquad\text{Propagatore gluone:}\ -\frac{ig^{\mu\nu}\delta^{\alpha\beta}}{q^2}$$

$$M_{if}=-\frac{g_s^2}{\left(p_1-p_3\right)^2}\left[\bar{u}\left(3\right)\gamma^\mu u\left(1\right)\right]\left[\bar{v}\left(2\right)\gamma_\mu v\left(4\right)\right]f$$

$$\alpha_s\left(q^2\right)=\frac{\alpha_s\left(\mu^2\right)}{1+\left(\frac{\alpha_s\left(\mu^2\right)}{12\pi}\right)\left(11n-2f\right)\ln\left(\frac{q^2}{\mu^2}\right)}$$

$$\alpha_s\left(q\right)=\frac{12\pi}{\left(11n-2f\right)\ln\left(\frac{q^2}{\Lambda^2}\right)}\qquad 100\,\text{MeV}<\Lambda<500\,\text{MeV}$$

11.1 Produzione di jet

$$\frac{d\sigma}{dx_1 dx_2 d\left(\cos\left(\theta^*\right)\right)} = \sum_{l,m} \frac{F_l\left(x_1\right)}{x_1} \frac{F_m\left(x_2\right)}{x_2} \frac{d\sigma_{l,m}}{d\left(\cos\left(\theta^*\right)\right)} K$$

Cross section elementare: $\frac{d\sigma_{l,m}}{d\left(\cos\left(\theta^*\right)\right)}$ Densità partoni: $\frac{F_{l,m}\left(x_{1,2}\right)}{x_{1,2}}$ $K \simeq 2.5$

$$F\left(x\right) = G\left(x\right) + \frac{4}{9}\left(Q\left(x\right) + \bar{Q}\left(x\right)\right)$$

11.2 Drell-Yan production

$$p + p \to l^+ + l^- + X \qquad q + \bar{q} \to l^+ + l^-$$

$$e^+ + e^- \to adroni, e^+ + e^- \to \bar{q} + q \qquad l^\pm + p \to l^\pm + X, l^\pm + q \to l^\pm + q$$

$$\sigma\left(q\bar{q} \to l^+ l^-\right) = \frac{4\pi\alpha^2}{9M^2} Q_f^2 K \qquad \frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9M^2} K S\left(x_1, x_2\right)$$

$$S\left(x_1, x_2\right) = \sum_f Q_f^2 \left[q_B\left(x_1\right) \bar{q}_T\left(x_2\right) + \bar{q}_B\left(x_1\right) q_T\left(x_2\right)\right]$$