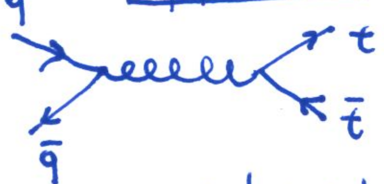
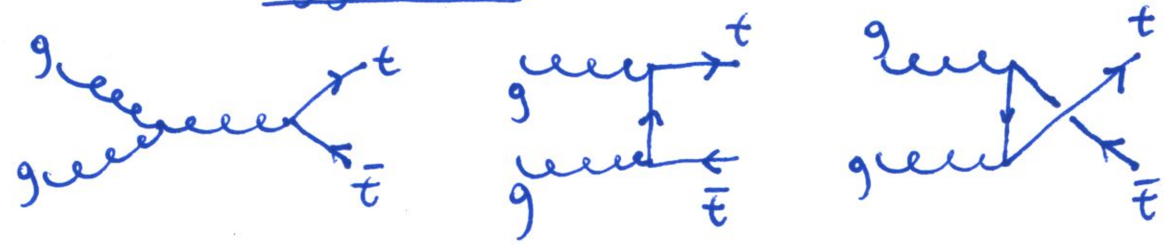
Top-antitop pair production

$q\bar{q} \to t\bar{t}$

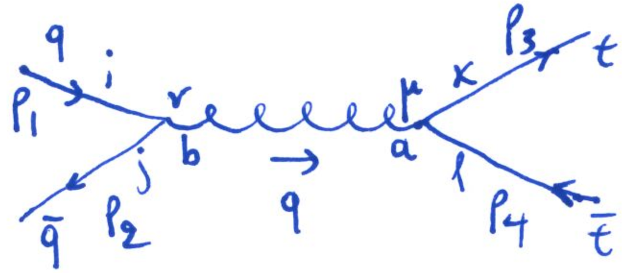


$q = u, d, c, s, b$

$gg \to t\bar{t}$



Amplitude for $q\bar{q} \to t\bar{t}$



$q = p_1 + p_2 = p_3 + p_4$

$$i\mathcal{M} = \bar{u}_k(p_3)\,(-i)\frac{g_s}{2}\lambda^a_{kl}\gamma^\mu v_l(p_4)\;(-i)\frac{g_{\mu\nu}}{q^2}\delta_{ab}\;\bar{v}_j(p_2)\,(-i)\frac{g_s}{2}\lambda^b_{ji}\gamma^\nu u_i(p_1)$$

$$\Rightarrow \mathcal{M} = \frac{g_s^2}{4(p_1+p_2)^2}\,\bar{u}_k(p_3)\lambda^a_{kl}\gamma^\mu v_l(p_4)\;\bar{v}_j(p_2)\lambda^a_{ji}\gamma_\mu u_i(p_1)$$

In summing over colors (average of initial) we use $\lambda^a_{kl}\lambda^a_{ji} = 2\delta_{ki}\delta_{lj} - \frac{2}{N_c}\delta_{kl}\delta_{ji}$

We calculate $|\mathcal{M}|^2$ and after some work we find the cross section

$$\frac{d\sigma}{dt} = \frac{\pi C_F \alpha_s^2}{N_c s^2}\left[\frac{(t-m_t^2)^2 + (s+t-m_t^2)^2}{s^2} + \frac{2m_t^2}{s}\right]$$

where $s = (p_1+p_2)^2$

$t = (p_1-p_3)^2$, $\alpha_s = \frac{g_s^2}{4\pi}$

and m_t is the top quark mass

Parton model

Deep inelastic scattering (DIS): collisions of leptons with hadrons
e.g. electrons and protons

DIS experiments have shown that the proton and other hadrons have pointlike constituents: partons

These partons are now identified as the quarks/antiquarks and gluons of the quark model and later full theory of QCD

Hadronic cross sections and factorization

Since hadrons are complicated their collisions involve collisions of their constituent valence and sea quarks/antiquarks and gluons

To describe and calculate the hadronic cross section in terms of the partonic cross section (for which we use Feynman rules), we use factorization: we convolute the partonic cross section with parton distribution functions that describe the momentum fraction of a proton carried by different quark flavors and by gluons.

For example: $\sigma^{p\bar{p}\to tX} = \sum_{f_1, f_2} \int dx_1\, dx_2\, \varphi_{f_1/p}(x_1, \mu_F)\, \varphi_{f_2/\bar{p}}(x_2, \mu_F)\, \sigma^{f_1 f_2 \to tX}(\mu_F, \mu_R)$

where $\varphi_{f_1/p}$ is the parton distribution for parton f_1 in the proton with momentum fraction x_1, μ_F is the factorization scale, and μ_R is the renormalization scale.

Quarks and Hadrons: Baryons and Mesons

quarks are not observed as isolated particles but are confined inside hadrons - strongly interacting bound states of quarks (but the top quark decays before it can hadronize due to its large mass)

There are two categories of hadrons:
baryons with three valence quarks (as well as sea quarks and gluons)
[and their antiparticles, antibaryons, with three valence antiquarks]
and mesons with a quark and an antiquark (as well as sea quarks and gluons)

The best known baryons are the proton and the neutron and the best known mesons are the pions

QCD exhibits asymptotic freedom at high energies:
the strong coupling $\alpha_s = \frac{g_s^2}{4\pi}$ gets smaller at higher energies

and confinement since α_s increases at lower energies
$\rightarrow$ quarks combine to form hadrons

All Standard Model processes obey baryon number conservation

Baryons with spin 1/2

proton	p	uud ← valence quarks	
neutron	n	udd	
	Λ^0	uds	$S=-1$
	Σ^+	uus	$S=-1$
	Σ^0	uds	$S=-1$
	Σ^-	dds	$S=-1$
	Ξ^0	uss	$S=-2$
	Ξ^-	dss	$S=-2$
	Λ_c^+	udc	$C=+1$
	Σ_c^{++}	uuc	$C=+1$
	Σ_c^+	udc	$C=+1$
	Σ_c^0	ddc	$C=+1$
	Λ_b^0	udb	$B=-1$

and many more

Baryons with spin 3/2

Δ^{++}	uuu	
Δ^+	uud	
Δ^0	udd	
Δ^-	ddd	
Σ^{*+}	uus	$S=-1$
Σ^{*0}	uds	$S=-1$
Σ^{*-}	dds	$S=-1$
Ξ^{*0}	uss	$S=-2$
Ξ^{*-}	dss	$S=-2$
Ω^-	sss	$S=-3$
Σ_c^{*++}	uuc	$C=+1$
Σ_c^{*+}	udc	$C=+1$
Σ_c^{*0}	ddc	$C=+1$

and many more

also antibaryons

antiproton $\bar{p}$ $\bar{u}\bar{u}\bar{d}$

antineutron $\bar{n}$ $\bar{u}\bar{d}\bar{d}$

etc.

S is strangeness

C is charm

B is beauty

Mesons with spin 0

$$\text{pions}\left\{\begin{array}{ll} \pi^+ & u\bar{d} \\ \pi^0 & \frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d}) \\ \pi^- & d\bar{u} \end{array}\right.$$

$$\text{kaons}\left\{\begin{array}{l} \left.\begin{array}{ll} K^+ & u\bar{s} \\ K^0 & d\bar{s} \end{array}\right\} S=+1 \\ \left.\begin{array}{ll} \bar{K}^0 & s\bar{d} \\ K^- & s\bar{u} \end{array}\right\} S=-1 \end{array}\right.$$

$$\eta \quad \frac{1}{\sqrt{6}}(u\bar{u}+d\bar{d}-2s\bar{s})$$

$$\eta' \quad \frac{1}{\sqrt{3}}(u\bar{u}+d\bar{d}+s\bar{s})$$

$$\left.\begin{array}{ll} D^+ & c\bar{d} \\ D^0 & c\bar{u} \end{array}\right\} C=+1$$

$$\left.\begin{array}{ll} \bar{D}^0 & u\bar{c} \\ D^- & d\bar{c} \end{array}\right\} C=-1$$

$$D_s^+ \quad c\bar{s} \; \} \; S=C=+1$$

$$D_s^- \quad s\bar{c} \; \} \; S=C=-1$$

$$\left.\begin{array}{ll} B^+ & u\bar{b} \\ B^0 & d\bar{b} \end{array}\right\} B=+1$$

$$\left.\begin{array}{ll} \bar{B}^0 & b\bar{d} \\ B^- & b\bar{u} \end{array}\right\} B=-1$$

and many more

Mesons with spin 1

$$\begin{array}{ll} \rho^+ & u\bar{d} \\ \rho^0 & \frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d}) \\ \rho^- & d\bar{u} \end{array}$$

$$\left.\begin{array}{ll} K^{*+} & u\bar{s} \\ K^{*0} & d\bar{s} \end{array}\right\} S=+1$$

$$\left.\begin{array}{ll} \bar{K}^{*0} & s\bar{d} \\ K^{*-} & s\bar{u} \end{array}\right\} S=-1$$

$$\omega \quad \frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$$

$$\left.\begin{array}{ll} D^{*+} & c\bar{d} \\ D^{*0} & c\bar{u} \end{array}\right\} C=+1$$

$$\left.\begin{array}{ll} \bar{D}^{*0} & u\bar{c} \\ D^{*-} & d\bar{c} \end{array}\right\} C=-1$$

$$\begin{array}{ll} \varphi & s\bar{s} \\ J/\psi & c\bar{c} \\ \Upsilon & b\bar{b} \end{array}$$

and many more