The Strong Interaction and LHC phenomenology

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Theoretical Physics Graduate School course

Lecture 2:
The QCD Lagrangian, Symmetries and Feynman Rules

The QED Lagrangian - recap

From the **QFT-II course** you know the form of the QED Lagrangian for a single fermion with mass *m*:

$$\mathscr{L}_{\rm QED} = \overline{\psi}\left(i\gamma^\mu D_\mu - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

where the **field-strength tensor** (classical electrodynamics) is defined from the four-vector potential

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

and the **covariant derivative** is given by

$$D_\mu = \partial_\mu + ieA_\mu$$

The form of the QED Lagrangian is the one required by **gauge invariance with respect to the abelian U(1) group gauge transformations**, where fermions and photons transform as

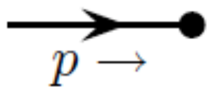
$$\psi(x) \to \psi'(x) = e^{i\phi(x)}\psi(x) \qquad A^\mu \to A'^\mu = A^\mu + \partial^\mu \chi(x)$$

Exercise: show that the fermion sector is invariant under U(1) if: $\chi(x) = -\frac{\phi(x)}{e}$

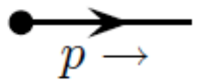
The field-strength tensor is also gauge invariant, so the full Lagrangian also

Exercise: show that the covariant derivative transforms as the fermion field (hence the name *covariant*)

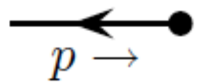
Feynman rules in QED

Incoming electron 

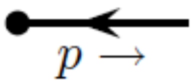
$= u_\alpha(p,s),$

Outgoing electron 

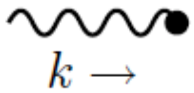
$= \bar{u}_\alpha(p,s),$

Incoming positron 

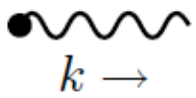
$= \bar{v}_\alpha(p,s),$

Outgoing positron 

$= v_\alpha(p,s).$

Incoming photon 

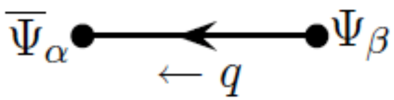
$= e_\mu(k,\lambda)$

Outgoing photon 

$= e^*_\mu(k,\lambda)$

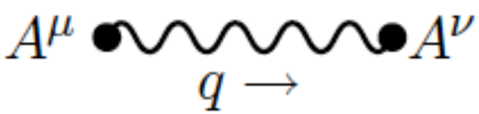
λ -> photon polarization

Fermion propagator



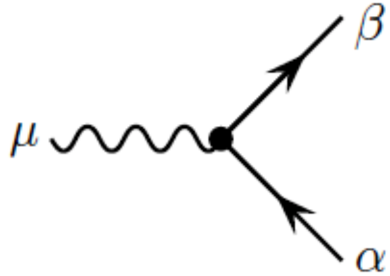
$$= \left[\frac{i}{\not{q} - m + i0}\right]_{\alpha\beta}$$

Photon propagator (Feynman gauge)



$$= \frac{-ig^{\mu\nu}}{q^2 + i0}.$$

Electron-photon vertex



$$= (+ie\gamma^\mu)_{\beta\alpha}.$$

In QED, as will be the case in QCD, gauge-fixing is required, but results independent of choice of gauge

From QED to QCD

The QCD Lagrangian has the **same structure** as the QED Lagrangian but the invariance is now with respect the **non-abelian group SU(3)**

Formally they are very similar, in practice the two theories are **extremely different**

Main difference is **non-abelian nature of the gauge group**, which implies that **gluons have self-interactions**, as opposed to QED, where photons couple only to fermions

In QED the coupling constant grows with the energy, while in **QCD it decreases** (asymptotic freedom, as found in deep-inelastic scattering and electron-positron data)

QED is perturbative for all relevant energies, while in QCD the coupling becomes strong, and hence the **theory becomes non-perturbative, for scales < 1 GeV**

We know present the **QCD Lagrangian** and compare it in detail with the QED one

$$\mathscr{L}_{\mathrm{QED}} = \overline{\psi}\left(i\gamma^{\mu}D_{\mu} - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Quark and gluon fields have new degree of freedom: color

$$\mathscr{L}_{\mathrm{QCD}} = \sum_{f}\overline{\psi}_i^{(f)}\left(i\gamma_{\mu}D_{ij}^{\mu} - m_f\delta_{ij}\right)\psi_j^{(f)} - \frac{1}{4}F_{\mu\nu}^{a}F_{a}^{\mu\nu}$$

Though the formal structure is the same as in QED, the new color degrees of freedom lead to a **strikingly different** theory

The SU(3) group

SU(N) is the special unitary groups of degree n: group of **n x n unitary matrices** with **determinant = 1**

$$U^\dagger U = 1\,, \quad \det U = 1\,.$$

The **Lie algebra** of these groups is defined by the commutation relations of the generators of the group

$$\left[t^A, t^B\right] = i f^{ABC} t^C$$

An important representation of the group is the **fundamental representation,** with the so-called **Gell-Mann matrices**, which are traceless and Hermitian. In the case of SU(3)

$$t^A \equiv \frac{1}{2}\lambda^A$$

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}.$$

The QCD Lagrangian

Let us examine in detail the QCD Lagrangian:

$$\mathscr{L}_{\rm QCD} = \sum_f \overline{\psi}_i^{(f)} \left(i\gamma_\mu D^\mu_{ij} - m_f \delta_{ij} \right) \psi_j^{(f)} - \frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu}$$

i,j = 1, 3 -> Color indices in the **fundamental representation** of SU(3)
a = 1, 8 -> Color index in the **adjoint representation of** SU(3)

The covariant derivative looks similar to the QED one, now acting in **color space** as well

$$D^\mu_{ij} = \partial_\mu \delta_{ij} + i g_s t^a_{ij} A^\mu_a$$

Generators of SU(3)

The field-strength tensor for QCD has a crucial difference wrt QED: the **self-interaction of gauge bosons**

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_{abc} A^b_\mu A^c_\nu$$

- ☑ All the interactions in QCD are proportional to the **strong coupling constant, g_s**
- ☑ QCD interactions do not distinguish between quark flavors
- ☑ The structure of the QCD Lagrangian is fixed by the requirement of the **invariance under SU(3)**

Gauge invariance

The structure of QCD is fully defined by the requirement of **SU(3) local gauge transformations:** the physical content of the theory is unchanged if quark and gluon fields transform under SU(3), and this transformation can be **different for each space-time point**

Quarks transform in the fundamental representation of SU(3):

$$\psi_i^{(f)} \to \psi_i^{(f)\prime} = U_{ij}(x)\psi_j^{(f)} \qquad U_{ij}(x) = \exp\left(i\theta^a(x)t^a_{ij}\right)$$

Since fermion sector of the Lagrangian must the independently gauge invariant (because in principle there is an arbitrary number of fermions n_f) then the **covariant derivative** must transform like quark fields

$$D^\mu_{ij}\psi_j \to \left(D^\mu_{ij}\psi_j\right)' = U_{ik}(x)D^\mu_{kj}\psi_j$$

This condition determines the transformation property of the **gluon field under SU(3)**

$$t^a A^\mu_a \to t^a A'^\mu_a = U(x)t^a A^\mu_a U^{-1}(x) + \frac{1}{g_s}\left(\partial^\mu U(x)\right)U^{-1}(x)$$

Exercise: check that with this transformation the fermion sector of the QCD Lagrangian is gauge invariant
Special care must be taken with the fact that SU(3) matrices **do not commute,** as opposed to the QED case

Gauge invariance

Therefore, the gauge invariance of the fermion sector of the QCD Lagrangian requires **gluons to transform**

$$t^a A_a^\mu \to t^a A_a'^\mu = U(x) t^a A_a^\mu U^{-1}(x) + \frac{1}{g_s} \left(\partial^\mu U(x)\right) U^{-1}(x)$$

Let us now check that the purely gauge sector is also gauge invariant under this transformation

$$\mathscr{L}_{\rm QCD} = \sum_f \overline{\psi}_i^{(f)} \left(i\gamma_\mu D^\mu_{ij} - m_f \delta_{ij} \right) \psi_j^{(f)} - \frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu}$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_{abc} A^b_\mu A^c_\nu$$

An useful relation (**exercise**: derive this expression) is provided by the commutator of two covariant derivs

$$\left[D_\mu , D_\nu \right] = i g_S t^a F^a_{\mu\nu}$$

(Recall that covariant derivatives are **operators** acting on fermion fields)

and since we just showed that under SU(3) transformations the **covariant derivative transforms as the quark field**, we have that

$$t^a F^a_{\mu\nu} \to t^a F'^a_{\mu\nu} = U(x) t^a F^a_{\mu\nu} U^{-1}(x)$$

Therefore, the gluonic sector is always gauge invariant since we can write, using $\mathrm{Tr}\left[t^a t^b \right] = \frac{1}{2}\delta^{ab}$

$$-\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} = -\frac{1}{2} F^a_{\mu\nu} F^{\mu\nu,b} \mathrm{Tr}\left[t^a t^b \right] = -\frac{1}{2} \mathrm{Tr}\left[F^a_{\mu\nu} t^a F^{\mu\nu,b} t^b \right]$$

trace is cyclic operator

Gauge invariance

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$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g_s f_{abc} A_\mu^b A_\nu^c$$

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$$\left[D_\mu , D_\nu \right] = i g_S t^a F_{\mu\nu}^a$$

and since we just showed that under SU(3) transformations the covariant derivative transforms as the quark field, we have that

$$t^a F_{\mu\nu}^a \to t^a F_{\mu\nu}'^a = U(x) t^a F_{\mu\nu}^a U^{-1}(x)$$

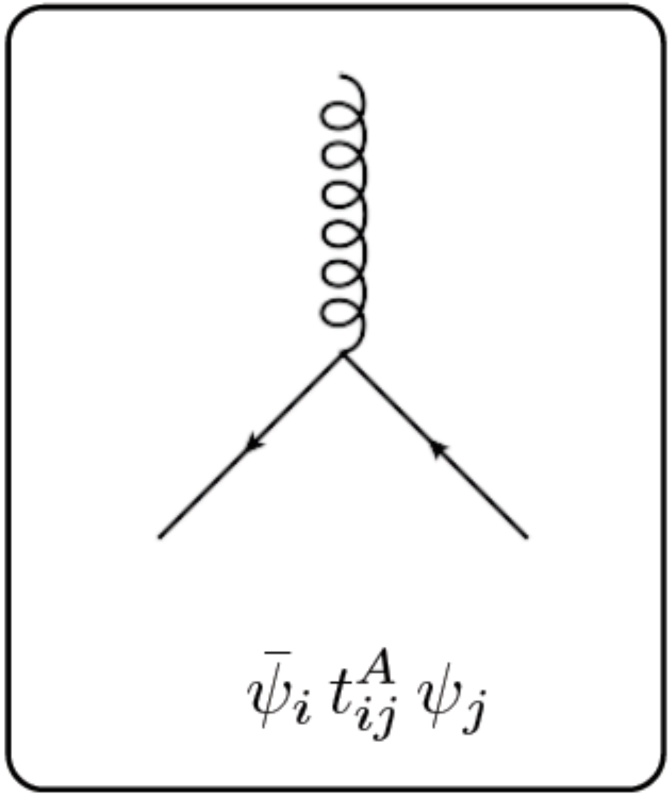
So also the **purely gauge sector of the QCD Lagrangian** in invariant under SU(3) transformations

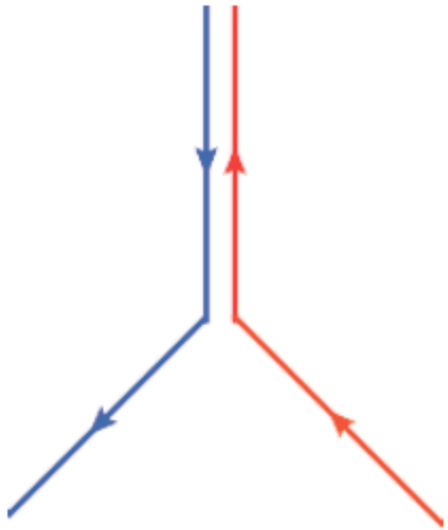
Note that as opposed to QED, the field-strength tensor itself is **not** gauge invariant

As in QED, a **mass term for the gluon** is forbidden by gauge invariance (**exercise:** check explicitely)

Color Flow

The various contractions of color indices in the QCD Lagrangian can be interpreted as **color flows** between the different types of fields





$$(1, 0, 0) \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

In this specific example, an incoming quark with **red color** emits a gluon and is transformed into an outgoing quark with **blue color**

Gluons carry both **color** and **anti-color:** they change the color charge of quarks and of other gluons

Feynman rules in QCD

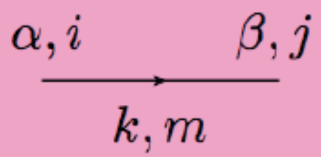
Now we turn to the **Feynman rules** derived from the QCD Lagrangian, in analogy with the QED ones

$$\mathscr{L}_{\rm QCD} = \sum_f \overline{\Psi}_i^{(f)} \left(i\gamma_\mu D^\mu_{ij} - m_f \delta_{ij} \right) \Psi_j^{(f)} - \frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu}$$

The quark and gluon propagators are obtained from the **non-interacting Lagrangian**

Same recipe as in QED: **replace i∂ with k** and take the inverse

$$\mathcal{L}_{\rm q,free} = \sum_f \bar{\psi}_i^{(f)} \left(i\partial\!\!\!/ - m_f \right) \delta_{ij} \psi_j^{(f)}$$



$$= \left(\frac{i}{k\!\!\!/ - m} \right)_{\alpha\beta} \delta_{ij}$$

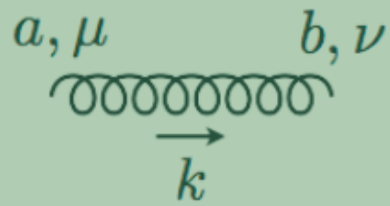
However this does not work for the gluon, since inverse does not exist

$$\mathcal{L}_{\rm g,free} = \frac{1}{2} A^\mu \left(\Box g_{\mu\nu} - \partial_\mu \partial_\nu \right) A^\nu$$

Exercise: check this is the form of the QCD Lagrangian and verify that it is non-invertible

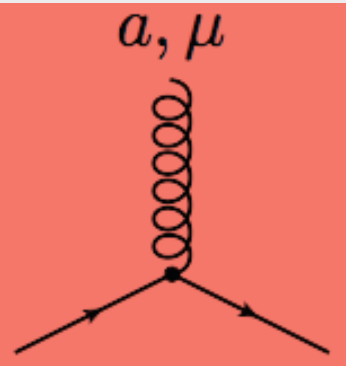
Need to **fix a gauge** to obtain the gluon propagator. In the **covariant gauges** it reads

$$\frac{-i}{k^2} \left(g_{\mu\nu} - (1-\xi) \frac{k_\mu k_\nu}{k^2} \right) \delta^{ab} =$$



All gauge dependence must explicitly cancel in the final calculations
Same as in QED

Feynman rules in QCD

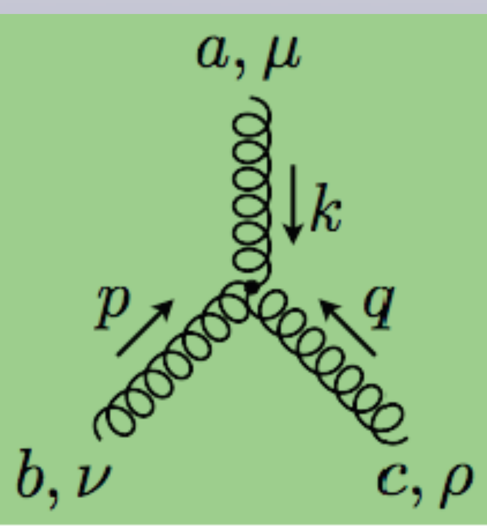


$$= \quad i g_s \gamma^\mu t^a$$

The **quark-gluon vertex** in QCD is analogous to the fermion-photon vertex in QED

The gluon mixes the color charge of the incoming and outcoming quark

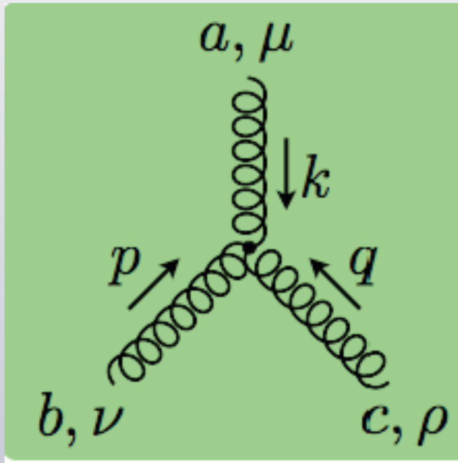
The **genuine non-abelian interactions** are the triple and quartic couplings between the gluons



$$= \quad g_s\, f^{abc} \Big[g^{\mu\nu}(k-p)^\rho + g^{\nu\rho}(p-q)^\mu + g^{\rho\mu}(q-k)^\nu \Big]$$

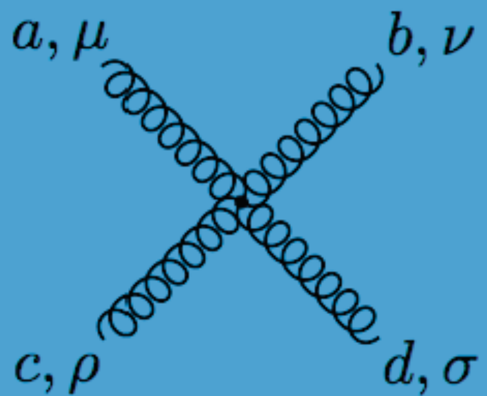
Feynman rules in QCD

The **genuine non-abelian interactions** are the triple and quartic couplings between the gluons



$$= g_s f^{abc}\left[g^{\mu\nu}(k-p)^\rho + g^{\nu\rho}(p-q)^\mu + g^{\rho\mu}(q-k)^\nu\right]$$

The **non-abelian nature of QCD** is shown by the presence of the SU(3) structure constants $\mathbf{f}_{\mathrm{ABC}}$ in the Feynman rules: these structure constants arise from the **non-commutativity** of SU(3) matrices



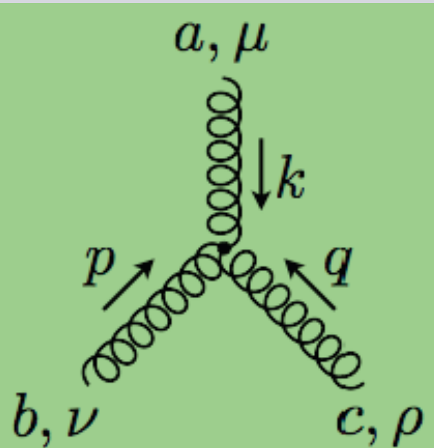
$$= -ig_s^2\left[f^{abe}f^{cde}\left(g^{\mu\rho}g^{\nu\sigma} - g^{\mu\sigma}g^{\nu\rho}\right) + f^{ace}f^{bde}\left(g^{\mu\nu}g^{\rho\sigma} - g^{\mu\sigma}g^{\nu\rho}\right) + f^{ade}f^{bce}\left(g^{\mu\nu}g^{\rho\sigma} - g^{\mu\rho}g^{\nu\sigma}\right)\right]$$

The structure of these Feynman rules can be traced back directly to the **QCD field-strength tensor**

Feynman rules in QCD

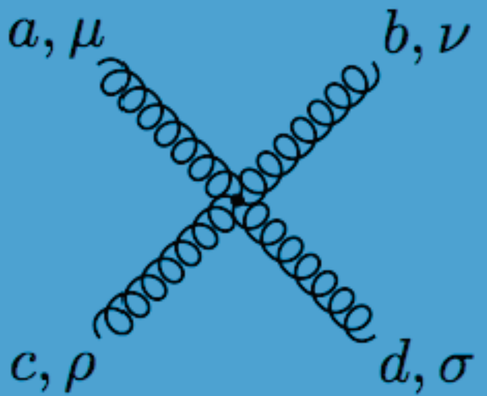
The structure of these Feynman rules can be traced back directly to the **QCD field-strength tensor**

$$
\begin{aligned}
F_a^{\mu\nu} F^a_{\mu\nu} \quad &\to \quad \ldots + g_S^2 f_{abc} f_{ade} A^{\mu,b} A^{\nu,c} A^d_\mu A^e_\nu \\
&- \quad g_S f_{abc} A^{\mu,b} A^{\nu,c} \left[\partial_\mu A^a_\nu - \partial_\nu A^a_\mu\right] - g_S f_{abc} A^b_\mu A^c_\nu \left[\partial^\mu A^{\nu,a} - \partial^\nu A^{\mu,a}\right]
\end{aligned}
$$



$$
= \quad g_s f^{abc} \left[g^{\mu\nu}(k-p)^\rho + g^{\nu\rho}(p-q)^\mu + g^{\rho\mu}(q-k)^\nu \right]
$$

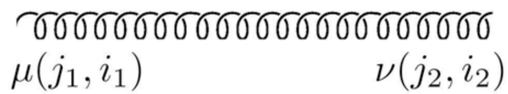
- The **three-gluon vertex** is proportional to **the four-momentum of one of the legs**
- The **four-gluon vertex** Feynman rule accounts for all possible permutations allowed by symmetry



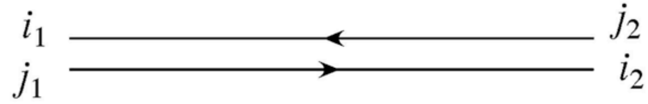
$$
= \quad -ig_s^2 \left[f^{abe} f^{cde} \left(g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\nu\rho}\right) + f^{ace} f^{bde} \left(g^{\mu\nu} g^{\rho\sigma} - g^{\mu\sigma} g^{\nu\rho}\right) + f^{ade} f^{bce} \left(g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma}\right) \right]
$$

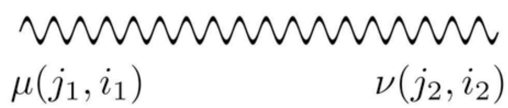
Feynman rules in QCD

The Feynman rules in QCD can also interpreted as **governing the (conserved) color flow** between the incoming and outgoing legs of a diagram

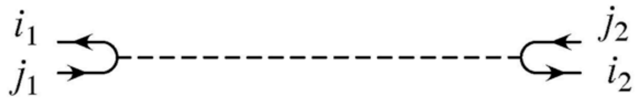


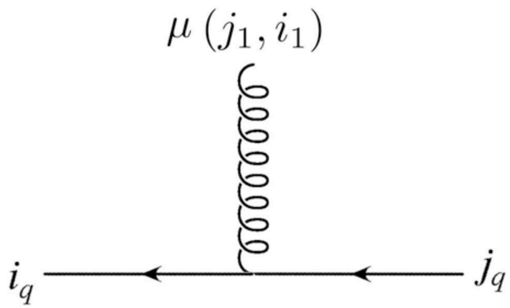
$$= \frac{-ig^{\mu\nu}}{p^2}\delta^{i_2}_{j_1}\delta^{i_1}_{j_2}$$



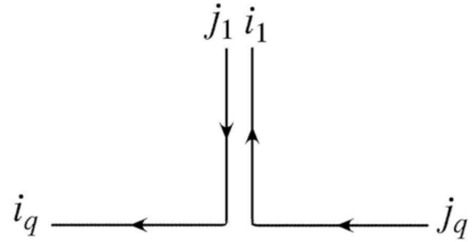


$$= -\frac{1}{N}\frac{-ig^{\mu\nu}}{p^2}\delta^{i_1}_{j_1}\delta^{i_2}_{j_2}$$





$$= -i\frac{g}{\sqrt{2}}\gamma^{\mu}\delta^{i_q}_{j_1}\delta^{i_1}_{j_q}$$

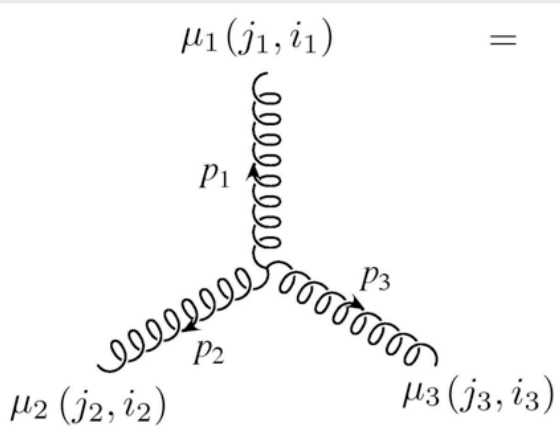


Note that **color lines are never interrupted** (note the delta functions in color space)

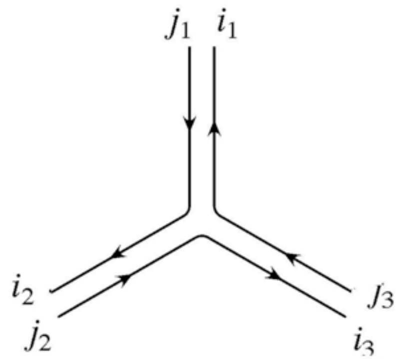
For the propagation of a color-singlet object (like the photon), **color-anticolor annihilation** must take place

Feynman rules in QCD

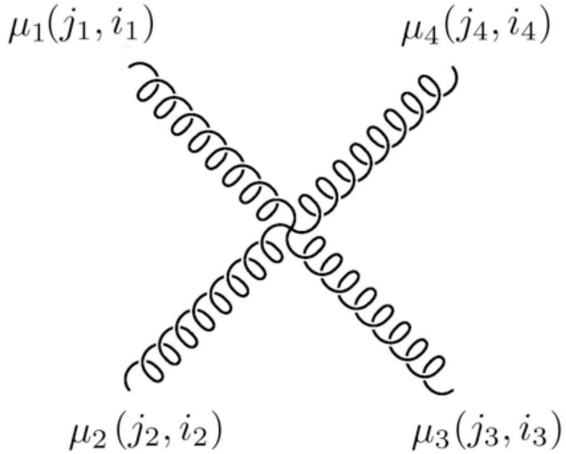
The color-flow interpretation is also valid for the **gluon self-interactions**



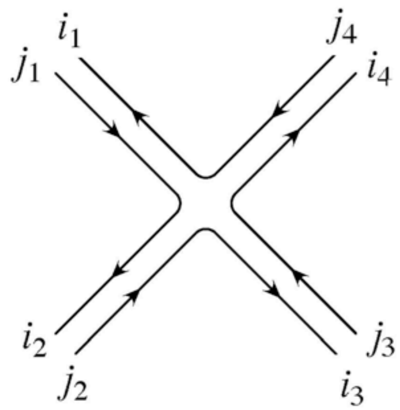
$$= -i\frac{g}{\sqrt{2}}\Big[(p_2-p_1)_{\mu_3}\, g_{\mu_1\mu_2} + (p_3-p_2)_{\mu_1}\, g_{\mu_2\mu_3} + (p_1-p_3)_{\mu_2}\, g_{\mu_3\mu_1}\Big] \times \delta^{i_1}_{j_3}\delta^{i_3}_{j_2}\delta^{i_2}_{j_1} + \text{perm.}$$



+perm.



$$= i\frac{g^2}{2}\Big[2\, g_{\mu_1\mu_3}g_{\mu_2\mu_4} - g_{\mu_1\mu_2}g_{\mu_3\mu_4} - g_{\mu_1\mu_4}g_{\mu_2\mu_3}\Big] \times \delta^{i_1}_{j_4}\delta^{i_4}_{j_3}\delta^{i_3}_{j_2}\delta^{i_2}_{j_1} + \text{perm.}$$



+perm.

Note also that the **color structure** of the QCD amplitudes factorizes from the **space-time structure**

Symmetries of the Lagrangian

The form of the QCD Lagrangian is completely fixed by the requirement of **invariance under SU(3)**

$$\mathscr{L}_{\rm QCD} = \sum_f \overline{\psi}_i^{(f)} \left(i\gamma_\mu D^\mu_{ij} - m_f \delta_{ij} \right) \psi_j^{(f)} - \frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu}$$

In addition, in was known from a long time that the strong interaction has other **approximate symmetries.** In particular, particles in the same **isospin** (isotopic spin) multiplet have similar mass and **scattering amplitudes** (Wigner-Eckart theorem). For example, protons and neutrons, or neutral and charged pions

How does these properties arise from **the QCD Lagrangian?**

In the quark model, **isospin** relates to the content in terms of up and down quarks

$$I_3 = \frac{1}{2} \left[(n_u - n_{\bar{u}}) - (n_d - n_{\bar{d}}) \right]$$

So **proton has I=1/2**, and **neutron has -1/2** -> **protons and neutrons form a SU(2) isospin multiplet**

Also **pions** have I=1 (positively charged pion, quark content u*dbar), I=0, (neutral pion, quark content u*ubar+d*dbar) and I=-1, (negatively charged pion, quark content ubar*d)

Ultimately, isospin arises because QCD interactions are **flavor-blind,** and the (accidental) fact that **up and down quarks have very close masses**

Symmetries of the Lagrangian

Formally, an **isospin transformation** acts into the quark field as a **unitary matrix**

$$\psi_i^{(f)} \to \sum_{f'} U^{ff'} \psi_i^{(f')}$$

SU(2) rotation in flavor space

Seems similar to color transformations, but note that this is a **global transformation,** as opposed to gauge transformations that are **local** in space-time

Also, isospin acts only in the **up and down** quark flavors

Exercise: check under which conditions the (fermion sector) QCD Lagrangian is invariant under these transformations

$$\begin{aligned}\mathscr{L}_{\rm QCD} &= \overline{\psi}_i^{(u)} \left(i\gamma_\mu D^\mu_{ij} - m_u \delta_{ij} \right) \psi_j^{(u)} + \overline{\psi}_i^{(d)} \left(i\gamma_\mu D^\mu_{ij} - m_d \delta_{ij} \right) \\ &+ \sum_{f, f\neq u,d} \overline{\psi}_i^{(f)} \left(i\gamma_\mu D^\mu_{ij} - m_f \delta_{ij} \right) \psi_j^{(f)} - \frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu}\end{aligned}$$

The transformed Lagrangian (restrict to up/down sector) is only invariant if i) **up and down quark masses vanish** or ii) **they are identical**

$$\sum_{f',f''} \sum_{f} \left(U^T_{f'f} U_{ff''} \right) \overline{\psi}_i^{(f')} \left(i\gamma_\mu D^\mu_{ij} - m_f \delta_{ij} \right) \psi_j^{(f'')}$$

Experimentally, we know that

$$m_{u,d} \ll \Lambda_S$$

Symmetries of the Lagrangian

In the limit of **vanishing quark masses,** the QCD Lagrangian has a larger set of **invariance properties**

In this limit, we can separate the fermion fields in left-handed and right-handed chiralities

$$\psi = \psi_R + \psi_L \qquad \psi_L = \frac{1}{2}(1-\gamma_5)\psi \qquad \psi_R = \frac{1}{2}(1+\gamma_5)\psi$$

and see that the right-handed and left-handed pieces of the Lagrangian are **separately invariant**

$$\sum_f \left(\overline{\psi}_R^{(f)} \left(i\gamma_\mu D^\mu \right) \psi_R^{(f)} + \overline{\psi}_L^{(f)} \left(i\gamma_\mu D^\mu \right) \psi_L^{(f)} \right)$$

This is a direct consequence that for **massless fermions chirality is conserved**

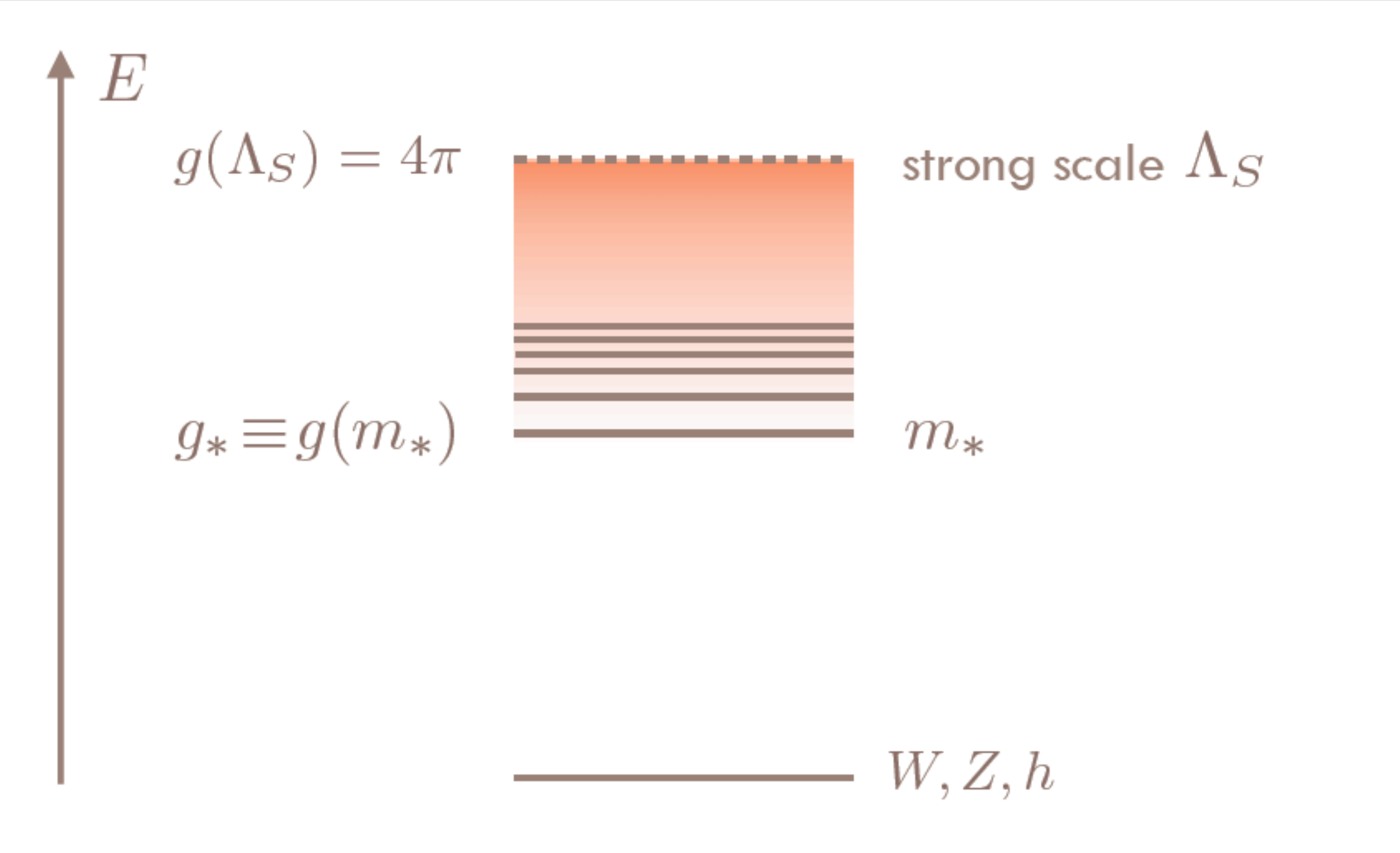
This symmetry of the QCD is known as **chiral symmetry,** and is spontaneously broken by the properties of the QCD vacuum (much as the Higgs mechanism). The **(approximately massless) pions** are the **Goldstone bosons** of the broken symmetry

This happens when the **vacuum state of the theory is not invariant** under the same symmetries as the Lagrangian. In the case of QCD it is known that

$$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{u}u + \bar{d}d|0\rangle \simeq (250\ \mathrm{MeV})^3$$

Beyond QCD: Composite Higgs

Similar mechanisms to the one that break chiral symmetry in QCD have been proposed to explain the **Higgs mass lightness** in **composite Higgs scenarios**



This Higgs is the Goldstone boson of the broken symmetries of some **new strong dynamics at high scales**

These theories provide a natural explanation of the Higgs lightness

Within the **reach of the LHC** in the next years

Understanding better **QCD** is also helpful to better understand **Beyond the Standard Model** theories that are also characterized by **strong dynamics**

QCD as a non-abelian QFT

The formulation of **Quantum Chromodynamics** as a **non-abelian Quantum Field Theory** allows to:

☑ Describe the **hadron spectrum**

☑ Explain the experimentally observed symmetries of the strong interaction

☑ Avoid mixing between the strong and the weak interactions

☑ Obtain a similar field-theoretical description of the strong forces, opening the path to an unified formalism of all fundamental interactions

As we will see, the **perturbative QFT description** of the strong interactions is extremely predictive, but we understand much less the phenomena governed by **strong coupling dynamics**

☑ Confinement

☑ Hadron spectrum beyond mesons and baryons: glueballs, multi-quark hadrons

☑ The structure of the QCD vacuum

☑ The dynamical properties of quarks and gluons in the proton: energy distribution, polarization, transverse structure

In the rest of these lectures we will focus on **perturbative QCD** with the emphasis on its role at the LHC