1 Feynman Diagrams

are a graphical way to represent interactions

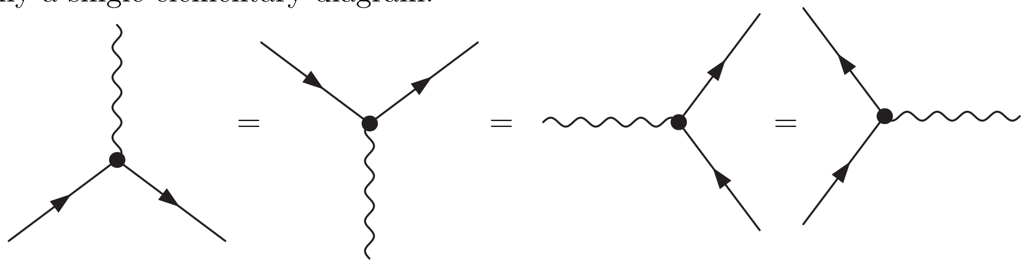
- they consist of
  - lines (propagators) and
  - dots (vertices)
- there are primary or elementary diagrams
  - with one vertex and the lines connecting to this vertex
- the elementary diagrams can be connected to more complicated diagrams
  - tree diagrams: usually the most important
  - and loop diagrams: they represent quantum corrections

a process is defined by the initial and the final state: what comes in and what goes out

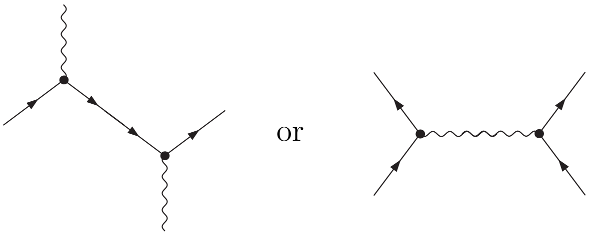
- many Feynman diagrams can contribute to a single process

2 QED

has only a single elementary diagram:



- diagrams can can only be connected by the lines

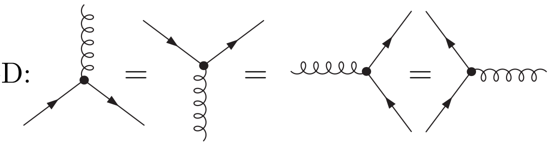


  - the lines have to stay the same
  - the arrow on a line keeps is direction when passing through a vertex
- lines entering or leaving a diagram are external lines
  - they represent real particles
- lines that do not enter or leave a diagram are internal lines
  - they represent virtual particles
  - the virtual particles "make" the interaction
  - they can have any energy or any momentum
  - energy and momentum are conserved at each vertex

3 QCD

has three elementary diagrams:

like in QED:



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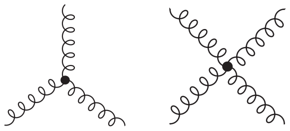
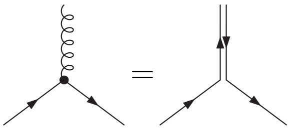


- in QED it is the electric charge that flows along the lines
- in QCD we can think of the "color" flowing along the lines

BUT! the photon has no charge, whereas the gluons have charge and anti-charge

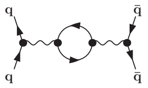
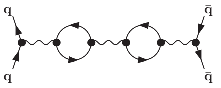
⇒ when thinking only about color, one can represent the gluon as two lines:

one coming in and one going out:

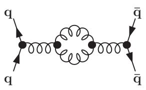
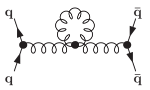
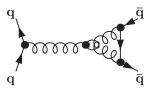


- the external lines in QCD are not directly observable:
  - we cannot see color at all, in principle!
    - when considering "normal" circumstances

additional material / explanations

- in QED the possible loop-diagrams  and  and ...

  make the interaction between the charges dependent on the energy of the process:
  - when the energy increases, the coupling increases, too
- for QCD we have additional diagrams

   and  and  and ...
- these diagrams change the behavior with energy:
  - when the energy increases, the coupling **decreases**!

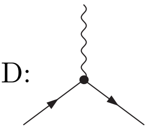
  ⇒ asymptotic freedom
    - explains, why we can use QCD in a perturbative approach

  ⇒ and confinement
    - explains, why we cannot see color (the quantum number of QCD)
    - explains, why boundstates can have a positive binding energy

4 weak interactions

have several elementary diagrams ...

like in QED:



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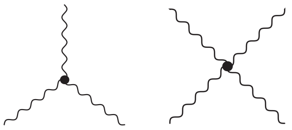


BUT: for the QED like vertex

- there are charged weak interactions
  - which **change** the particle, with which the W-boson interacts
- and neutral weak interactions, which look like QED,
  - but have a different, more complicated value at the vertex
  - when we can have a photon as an internal line, we can always also have a Z-boson
    - ∗ this is written then as γ/Z at the internal line.
  - the opposite is not true: neutrinos couple to the Z-boson, but not to the photon

The charged weak interaction is the **only** "force" that allows radioactive decay or nuclear fusion (sun)

- the W-boson couples always to **pairs** of particles:
  - (additional material !): the Higgs doublet: $\begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v+h+iG^0) \end{pmatrix}$
  - leptons: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$
  - quarks: $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$
  - these fermions are **only left-handed** !
- the wavy line has no arrow: the charge of the W boson has to be asigned by charge conservation !
  - this is written then as γ/Z at the internal line.

additional material / explanations

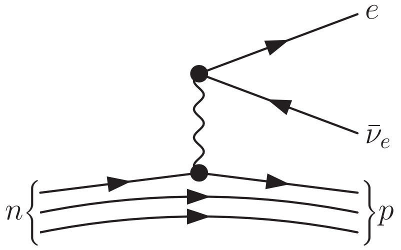
- the "weakness" of the weak interaction comes from the "large" mass of the weak vector bosons:
  - the Feynman diagram describing the weak decay has as an element also the propagator of the W-boson $\frac{i}{p^2-m_W^2} \sim \frac{-i}{m_W^2}$, which is nearly constant for typical energies of the nuclear (or most other) weak decays.

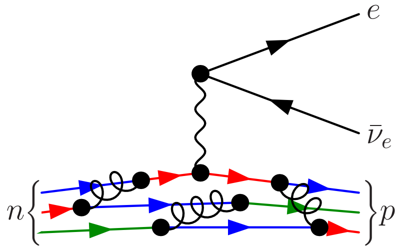
5 parton processes

- QCD exhibits the phenomenon of confinement: Feynman diagrams showing boundstates of quarks at low energies can no longer be ordered according to the number of internal gluon lines. But since gluons do not change the properties of the quarks (except for color, which cannot be seen anyway), the gluon lines do not change the other interactions of the quarks.

  ⇒ in boundstates we can ignore the internal gluon lines that describe the binding of the boundstate.

  - we only have to keep track of internal gluon lines that give rise to quark pairs or that come from the annihilation of quark pairs
  - to show baryon and meson decays we draw also the "spectator" quark lines





- QCD exhibits the phenomenon of asymptotic freedom: at "high" energies (the proton moves very close to the speed of light) only a single part of the proton, called **parton**, interacts. The other parts of the proton do not feel this interaction and are only weakly bound to the interacting **parton**: they only notice "later" that some color is missing and usually fragment into a **jet**.

  ⇒ for colliding protons (or antiprotons) we **only** use the partons that enter the collision

  ∗ the rest of the proton, the "spectators" are not specified. They can be indicated outside the collision.

  ⇒ Momentum conservation in the diagram applies for the incoming momenta of the partons, not for the momenta of the protons (antiprotons)!

  ∗ the mismatch between the momenta of the colliding partons and the momenta of the colliding protons (antiprotons) is carried away by the jets