



# Introduction to Nuclear and Particle Physics 8.701

## Lecture 2 SM interactions / Relativistic Kinematics

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# Outline

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## ■ Standard Model (SM) Interactions

- SM Forces
- Quantum Electrodynamics (QED) incl. vacuum polarization and behaviour of coupling constant
- Quantum Chromodynamics (QCD) incl. vacuum polarization and behaviour of QCD coupling constant
- Weak Interactions
  - Leptons
  - Quarks

## ■ Relativistic Kinematics

- Review of basic concepts
- Centre-of-mass frame vs. laboratory frame
- Mandelstam variables
- Decay length
- Collider kinematics

## ■ Summary



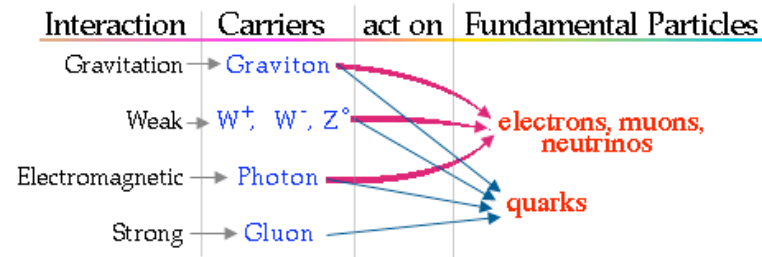


# Standard Model Interactions

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## ■ SM forces

- As far as we know, there are just **four fundamental forces** in nature:



- The Standard Model (SM) refers to three of these fundamental forces:

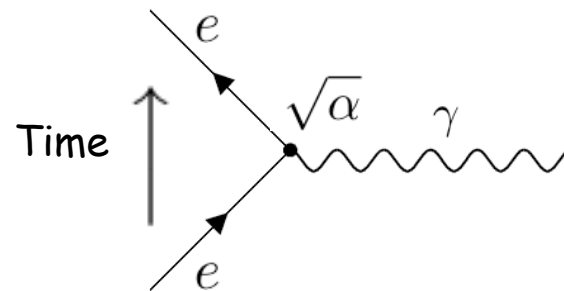
|                                  | Strong                                          | Electromagnetic                                        | Weak                                                                               |
|----------------------------------|-------------------------------------------------|--------------------------------------------------------|------------------------------------------------------------------------------------|
| <b>Mediator</b>                  | gluon $g$ ( $m=0$ )                             | photon ( $m=0$ )                                       | $W^\pm$ ( $m \approx 80 \text{ GeV}/c^2$ ), $Z$ ( $m \approx 90 \text{ GeV}/c^2$ ) |
| <b>Acts on</b>                   | Color charge                                    | Electric charge                                        | flavor                                                                             |
| <b>Particles experiencing it</b> | quarks, gluons                                  | charged particles                                      | leptons, quarks, $W^\pm$ , $Z$                                                     |
| <b>Range</b>                     | $1F \approx 1/m_\pi$<br>Color confinement range | $\infty$                                               | $10^{-3} \approx 1/m_W$                                                            |
| <b>Typical life time</b>         | $10^{-23} \text{ s}$                            | $10^{-20} - 10^{-16} \text{ s}$                        | $10^{-12} \text{ s}$                                                               |
| <b>Typical cross-section</b>     | $10 \text{ mb}$<br>$\pi p \rightarrow \pi p$    | $10^{-3} \text{ mb}$<br>$\gamma p \rightarrow \pi^0 p$ | $10^{-11} \text{ mb}$<br>$\nu p \rightarrow \nu p$                                 |
| <b>Typical coupling</b>          | 1                                               | $10^{-2}$                                              | $10^{-6}$                                                                          |



# Standard Model Interactions

## ■ QED: Fundamental Feynman graph

- All **electromagnetic phenomena** are ultimately reducible to the following **QED elementary coupling**:



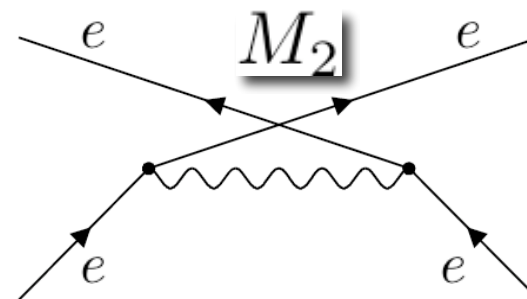
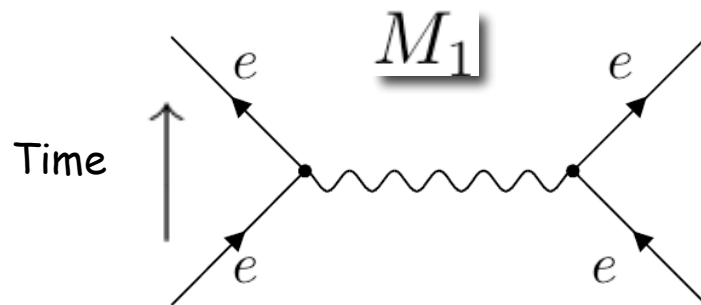
U(1) gauge theory

→ 1 charge with 1 boson (photon)

Coupling: Fine structure constant  $\alpha$

- Two elements: **Charged particle**, photon
- Meaning: **Charged particle**  $e$  enters, emits (or absorbs) a photon  $\gamma$  and exits.

- Example of a complete process: Moeller scattering  $e + e \rightarrow e + e$



Note:  
Amplitude of  
process  $i$

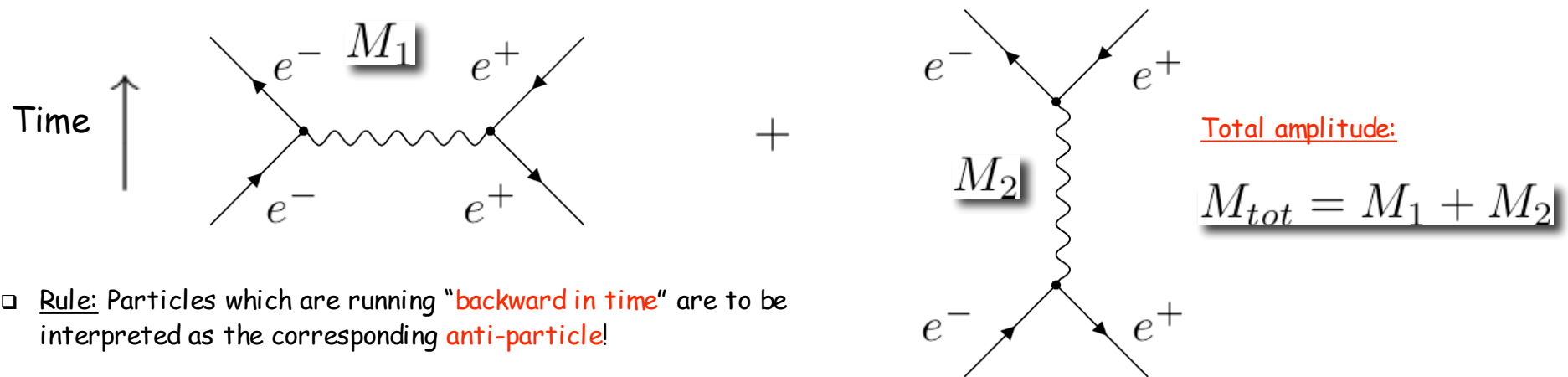
$M_i$

- Meaning: Interaction of two **electrons** which is mediated by a photon
- Classical case: Coulomb repulsion



# Standard Model Interactions

- Example of a complete process: Bhabha scattering  $e^- + e^+ \rightarrow e^- + e^+$



- Rule: Particles which are running "backward in time" are to be interpreted as the corresponding anti-particle!
- Bhabha scattering is related to Moeller scattering by a general principle which is known as crossing symmetry:

$$A + B \rightarrow C + D$$

- Rule: Any particle can be "crossed" over the other side at the equation, provided it turns into its anti-particle:

$$\left. \begin{array}{l} A \rightarrow \overline{B} + C + D \\ A + \overline{C} \rightarrow \overline{B} + D \\ \overline{C} + D \rightarrow \overline{A} + B \end{array} \right\}$$

These processes are dynamically allowed,  
but not necessarily kinematically!

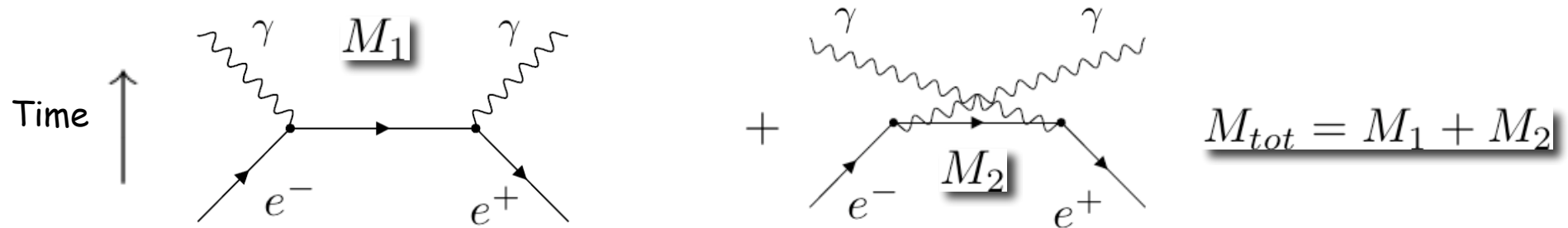
Bhabha scattering and Moeller scattering  
are related by crossing symmetry!

Example: If A weighs less than B, C and D,  
then this process is kinematically not  
allowed!

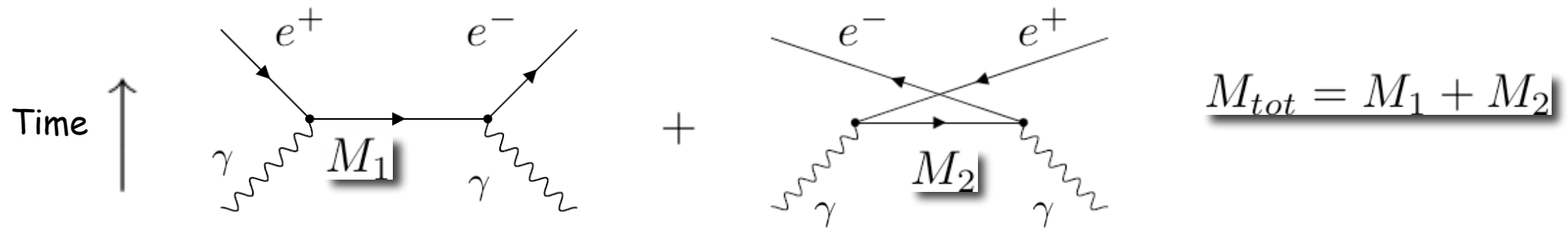


## Standard Model Interactions

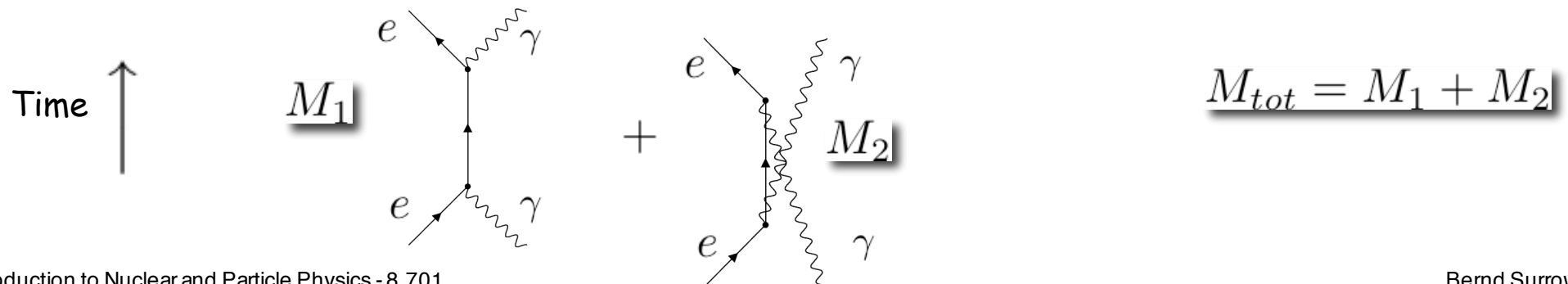
- Example of a complete process: Pair annihilation  $e^- + e^+ \rightarrow \gamma + \gamma$



- Example of a complete process: Pair production  $\gamma + \gamma \rightarrow e^- + e^+$



- Example of a complete process: Compton scattering  $e + \gamma \rightarrow e + \gamma$

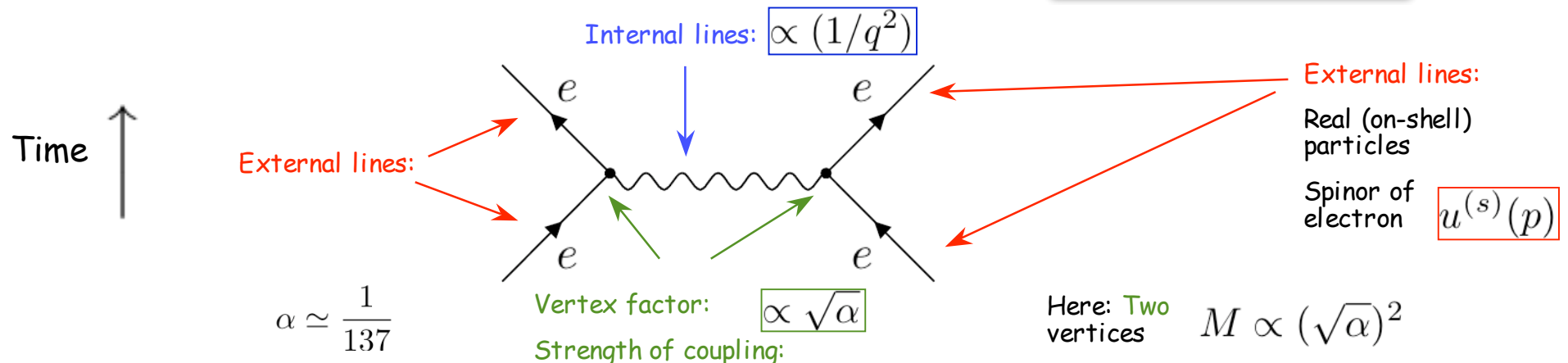




# Standard Model Interactions

## • Remarks on Feynman diagrams

- Feynman diagrams are purely symbolic in place of mathematical expression of a scattering amplitude
- Feynman diagrams **do not** represent particle trajectories!
- Example: "Components" of a Feynman diagram using  $M_1$  of Moeller scattering  $e + e \rightarrow e + e$



- Each Feynman diagram represents a matrix,  $M_i$ , to account for a particular process.
- Feynman rules enforce conservation of energy and momentum at each vertex, and hence for the diagram as a whole.
- Procedure:
  - Draw all diagrams, i.e. amplitudes, that have the appropriate external lines.
  - Sum of all diagrams, i.e. amplitudes, with the given external lines represents the actual physical process.
- Problem: There are infinite many Feynman diagrams!

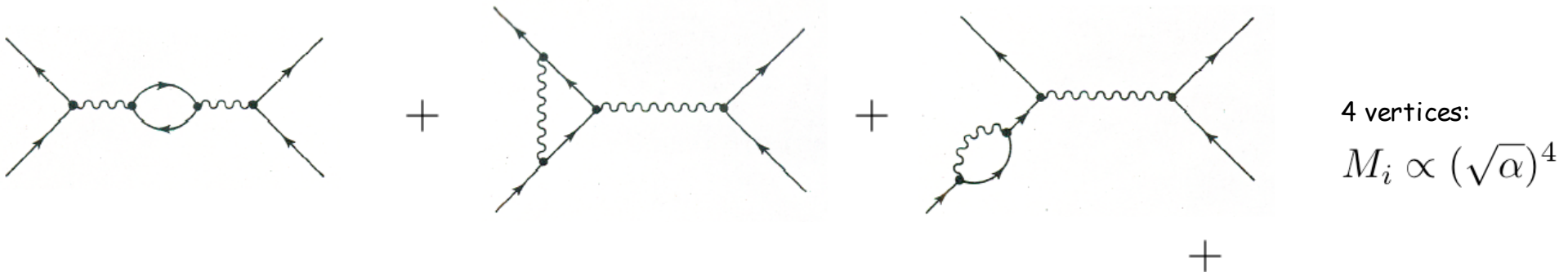


# Standard Model Interactions

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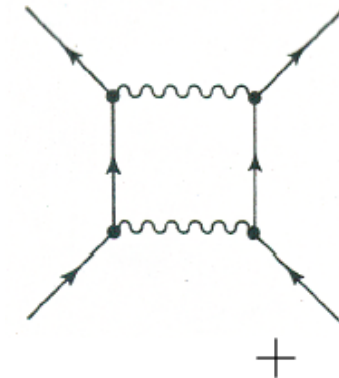
- Example: Moeller scattering at higher orders

- Besides above two leading order Feynman diagrams for Moeller scattering there are other higher-order diagrams:



4 vertices:  
 $M_i \propto (\sqrt{\alpha})^4$

- Calculations get very complicated!
- **BUT**: Each vertex contributes a factor  $\sqrt{\alpha}$
- $\alpha$ : QED fine structure constant (general: QED coupling constant)
- **Higher order** terms are suppressed since  $\alpha \ll 1$  (**perturbation theory**)!
- What matters "mainly" is the **leading order** contribution!
- However: There are many examples where measurements are so precise that higher order terms have to be taken into account! → **TEST OF QED**
- Example: Measurement of anomalous magnetic moment of muon!



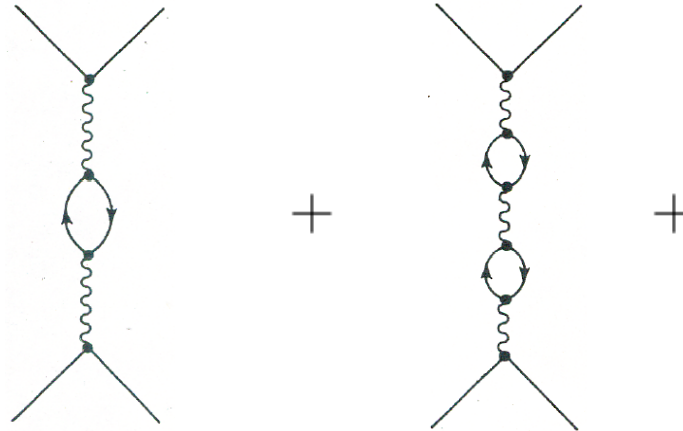
higher order  
diagrams..!



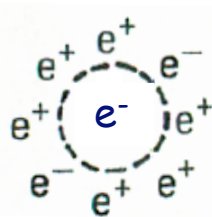
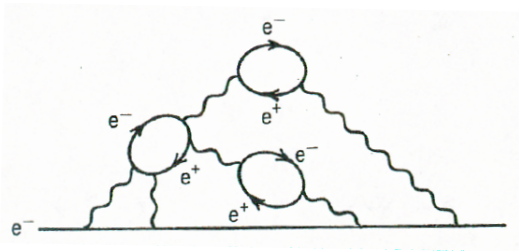
# Standard Model Interactions

- QED vacuum polarization

- In QED, the vacuum behaves like a dielectric, creating  $e^-/e^+$  pairs out of the vacuum:

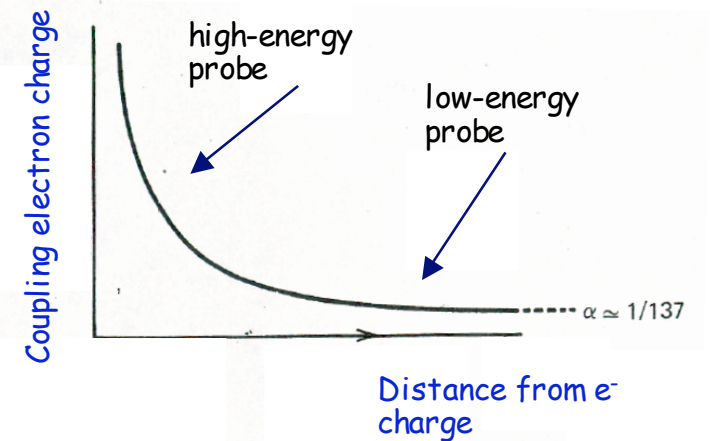


- Or view it like this:



Bare electron charge is screened

Effective charge  $\ll$  bare charge





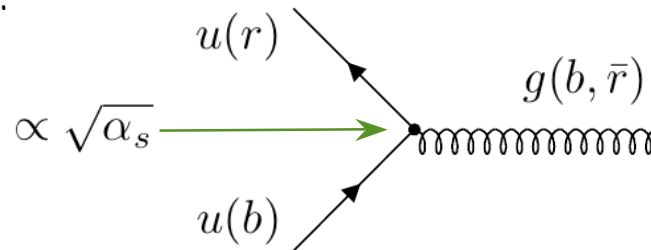
# Standard Model Interactions

## • QCD: Quantum Chromodynamics (1)

- In Quantum Chromodynamics: SU(3) gauge theory  $\rightarrow$  3 charges with 8 bosons (gluons)
- Color plays the role of charge and the fundamental process is: quark  $\rightarrow$  quark + gluon
- Fundamental vertex:

Vertex factor:

Strong coupling constant  $\alpha_s$ !



**Note:** Color is always conserved!  
 $\rightarrow$  gluon is carrying away the difference: Here b and anti-red!

- Types of gluons:  $r\bar{r} \quad r\bar{b} \quad r\bar{g} \quad b\bar{r} \quad b\bar{b} \quad b\bar{g} \quad g\bar{r} \quad g\bar{b} \quad g\bar{g}$

$$\left. \begin{array}{l} \text{color octet} \\ \left\{ \begin{array}{ll} |1\rangle = (r\bar{b} + b\bar{r})/\sqrt{2} & |5\rangle = -i(r\bar{g} - g\bar{r})/\sqrt{2} \\ |2\rangle = -i(r\bar{b} - b\bar{r})/\sqrt{2} & |6\rangle = (b\bar{g} + g\bar{b})/\sqrt{2} \\ |3\rangle = (r\bar{r} - b\bar{b})/\sqrt{2} & |7\rangle = -i(b\bar{g} - g\bar{b})/\sqrt{2} \\ |4\rangle = (r\bar{g} + g\bar{r})/\sqrt{2} & |8\rangle = (r\bar{r} + b\bar{b} - 2g\bar{g})/\sqrt{6} \end{array} \right. \end{array} \right\} \text{SU(3)}$$

$$\left. \begin{array}{l} \text{color singlet} \\ \left\{ \begin{array}{ll} |9\rangle = (r\bar{r} + b\bar{b} + g\bar{g})/\sqrt{3} & \text{No net color...like a photon!} \end{array} \right. \end{array} \right\}$$



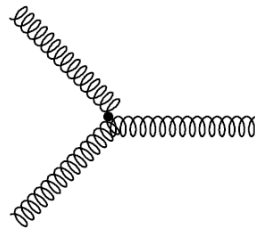
# Standard Model Interactions

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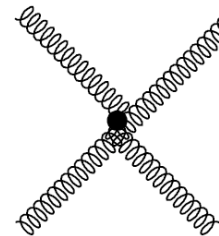
- QCD: Quantum Chromodynamics (2)

- Confinement requires that all **naturally occurring particles** be **color singlets**!
- $|9\rangle$  is a color **singlet state**. If it exists as mediator, it should also occur as a free particle
- As such a mediator: Exchange between color singlet particles, e.g. a proton and neutron.  
Therefore: Long-range force with strong coupling.
- **However**: **Strong force** is of very **short range**.  
Therefore: Experiments tell us that there are only **8 gluons**  $\Rightarrow$  **color octets**:  $SU(3)$
- Because gluons themselves carry color (in contrast to the photon which is electrically neutral): gluons couple directly to one another:

3 gluon vertices



4 gluon vertices



- **QCD calculations**: Apply QCD Feynman rules to calculate various processes!
- How does the QCD coupling constant behave compared to the QED coupling constant?



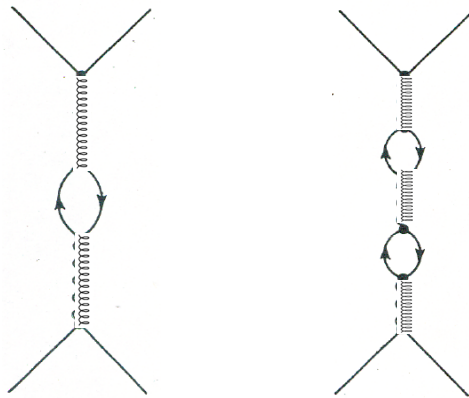
# Standard Model Interactions

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- QCD vacuum polarization (1)

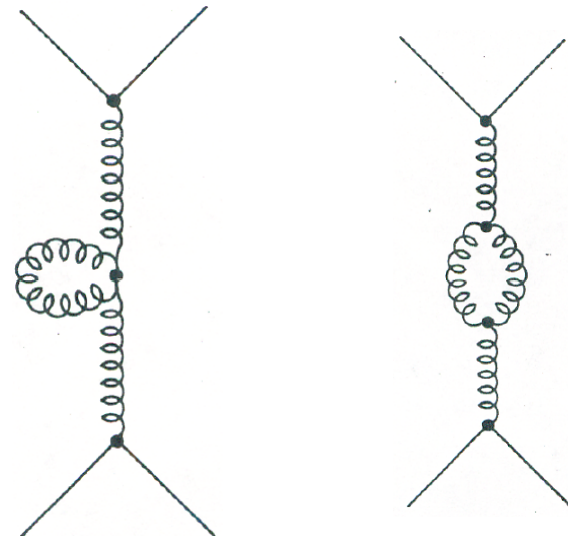
- Clear difference between QED and QCD Self-coupling of gluons which is absent in case of QED.

- QCD vacuum polarization diagrams:



**Quark polarization**

But also:



**Gluon polarization**

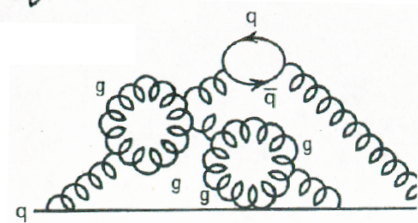
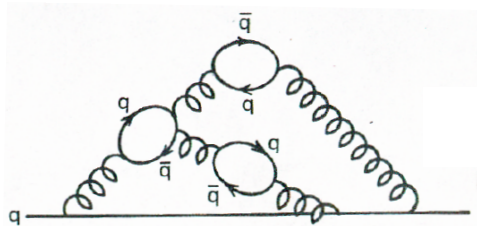
**Note:** Behavior is opposite for  $\alpha_s$

- Quark polarization:  $\alpha_s$  is large at short distances!
  - Gluon polarization:  $\alpha_s$  is small at short distances!

A priori not  
clear who wins!

## • QCD vacuum polarization (2)

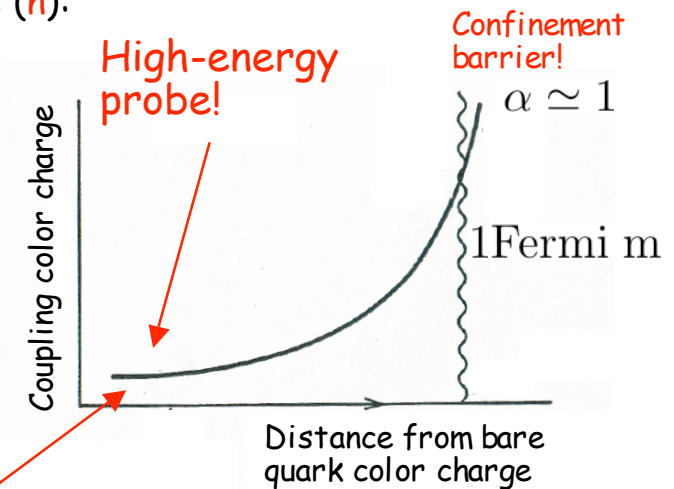
- The winner depends on the relative number at **flavors** ( $f$ ) and **colors** ( $n$ ):
- **Critical parameter:**  $a \equiv 2f - 11n$
- Standard Model:  $f = 6, n = 3 \rightarrow a = -21$
- Consequence: QCD coupling constant decreases at short distances!
- Another "last picture":



But also:

## Asymptotic freedom

Quarks are quasi-free  
 $\rightarrow$  Small coupling at short distances  
 (high-energy)!



Discovery of asymptotic freedom in the theory of strong interaction (**Q**uantum **C**hromo **D**ynamics): Nobel prize in physics 2004





# Standard Model Interactions

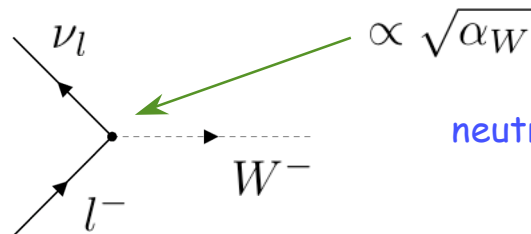
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- Weak interactions (1)

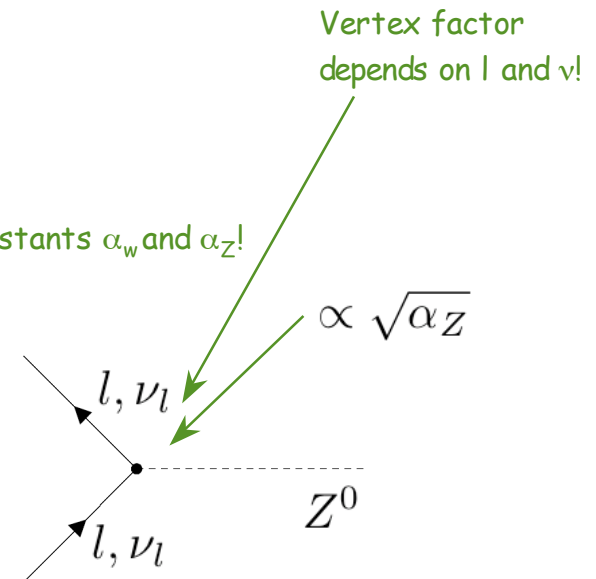
- $SU(2)$  gauge theory: 3 mediators:  $Z^0$   $W^\pm$
- Electroweak unification:  $SU(2) \times U(1)$ : 4 mediators:  $Z^0$ ,  $W^\pm$  and  $\gamma$
- Quarks and leptons take part in weak interactions

- 2 types of interactions:
  - charged current: Involving  $W^\pm$
  - neutral current: Involving  $Z^0$  and  $\gamma$

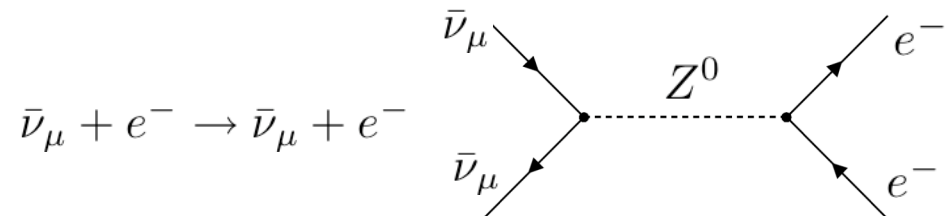
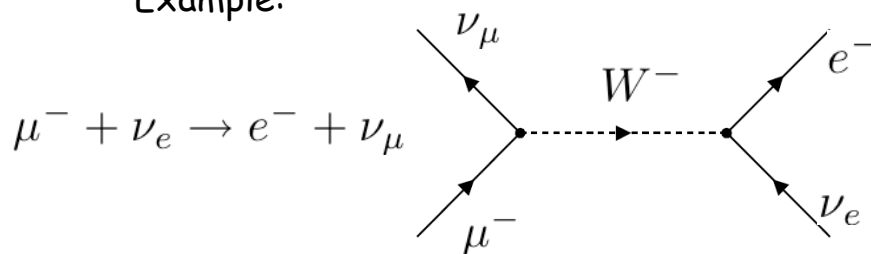
- Leptons:  
charged vertex:



neutral vertex:



Example:



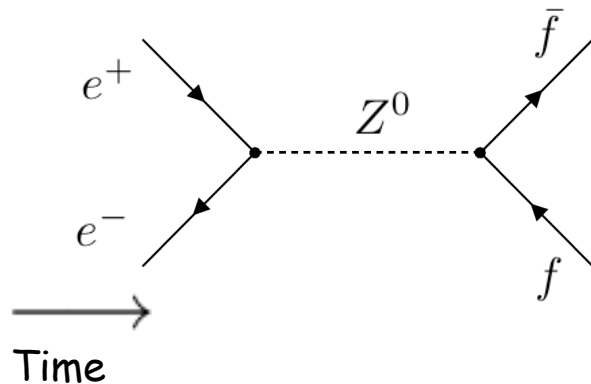
First "picture" of neutral weak process discovered at CERN in 1973



- Weak interactions (2)

- Note: The Glashow-Weinberg-Salam (GWS) model ( $SU(2) \times U(1)$ ) includes neutral weak processes as an essential ingredient. Their existence was confirmed experimentally at CERN in 1973!

- Production at  $Z^0$  at LEP:



$$\left( \begin{array}{cccccccccccc} e^+ & \mu^+ & \tau^+ & \bar{\nu}_e & \bar{\nu}_\mu & \bar{\nu}_\tau & \bar{u} & \bar{d} & \bar{s} & \bar{c} & \bar{b} \\ e^- & \mu^- & \tau^- & \nu_e & \nu_\mu & \nu_\tau & u & d & s & c & b \end{array} \right)$$

... established 3 families in nature...:

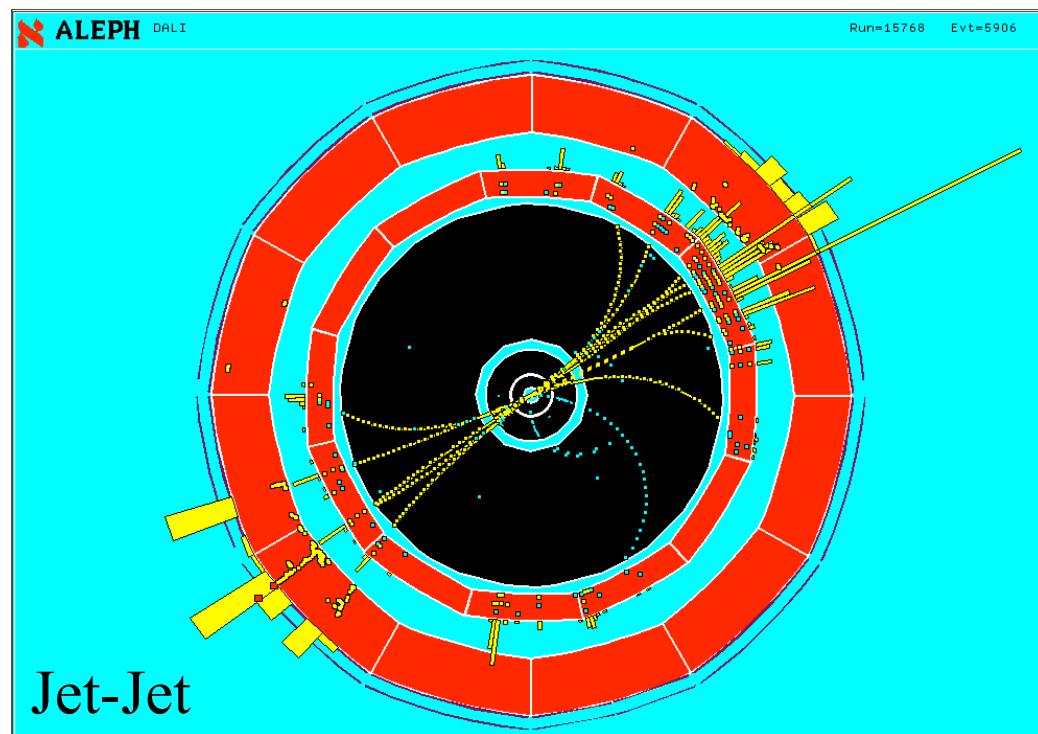
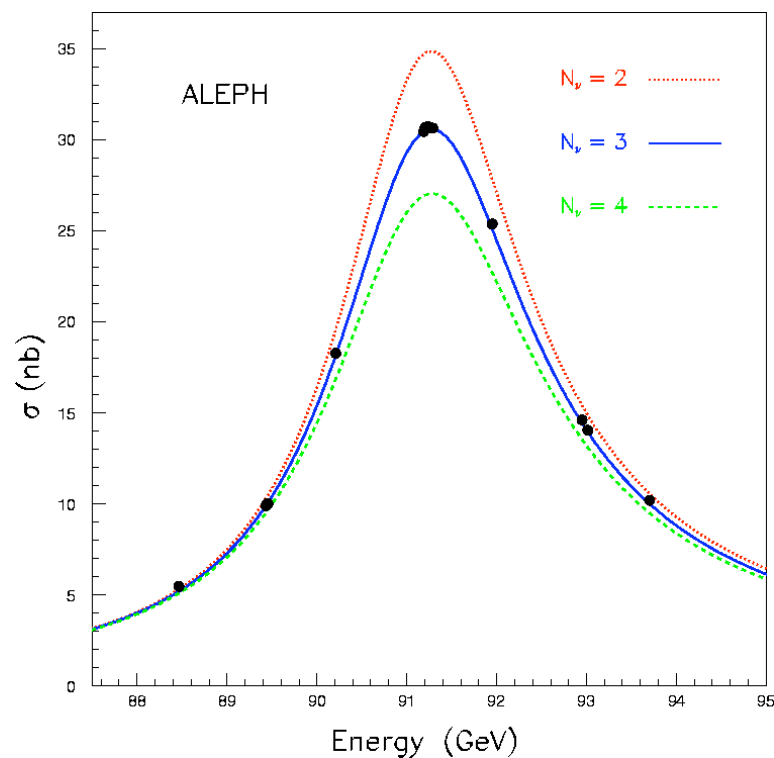


# Standard Model Interactions

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- Weak interactions (3)

- Production of  $Z^0$  bosons at LEP:





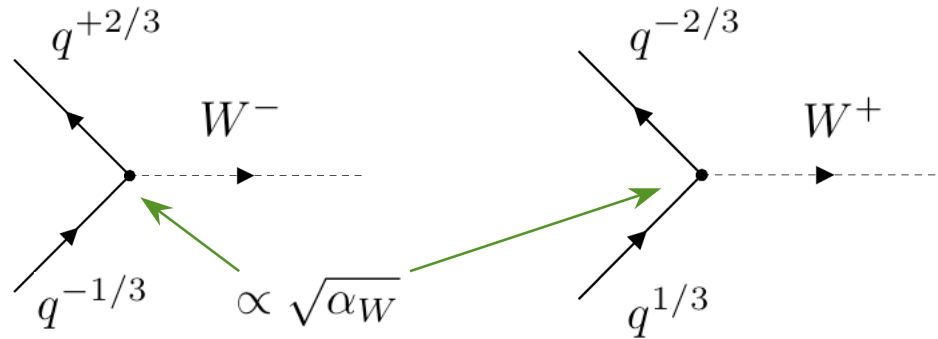
# Standard Model Interactions

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- Weak interactions (3)

- Quarks

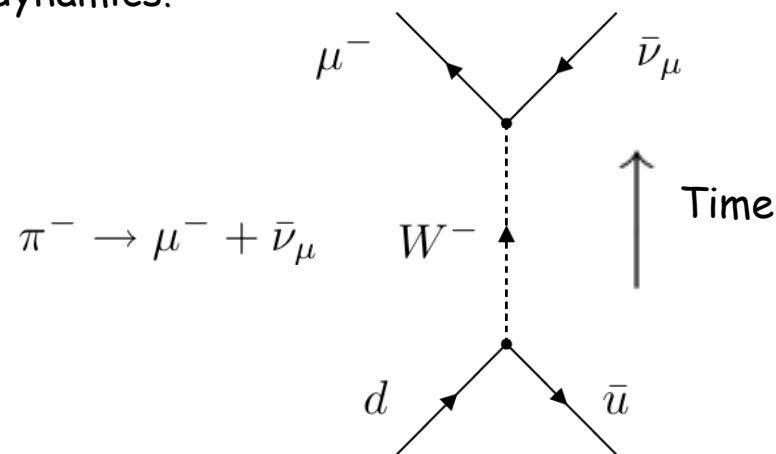
Fundamental vertex:  $W^\pm$



**Note:** A quark of charge  $-1/3$  ( $d, s, b$ ) converts into the corresponding quark with charge  $+2/3$  ( $u, c, t$ ) with the emission of  $W^-$  (vice versa for  $W^+$ )

**Note:** Flavor is not conserved in weak interactions! Since the quark flavor changes at a weak vertex (Recall: Color change of quarks at QCD vertex!), weak interactions are sometimes called flavordynamics!

Example:

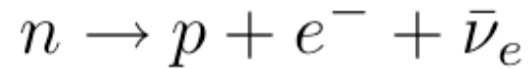




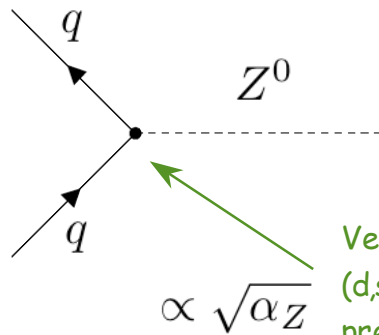
# Standard Model Interactions

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Example: Beta-decay of the neutron:



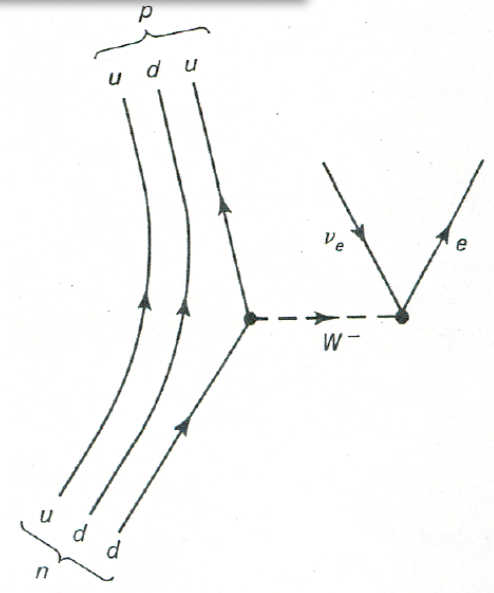
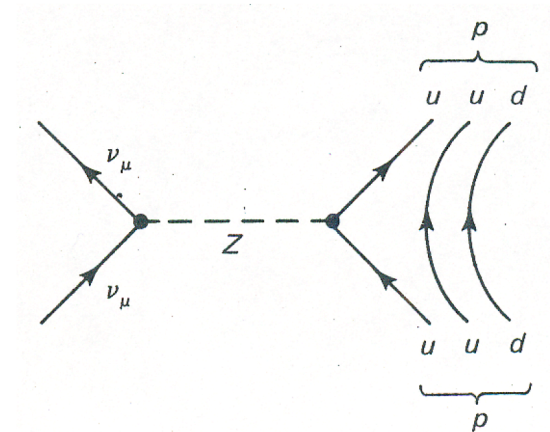
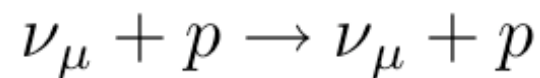
Fundamental vertex:  $Z^0$



**Note:** Quark flavor is not changed!

Vertex factor for (u,c,t) and (d,s,b) different (GSW prediction!)

Example:





# Standard Model Interactions

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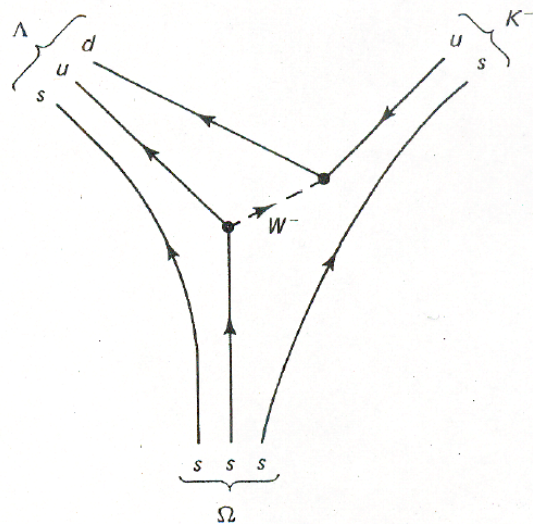
## □ Flavor changing reactions

- In the spirit of the **charged weak coupling** with respect to **leptons** which yield **only changes within each family**, i.e. :  $e^- \leftrightarrow \nu_e$   $\mu^- \leftrightarrow \nu_\mu$   $\tau^- \leftrightarrow \nu_\tau$

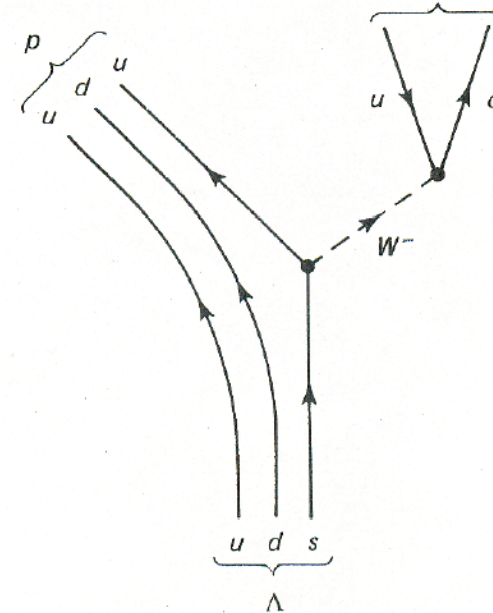
- One might assume that this also holds for quarks:  $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$

- **However:** The following observed decays involve the conversion of a **strange quark s** into an **up-quark**:

$$\Omega^- \rightarrow \Lambda + K^-$$



$$\Lambda \rightarrow p^+ + \pi^-$$



- Flavor changes do occur across quark families!



## Standard Model Interactions

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• Therefore:

- The flavor **eigenstate of u** is not the partner to the **flavor eigenstate of d**, but to a **linear combination of d, s and b here written as d'**:

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix}$$

- Linear-combination:

$$\begin{pmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix}$$

- Note:

The matrix is called after their “inventors”: **3 X 3 Kobayashi - Maskawa matrix!**

Earlier scheme (2 families) by **Cabibbo** (1963):

Cabibbo angle:  $\Theta_c \approx 13.1^\circ$

$$|d'\rangle = |d\rangle \cos \Theta_c + |s\rangle \sin \Theta_c$$

$$|s'\rangle = |d\rangle (-\sin \Theta_c) + |s\rangle \cos \Theta_c$$



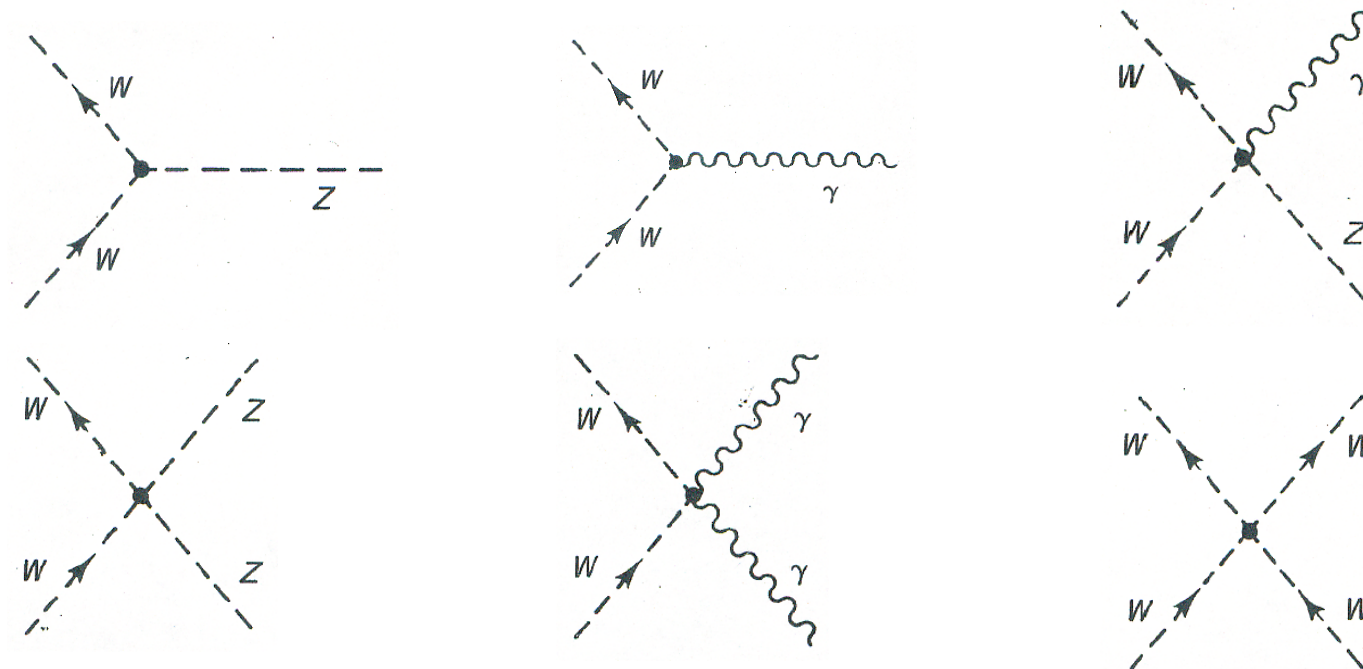
## Standard Model Interactions

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- Experimental data: K. Hagiwara et al., Phys. Rev. D66 (2002) 010001.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9739 \text{ to } 0.9751 & 0.221 \text{ to } 0.227 & 0.0029 \text{ to } 0.0045 \\ 0.221 \text{ to } 0.227 & 0.9730 \text{ to } 0.9744 & 0.039 \text{ to } 0.044 \\ 0.0048 \text{ to } 0.014 & 0.037 \text{ to } 0.043 & 0.9990 \text{ to } 0.9992 \end{pmatrix}$$

- Self coupling of weak-bosons and photon:

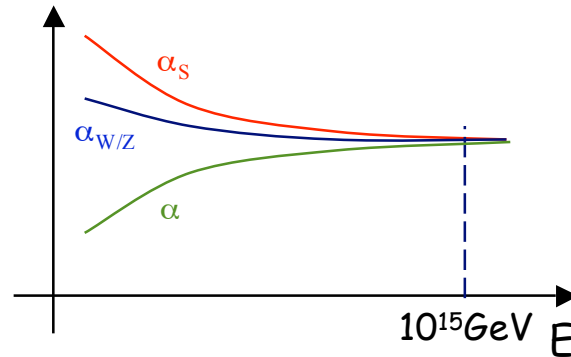




# Standard Model Interactions

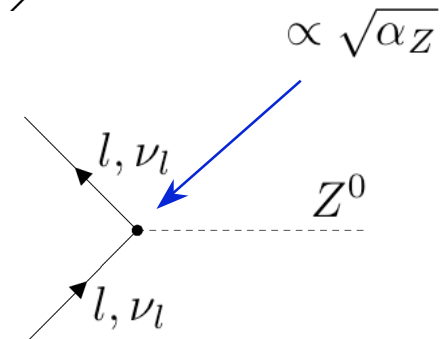
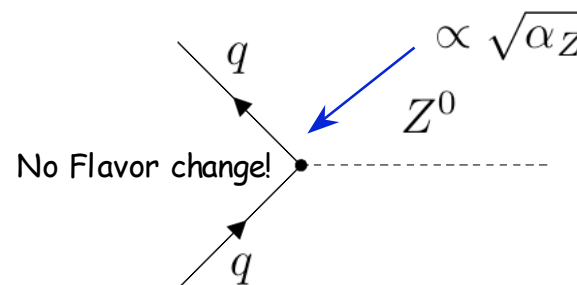
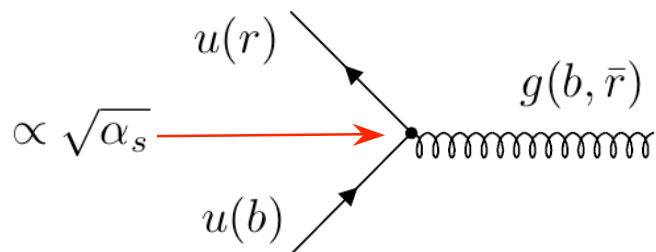
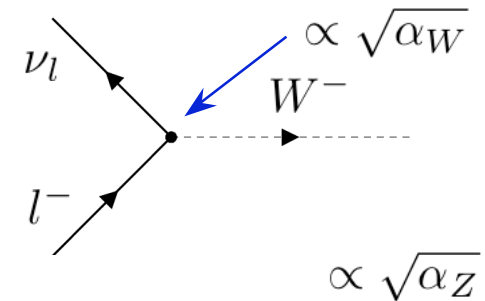
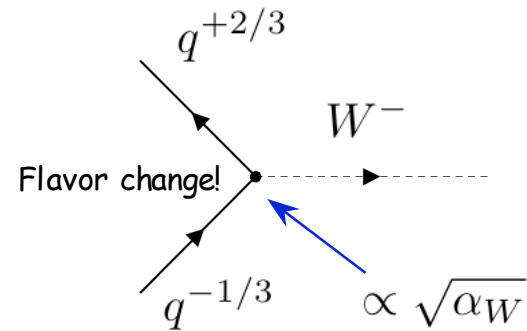
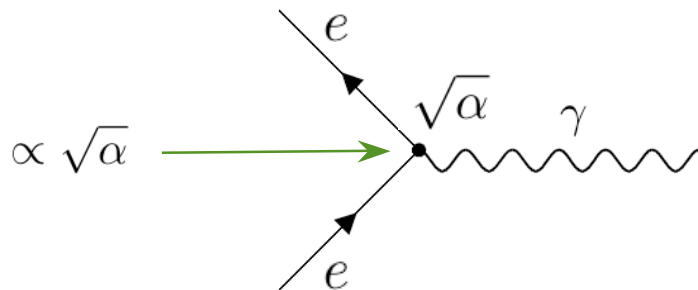
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- Last remark:



Grand Unified Theories  
(GUT): One Force

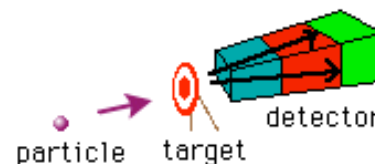
- Summary: SM interactions





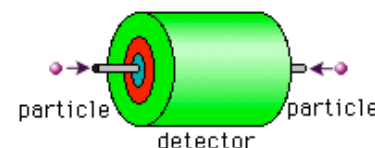
## ■ Standard Model (SM) Interactions

- ✓ SM Forces
- ✓ Quantum Electrodynamics (QED) incl. vacuum polarization and behaviour of coupling constant
- ✓ Quantum Chromodynamics (QCD) incl. vacuum polarization and behaviour of QCD coupling constant
- ✓ Weak Interactions
  - ✓ Leptons
  - ✓ Quarks



## ■ Relativistic Kinematics

- Review of basic concepts
- Centre-of-mass frame vs. laboratory frame
- Mandelstam variables
- Decay length
- Collider kinematics



## ■ Summary



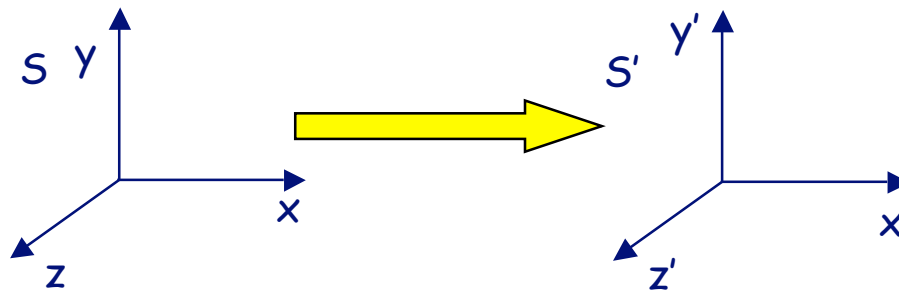


## ■ Relativistic Kinematics

- Review of basic concepts

### (1) Lorentz Transformations

Given two inertial frames  $S$  and  $S'$ , with  $S'$  moving at uniform speed  $v$  with respect to  $S$ :



Events are related in space-time as follows (**Lorentz Transformations**):

$$x' = \gamma(x - vt)$$

$$y' = y$$

$$z' = z$$

$$t' = \gamma \left( t - \frac{v}{c^2} x \right)$$

With:  $\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$        $\beta = v/c$



## (2) Consequences

### a. Relativity at simultaneity:

If two events  $A$  and  $B$  occur at the same time in  $S$ , but at different locations, then they do not occur at the same time in  $S'$ :

$$t'_A = t'_B + \frac{\gamma v}{c^2} (x_A - x_B)$$

### b. Lorentz contraction:

A moving object is shortened by a factor:

$$L = L' / \gamma$$

### c. Time dilation:

Moving clocks run slow:

$$T = T' \gamma$$

Example: Muon decay in earth atmosphere

$$\tau_\mu = 2.2\mu s \quad v \approx c \quad \gamma \approx 10$$

$$c\tau_\mu \approx 660m$$

Decay length of decaying particle:  $l = c\beta\gamma\tau$



## Relativistic Kinematics

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### d. Velocity addition:

Particle moves with speed  $u'$  with respect to  $S'$ . What is the speed,  $u$ , with respect to  $S$ ? **Note:**  $S'$  moves with speed  $v$  with respect to  $S$ :

$$u = \frac{u' + v}{1 + (u'v/c^2)} \quad \text{If } u'=c \text{ then } u=c!$$

### (3) Four vectors

$$x^\mu = (x^0, x^1, x^2, x^3) = (ct, x, y, z)$$

$$(x')^\mu = \Lambda^\mu_\nu x^\nu$$

**Einstein convention:**

Sum over double occurring indices!

$$\Lambda = \begin{pmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



## (4) Invariant quantities

Easy to show that the following expression is **invariant** in any inertial system:

$$(x^0)^2 - (x^1)^2 - (x^2)^2 - (x^3)^2 = (x'^0)^2 - (x'^1)^2 - (x'^2)^2 - (x'^3)^2$$

This expression,  $I$ , is a relativistic invariant quantity!

With Metric Tensor:

$$g = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$I = g_{\mu\nu} x^\mu x^\nu$$

Short:  $I = x_\mu x^\mu$

Covariant four vector:

$$x_\mu = g_{\mu\nu} x^\nu$$

Contra variant four vector:

$$x^\mu$$



# Relativistic Kinematics

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Product of any two four vectors:

$$a^\mu \cdot b_\mu = a_\mu \cdot b^\mu = a^0 \cdot b^0 - a^1 \cdot b^1 - a^2 \cdot b^2 - a^3 \cdot b^3$$

$$a \cdot b \equiv a_\mu b^\mu \quad \text{With:} \quad b_\mu = a_\mu \quad a^2 \equiv a \cdot a = (a^0)^2 - (\vec{a})^2$$

$$a^2 > 0 \quad \text{timelike}$$

$$a^2 < 0 \quad \text{spacelike}$$

$$a^2 = 0 \quad \text{lightlike}$$

$$(5) \text{ Energy and Momentum} \quad \vec{\eta} = \gamma \cdot \vec{v} \quad \eta^\mu = \gamma(c, v_x, v_y, v_z)$$

$$\vec{p} = m\vec{\eta} = \gamma m\vec{v} \quad p^0 = \gamma mc \quad p^\mu = \left(\frac{E}{c}, p_x, p_y, p_z\right)$$

$$p_\mu \cdot p^\mu = \frac{E^2}{c^2} - (\vec{p})^2 = m^2 c^2$$

$$E = \gamma mc^2$$

**Invariant mass squared!**



# Relativistic Kinematics

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- Note on conserved and invariant quantities
  - A **conserved** quantity remains the same, in a particular frame, before and after an event
  - An **invariant** quantity is the same in all inertial reference frames
  - Energy/momentum is **conserved**, but not invariant
  - Mass is **invariant**, but not conserved



## Relativistic Kinematics

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- Centre-of-mass frame / lab frame

Lorentz transformation:

$$\begin{pmatrix} E^* \\ p_{\parallel}^* \end{pmatrix} = \begin{pmatrix} \gamma_f & -\gamma_f \beta_f \\ -\gamma_f \beta_f & \gamma_f \end{pmatrix} \begin{pmatrix} E \\ p_{\parallel} \end{pmatrix}, \quad p_T^* = p_T$$

Energy and momentum viewed from a frame  
moving with velocity:  $\beta_f$

Consider the following process:  $A + B \rightarrow C + D$

Mandelstam variables:

$$\begin{aligned} s &= (p_A + p_B)^2 \\ t &= (p_A - p_C)^2 \\ u &= (p_A - p_D)^2 \end{aligned}$$

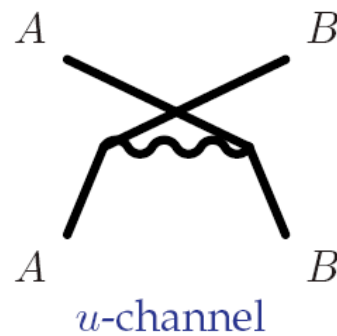
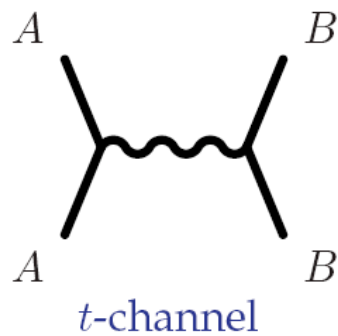
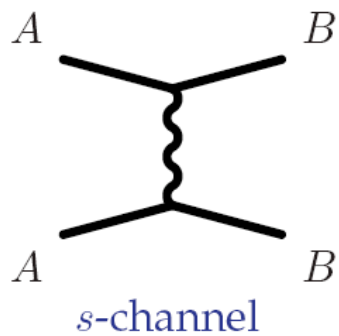


# Relativistic kinematics

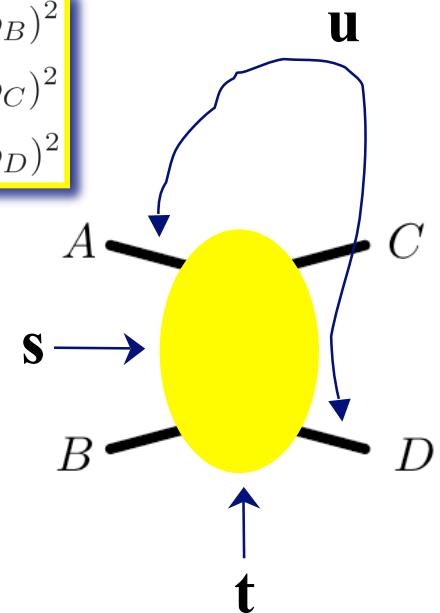
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The **Mandelstam variables**  $s$ ,  $t$  and  $u$  are related to **three distinct topological channels** with which **Feynman diagrams** might be drawn to represent the interaction:

$$A + B \rightarrow A + B$$



$$\begin{aligned} s &= (p_A + p_B)^2 \\ t &= (p_A - p_C)^2 \\ u &= (p_A - p_D)^2 \end{aligned}$$



**CM frame**

$$p_A^* = (E_A^*, \vec{p}_A^*) \quad p_B^* = (E_B^*, \vec{p}_B^*)$$

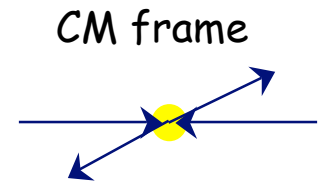
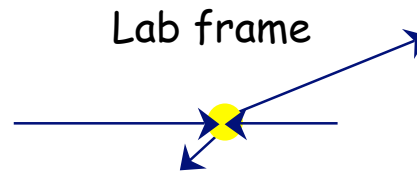
$$p_C^* = (E_C^*, \vec{p}_C^*) \quad p_D^* = (E_D^*, \vec{p}_D^*)$$

**Lab frame**

$$p_A = (E_A, \vec{p}_A) \quad p_B = (E_B, \vec{p}_B)$$

$$p_C = (E_C, \vec{p}_C) \quad p_D = (E_D, \vec{p}_D)$$

Let's work out an example using the Mandelstam variable  $s$ :



$$\vec{p}_A^* + \vec{p}_B^* = \vec{p}_C^* + \vec{p}_D^* = 0$$

$$(p_A + p_B)^2 = (p_A^* + p_B^*)^2 = s$$



# Relativistic kinematics

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Relate CM system and Lab system: Calculate CM energy  $\sqrt{s}$

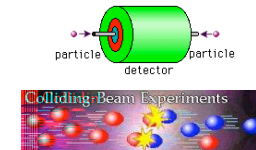
$$(p_A + p_B)^2 = (p_A^* + p_B^*)^2 = s$$

$$(\sqrt{s})^2 = (E_A + E_B)^2 - (\vec{p}_A + \vec{p}_B)^2$$

$$= m_A^2 + m_B^2 + 2E_A E_B (1 - \beta_A \beta_B \cos \theta)$$

**The CM system is your friend!**

- Collider configuration:  $\cos \theta = -1$   $\beta_A = \beta_B \simeq 1$



$$\sqrt{s} = \sqrt{4E_A E_B}$$

For HERA:  $E_A = 27.5 \text{ GeV}$   $E_B = 920 \text{ GeV}$   $\sqrt{s} = 318 \text{ GeV}$

- Fixed-target configuration:  $\cos \theta = 0$   $\beta_B = 0$



$$\sqrt{s} = \sqrt{2E_A m_B}$$

Same CM energy as HERA for:

$m_B \simeq 1 \text{ GeV}$   $E_A = 50600 \text{ GeV}$



## Summary

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### □ Conservation laws: Analysis of particle reactions:

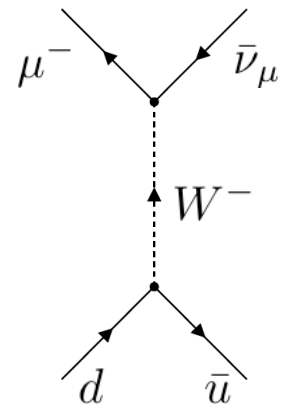
1. Energy and momentum
2. Angular momentum
3. Electric charge
4. Color charge
5. Baryon number:  $A = 1$  for Baryons;  $A = -1$  for Anti-Baryons;  $A = 0$  for non Baryons.
6. Lepton number:

Particles at each generation (Leptons) are conserved:  $L_e, L_\mu, L_\tau$

$$L_i = -1 \quad \text{Anti-Particle}$$

$$L_i = +1 \quad \text{Particle}$$

Example  $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$



7. Flavor is conserved in strong and electromag. interactions, but not in weak interactions!