

# Practical QCD at colliders

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1<sup>st</sup> Lecture

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# Today's high energy colliders

Today's high energy physics program relies mainly on results from

Collider	Process	status
LEP/LEP2	$e^+e^-$	1989-2000
Hera	$e^\pm p$	1992-2007
Tevatron	pp	1983-2011
LHC- Run I	pp	2010-2012
LHC- Run II	pp	started 2015

- LEP high precision measurements of masses, couplings, EW parameters ...
- Hera: mainly measurements of parton densities and diffraction
- Tevatron: mainly discovery of top and many QCD measurements
- LHC designed to
  - discover the Higgs [done in Run I]
  - unravel possible BSM physics [elusive up to now]

# Today's status of particle physics

- The Higgs boson: the last missing ingredient of the Standard Model of particle physics
- The SM is a consistent theory up to very high energy, but it can not be a complete theory because of many theory and experimental puzzles (Dark matter and dark energy, neutrino masses, flavour physics, hierarchy problem, no theory of quantum gravity...)

The days of guaranteed discoveries or no-lose theorems are over. Progress will be driven by LHC data.

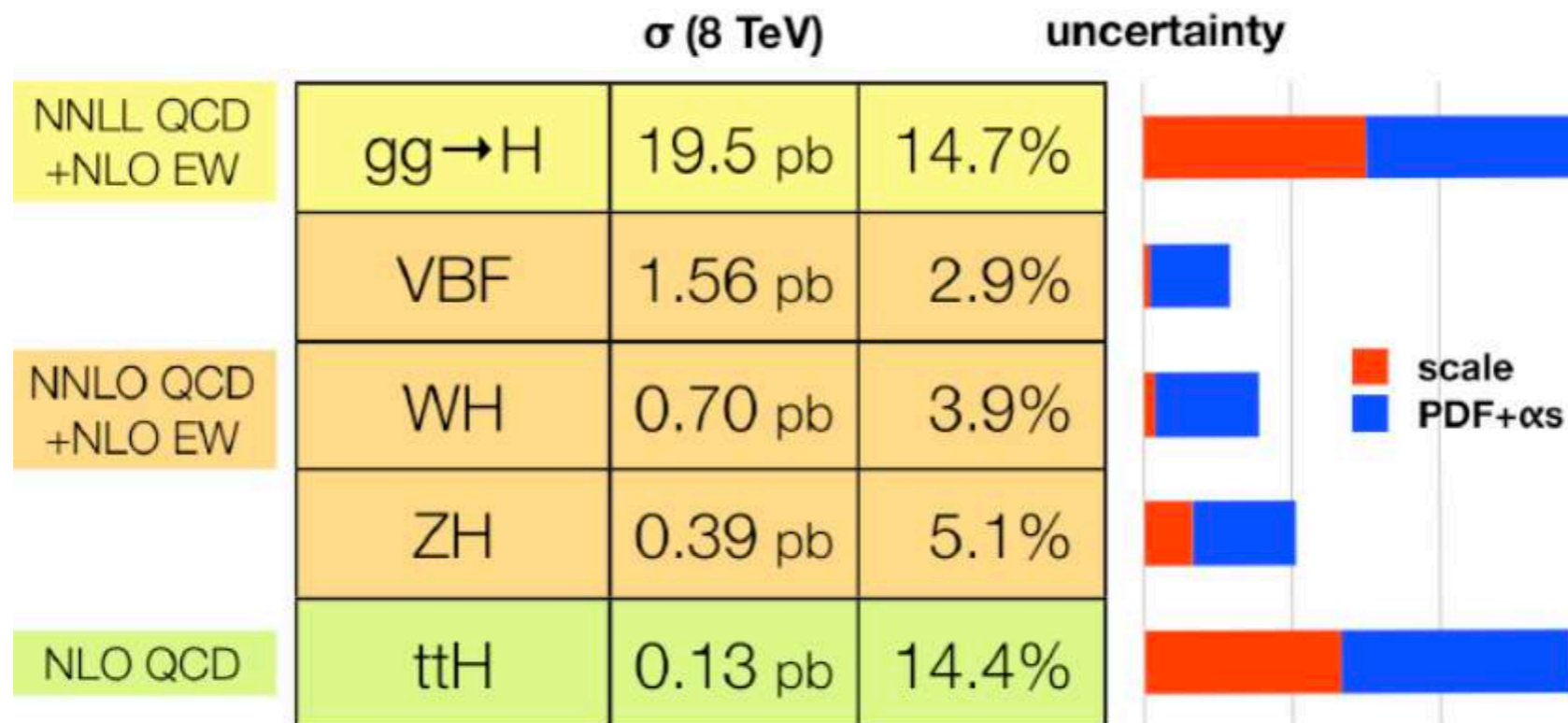
The LHC program in the coming decades will focus on

- **Direct searches:** production of new (heavy states) ...
- **Indirect searches:** Higgs couplings and branchings, rare decay modes ...
- **Consistency tests:** precision electroweak data

# Today's status of particle physics

Improving our theory description of data crucial to enhance sensitivity when looking for new physics.

Example: extraction of Higgs couplings limited by theory uncertainties

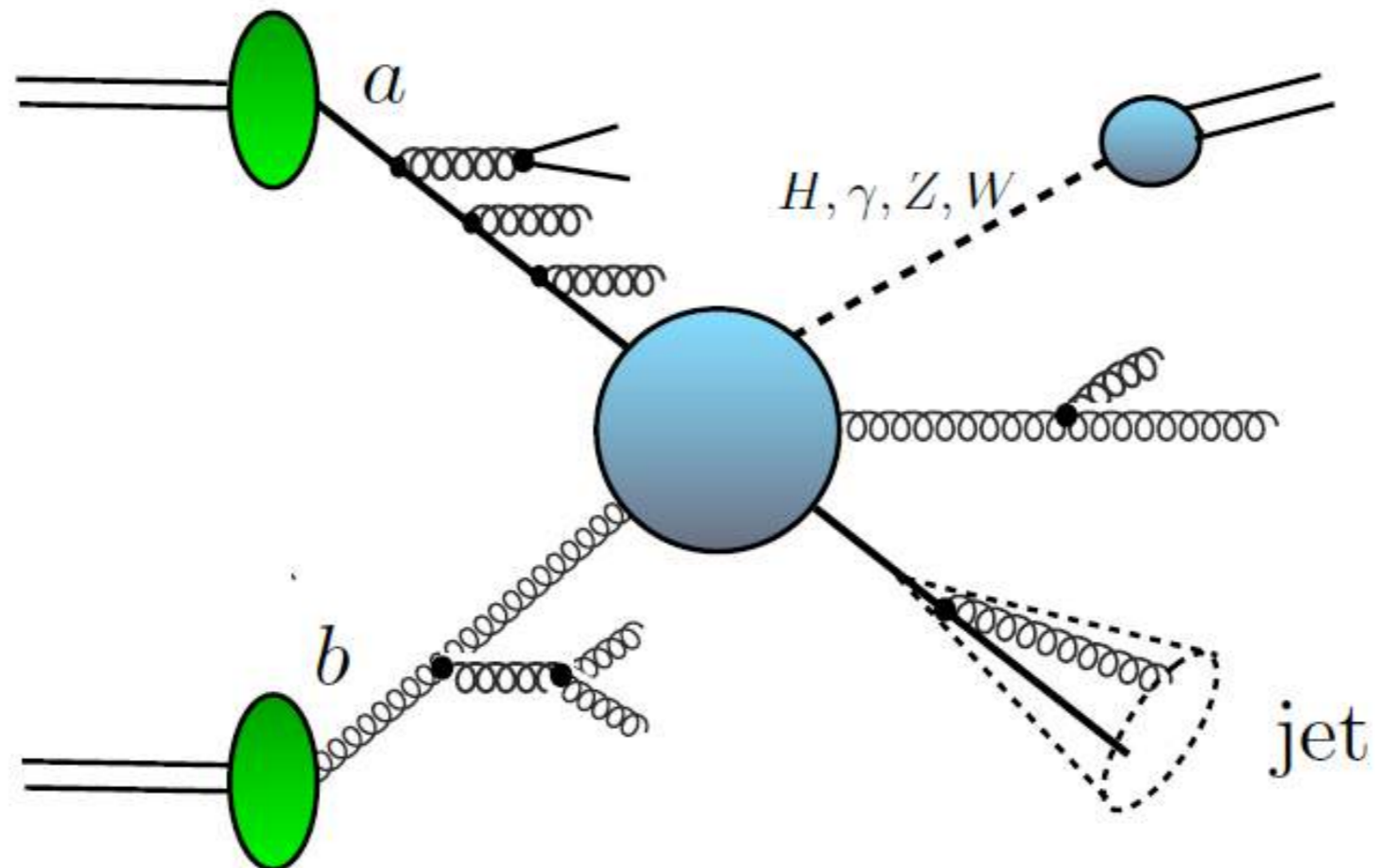


Sharpen the tools  $\Rightarrow$  get more accurate predictions  $\Rightarrow$  get improved indirect sensitivity to New Physics (which would modify SM couplings)

# Propose of these lectures

In these lectures: perturbative QCD as a tool for precision QCD at colliders

- Introduction to QCD (or refresh your knowledge of QCD)
- Basic concepts which appear over and over in different contexts
- Understand the terminology
- Recent developments in the field

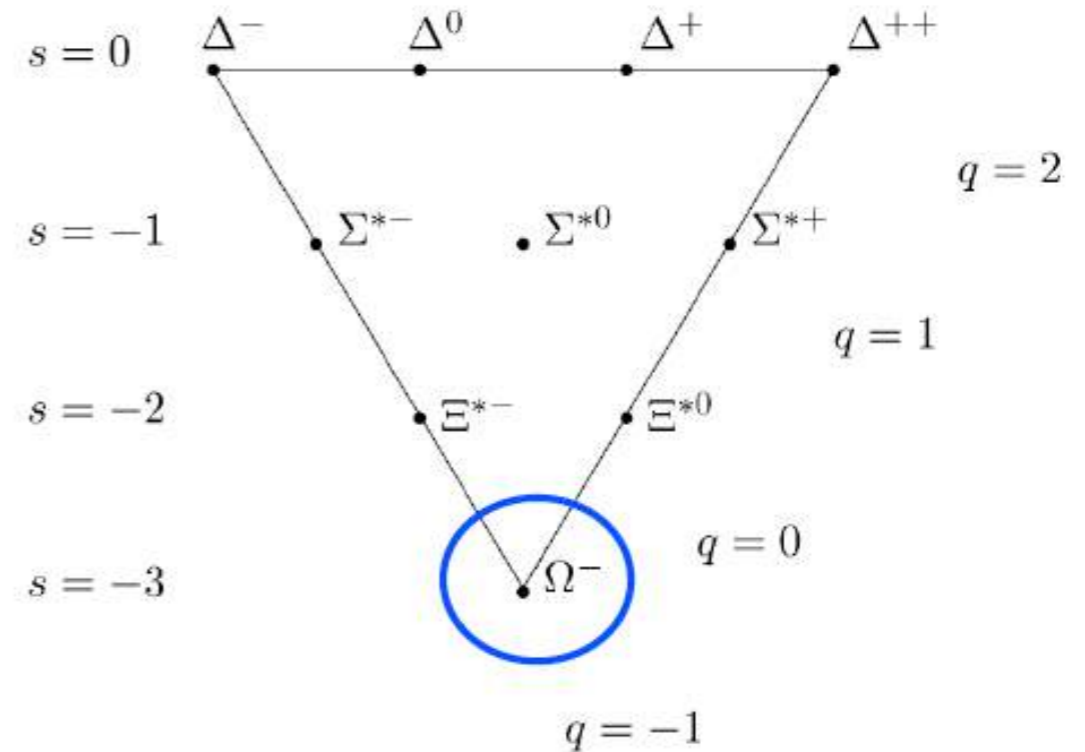
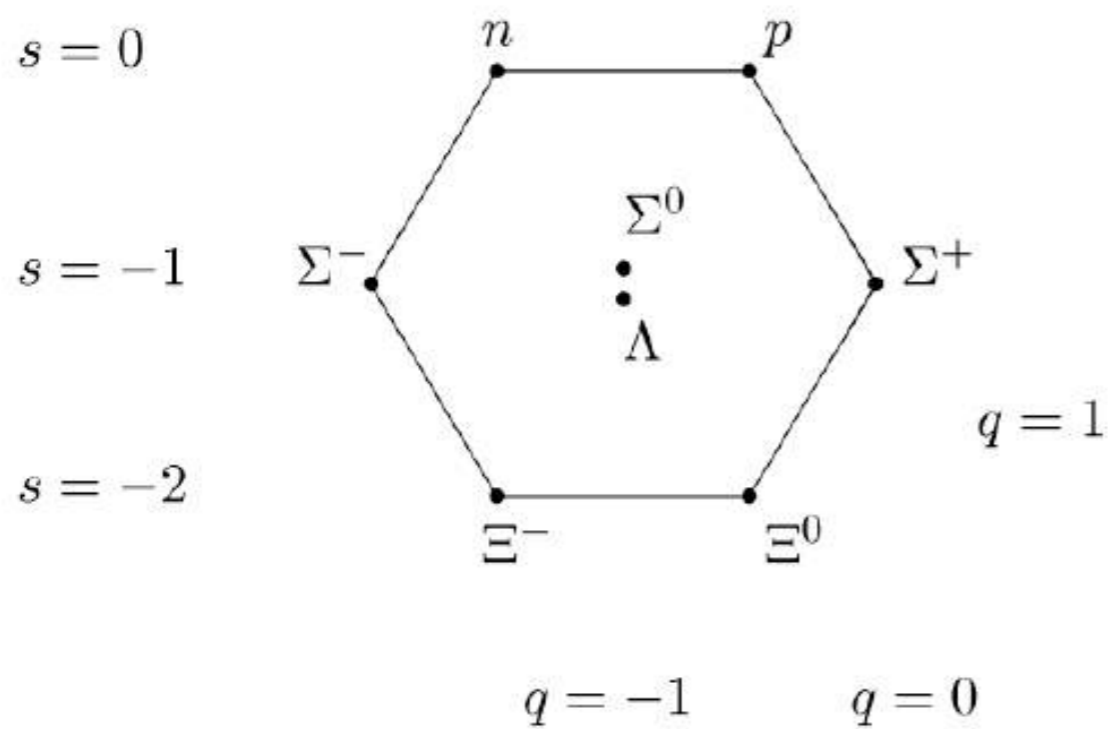


# Some bibliography

- **A QCD primer**  
G. Altarelli (TASI lectures 2002) hep-ph/0204179
- **QCD and Collider Physics (a.k.a. The Pink Book)**  
R.K. Ellis, W. J. Stirling, B. R. Webber, Cambridge University Press (1999)
- **Foundations of Quantum Chromodynamics**  
T. Muta, World Scientific (1998)
- **Quantum Chromodynamics: High Energy Experiments and Theory**  
G. Dissertori, I. Knowles, M. Schmelling, International Series of Monograph on Physics (2009)
- **The theory of quark and gluon interactions**  
F. J. Yndurain, Springer-Verlag (1999)
- **Gauge Theory and Elementary Particle Physics**  
T. Cheng and L. Li, Oxford Science Publications (1984)
- **Fifty years of quarks**  
H. Fritsch, M. Gell-Mann, World Scientific (2015)
- many write-ups of QCD lectures given at previous CERN schools ...

# The beginning: the eightfold way

Organise hadron spectrum to manifest some symmetry-pattern

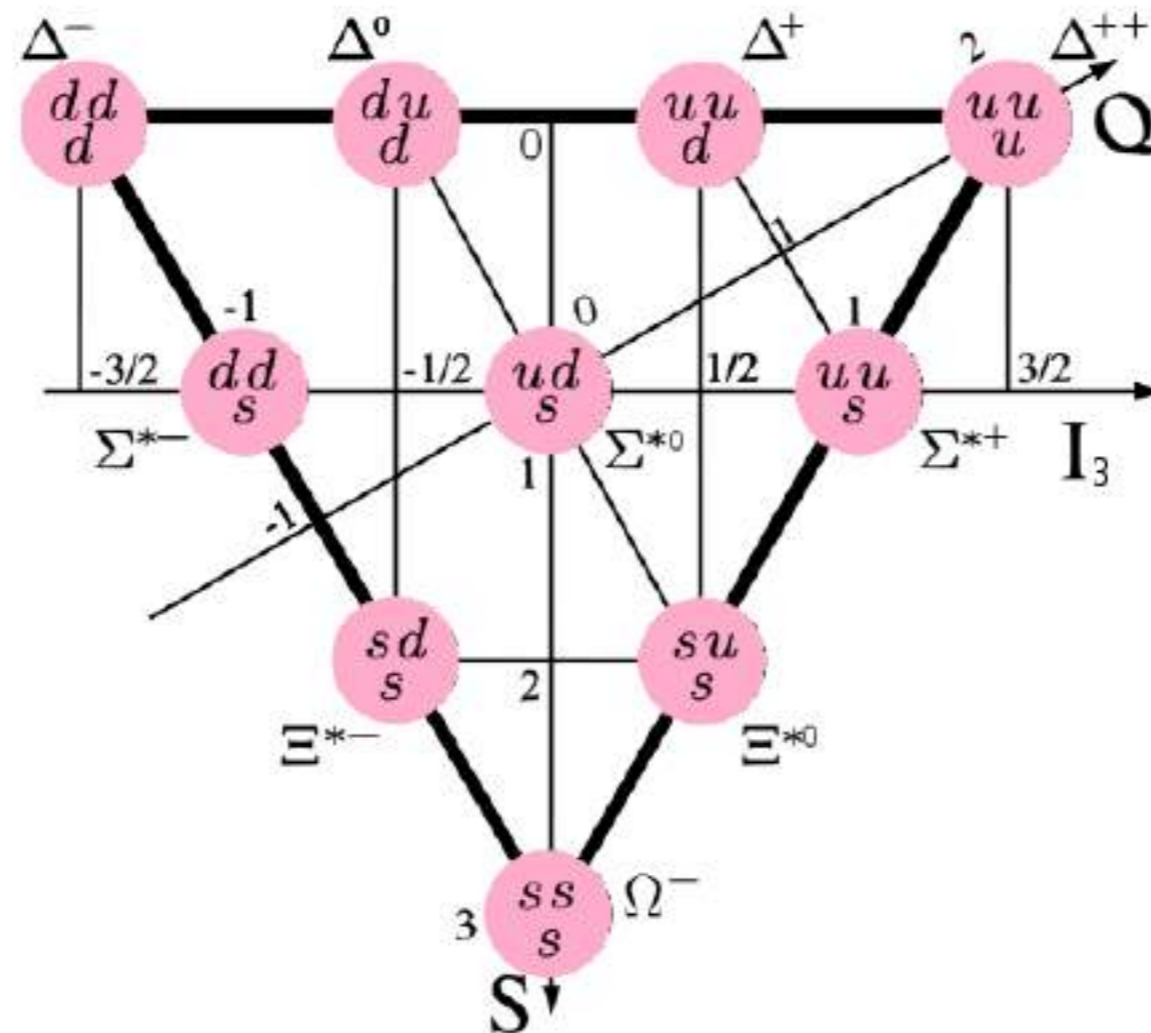


One hadron missing, but predicted following the pattern

But what is the reason for this pattern?

# Quarks (1964)

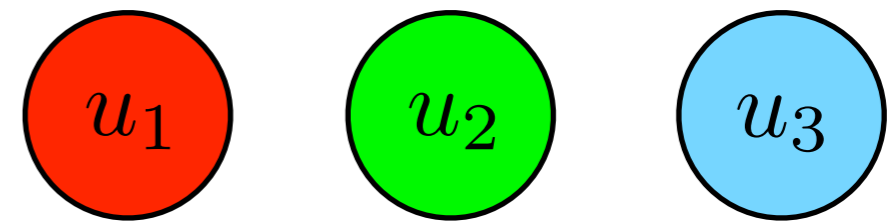
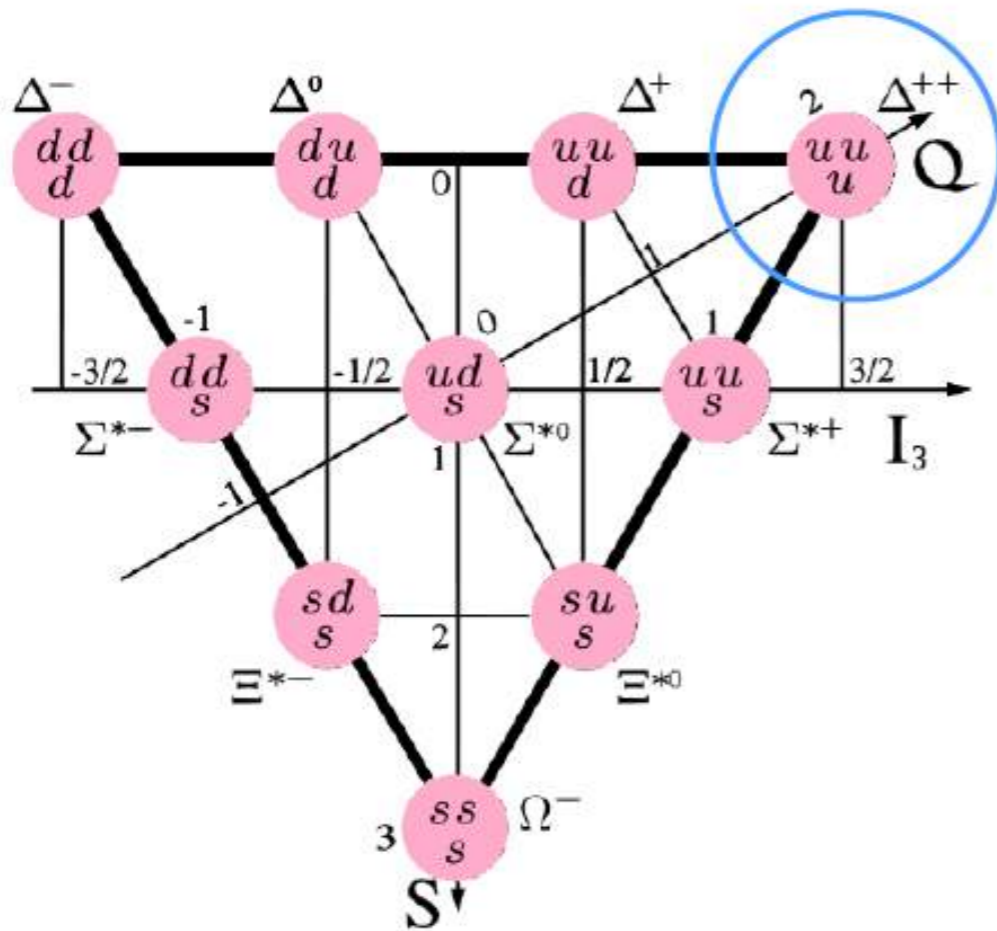
Gell-Mann and Zweig propose the existence of elementary spin 1/2 particles (the quarks). Three types of quarks, **up, down, strange** (plus their antiparticles) can explain the composition of all observed hadrons





# First experimental evidence for colour

- I. Existence of  $\Delta^{++}$  particle: particle with three up quarks of the same spin and with symmetric spacial wave function. Without an additional quantum number Pauli's principle would be violated  
 $\Rightarrow$  color quantum number



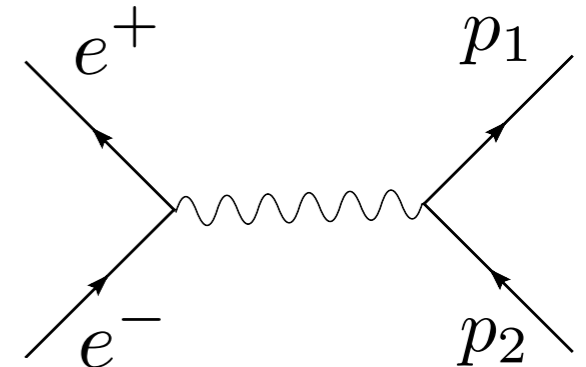
$$\Delta^{+++} = \epsilon_{ijk} u_i u_j u_k$$

New quantum number solves spin-statistics problem (wave function becomes asymmetric)

# First experimental evidence for colour

II. R-ratio: ratio of  $(e^+e^- \rightarrow \text{hadrons})/(e^+e^- \rightarrow \mu^+\mu^-)$

$$R \equiv \frac{e^+e^- \rightarrow \text{hadrons}}{e^+e^- \rightarrow \mu^+\mu^-} \propto N_c \sum_f Q_f^2$$



Experimental data confirms  $N_c = 3$ . (Will come back to R later.)

Color becomes the charge of strong interaction. Interaction is so strong, that the only observed hadrons in nature are those where quarks are combined in **colour singlet states**

**Colour SU(3) is an exact symmetry of nature**

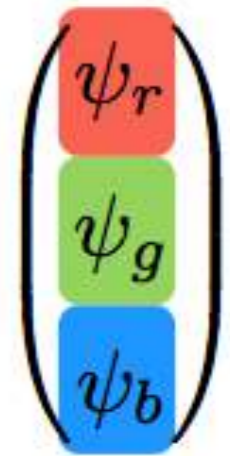
# QCD

Model for strong interactions: non-abelian **gauge theory SU(3)**

$$U^\dagger U = U U^\dagger = 1 \quad \det(U) = 1$$

Hadron spectrum fully classified with the following assumptions

- hadrons (baryons,mesons): made of **spin 1/2 quarks**
- each quark of a given flavour comes in  **$N_c=3$  colors**
- color SU(3) is an **exact symmetry**
- hadrons are colour neutral, i.e. **colour singlet** under SU(3)
- observed hadrons are colour neutral  $\Rightarrow$  hadrons have **integer charge**

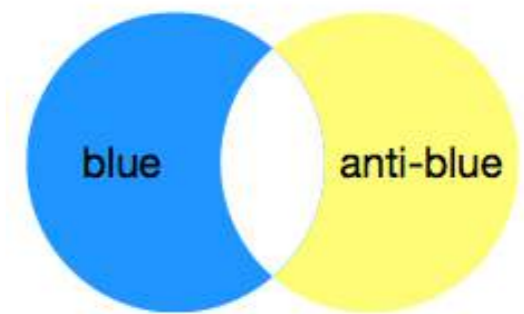


# Color singlet hadrons

Quarks can be combined in 2 elementary ways into color singlets of the  $SU_c(3)$  group

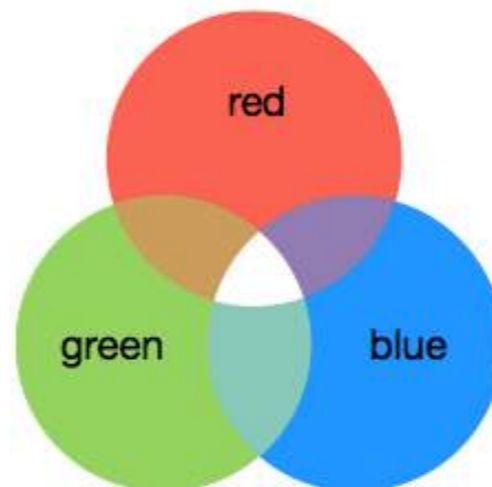
Mesons (bosons, e.g. pion ...)

$$\sum_i \psi_i^* \psi_i \rightarrow \sum_{ijk} U_{ij}^* U_{ik} \psi_j \psi_k = \sum_k \psi_k^* \psi_k$$

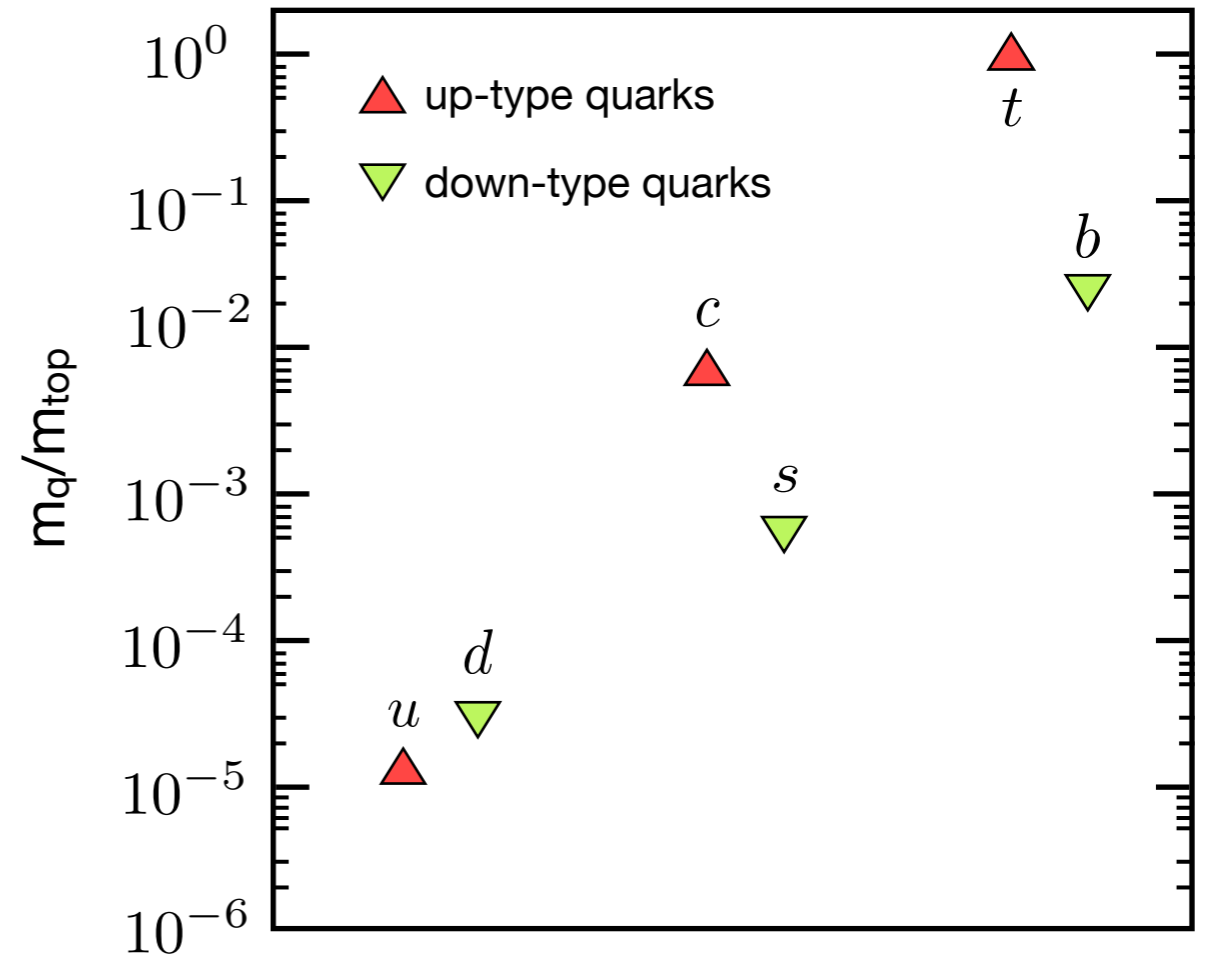
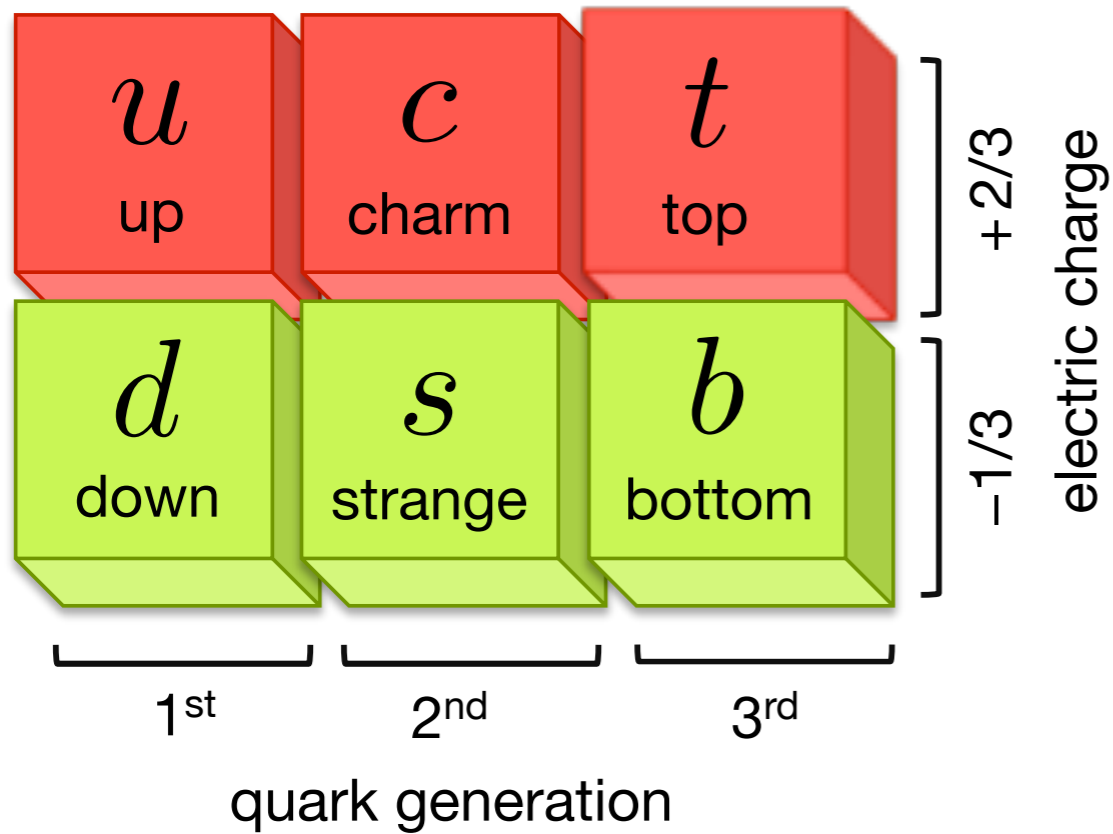


Baryons (fermions, e.g. proton, neutrons ...)

$$\sum_{ijk} \epsilon_{ijk} \psi_i \psi_j \psi_k \rightarrow \sum_{ii'jj'kk'} \epsilon_{ijk} U_{ii'} U_{jj'} U_{kk'} \psi_{i'} \psi_{j'} \psi_{k'} = \sum_{i'j'k'} \epsilon_{i'j'k'} \det(U) \psi_{i'} \psi_{j'} \psi_{k'}$$



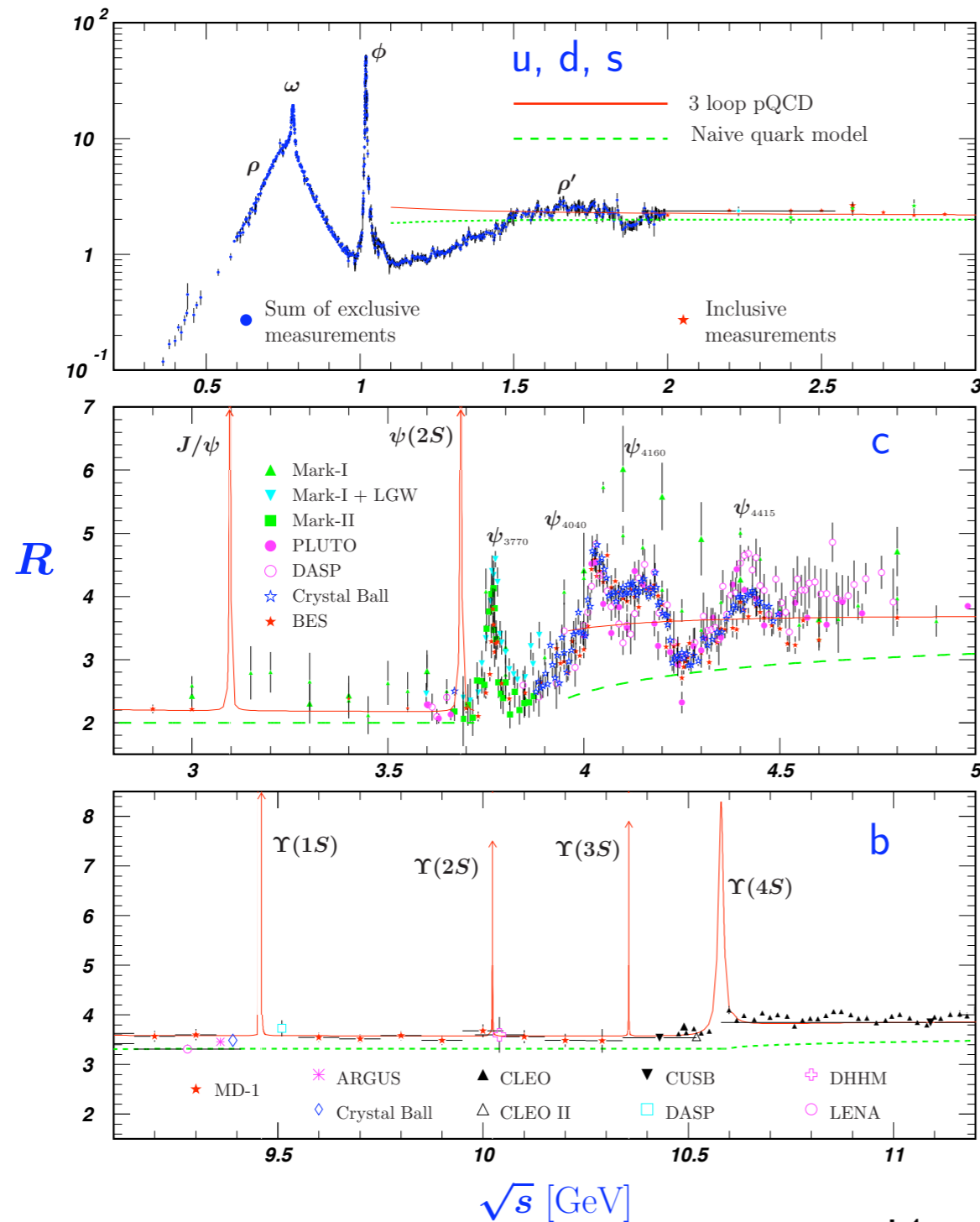
# Quark mass spectrum



charge $2/3$ mass =	up few MeV	charm $\sim 1.6$ GeV	top $\sim 172$ GeV
charge $-1/3$ mass =	down few MeV	strange $\sim 100$ MeV	bottom $\sim 5$ GeV

# The R-ratio: comparison to data

R changes crossing quark flavour thresholds  $R = N_c \sum_q e_q^2$



$$n_f = 3$$

$$R = 2$$

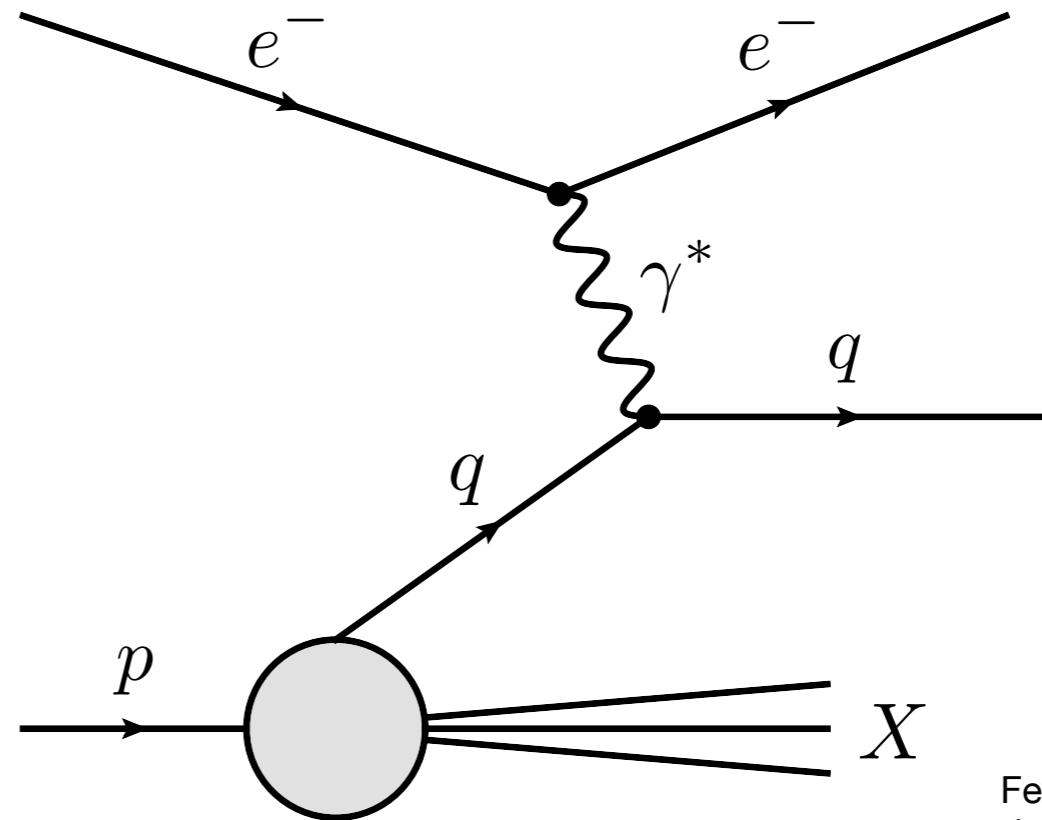
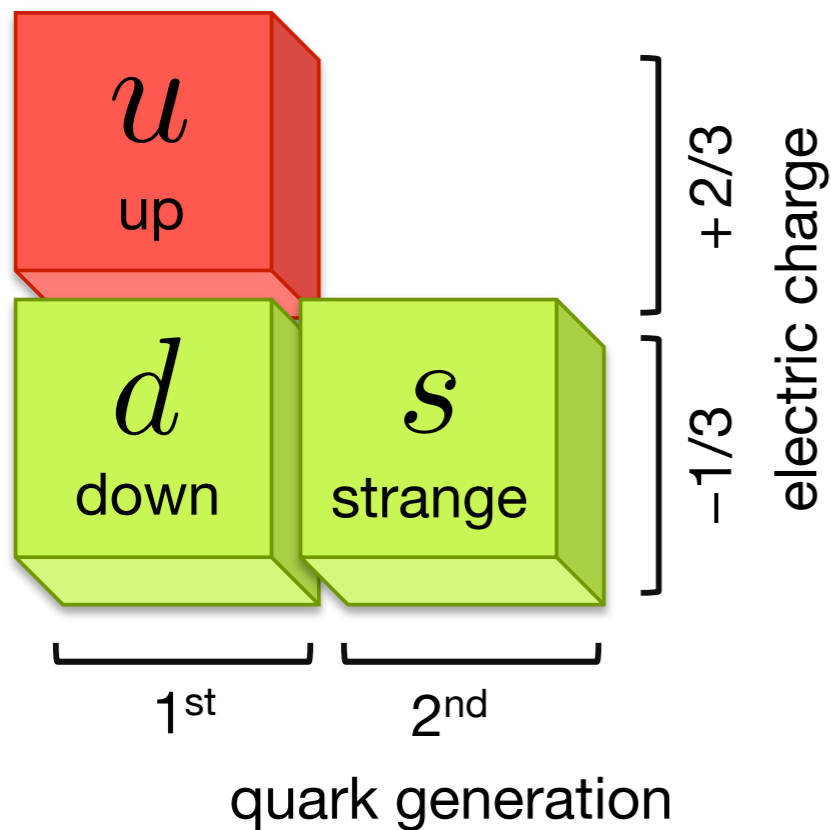
$$n_f = 3 \rightarrow 4$$

$$R = \frac{10}{3}$$

$$n_f = 4 \rightarrow 5$$

$$R = \frac{11}{3}$$

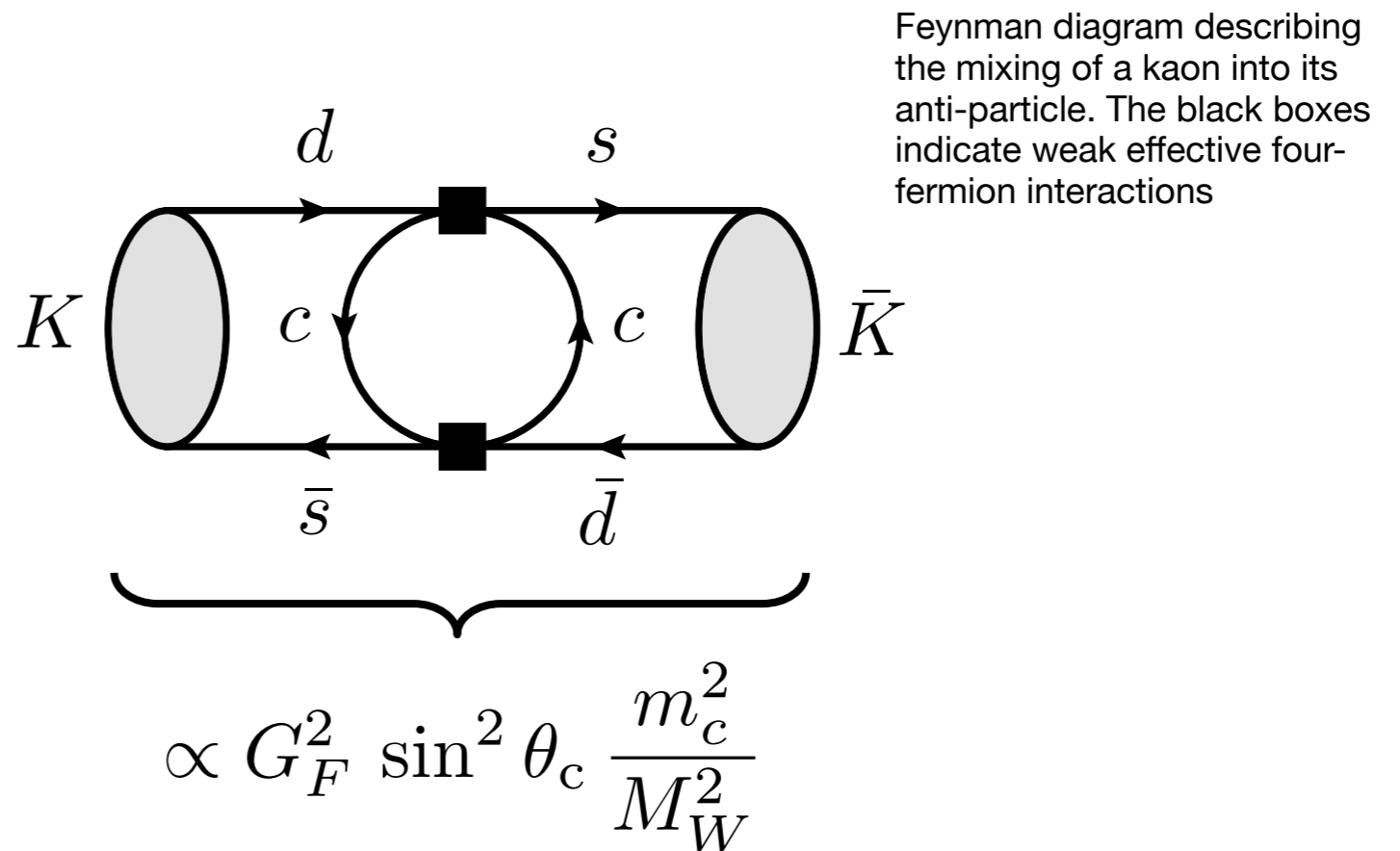
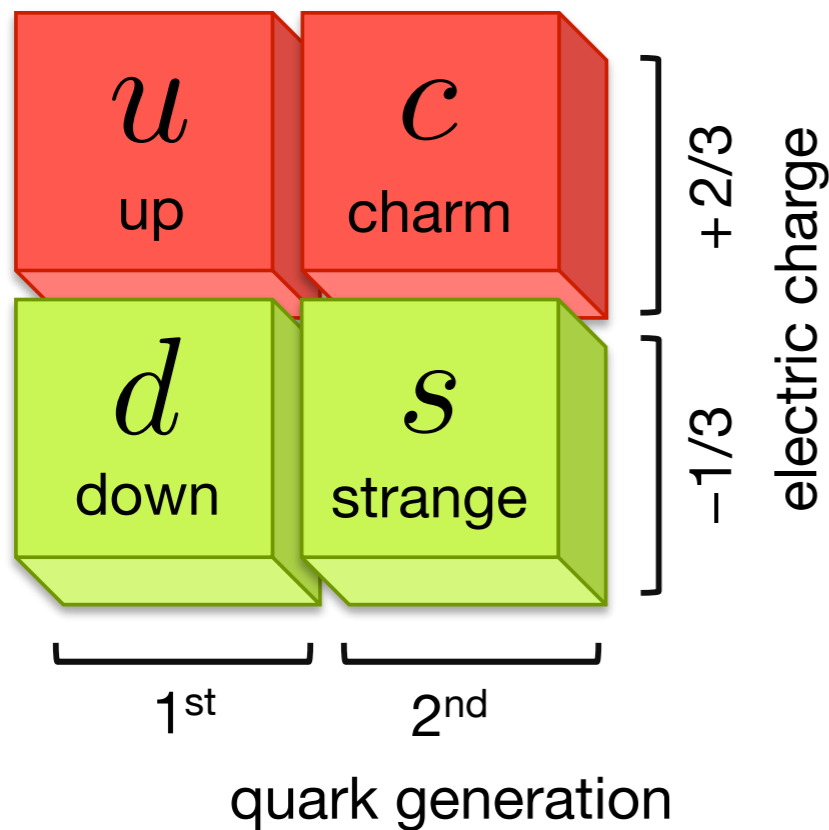
# QCD matter sector



Feynman diagram describing DIS of an electron on a proton

- The light quark's existence was validated by the SLAC's deep inelastic scattering (DIS) experiments in 1968: strange was a necessary component of Gell-Mann and Zweig's three-quark model, it also provided an explanation for the kaon and pion mesons discovered 1947 in cosmic rays

# QCD matter sector



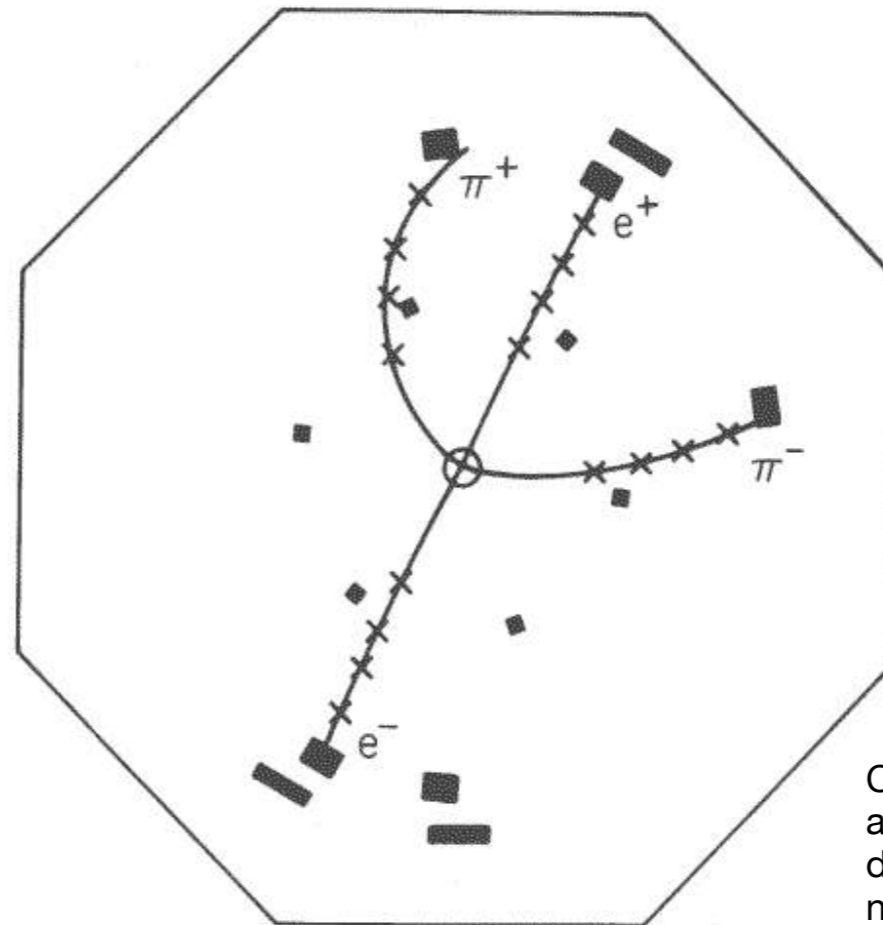
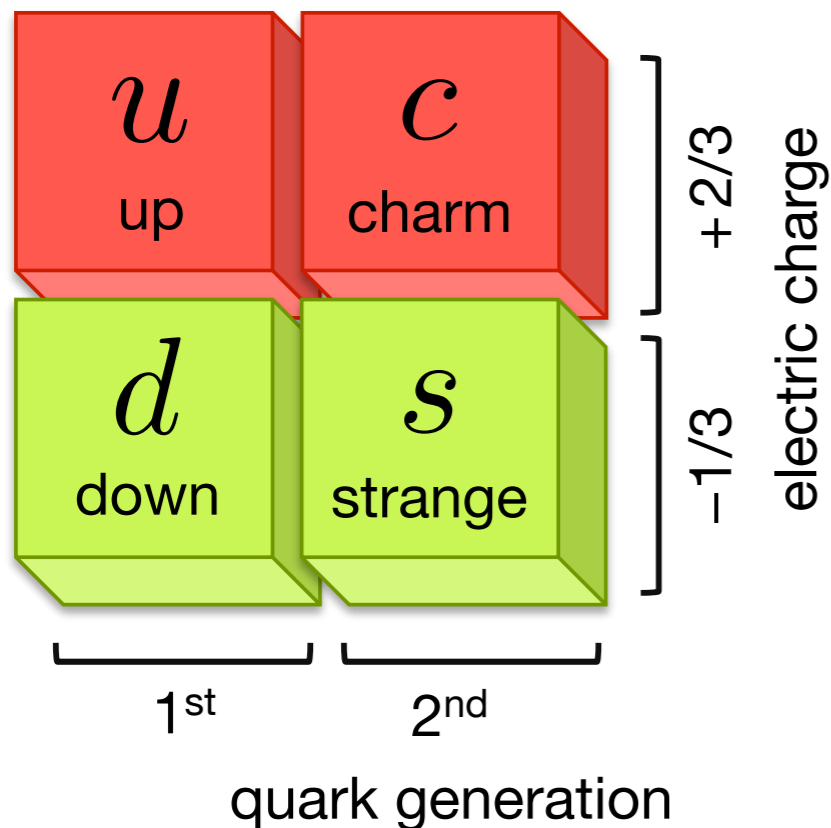
Feynman diagram describing the mixing of a kaon into its anti-particle. The black boxes indicate weak effective four-fermion interactions

- In 1970 Glashow, Iliopoulos, and Maiani (GIM mechanism) presented strong theoretical arguments for the existence of the as-yet undiscovered charm quark, based on the absence of flavour-changing neutral currents

[S. L. Glashow, J. Iliopoulos and L. Maiani, *Phys. Rev. D* **2** (1970) 2]



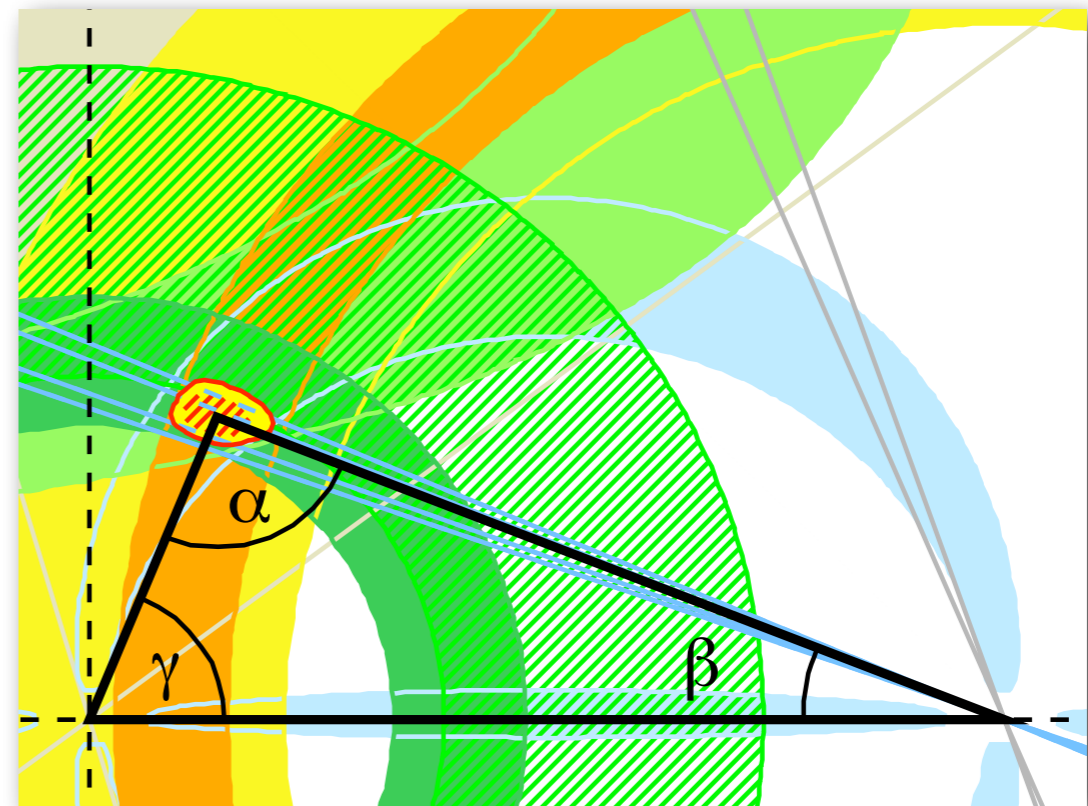
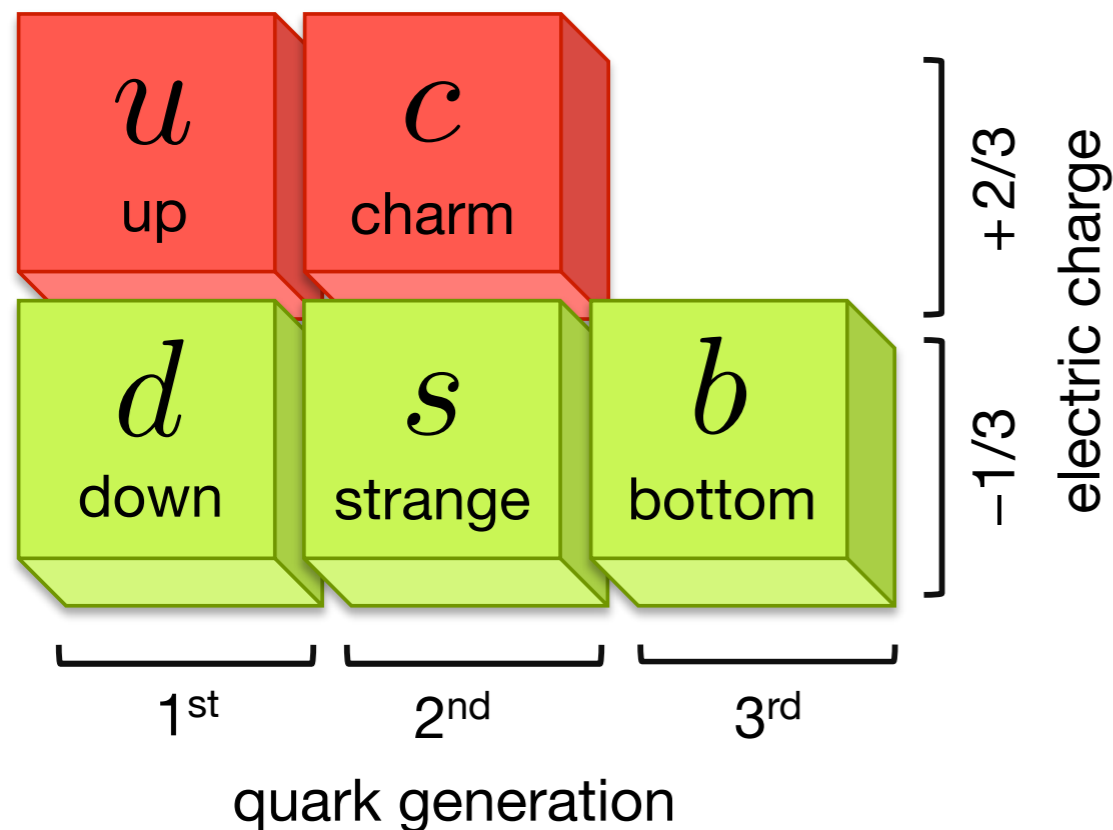
# QCD matter sector



Computer reconstruction of a  $\psi'$  decay in the Mark I detector at SLAC, making a near-perfect image of the Greek letter  $\psi$

- Charm quarks were observed almost simultaneously in November 1974 at SLAC and at BNL as charm anti-charm bound states (charmonium). The two groups had assigned the discovered meson two different symbols,  $J$  and  $\psi$ . Thus, it became known as the  $J/\psi$  (Nobel Prize 1976)

# QCD matter sector

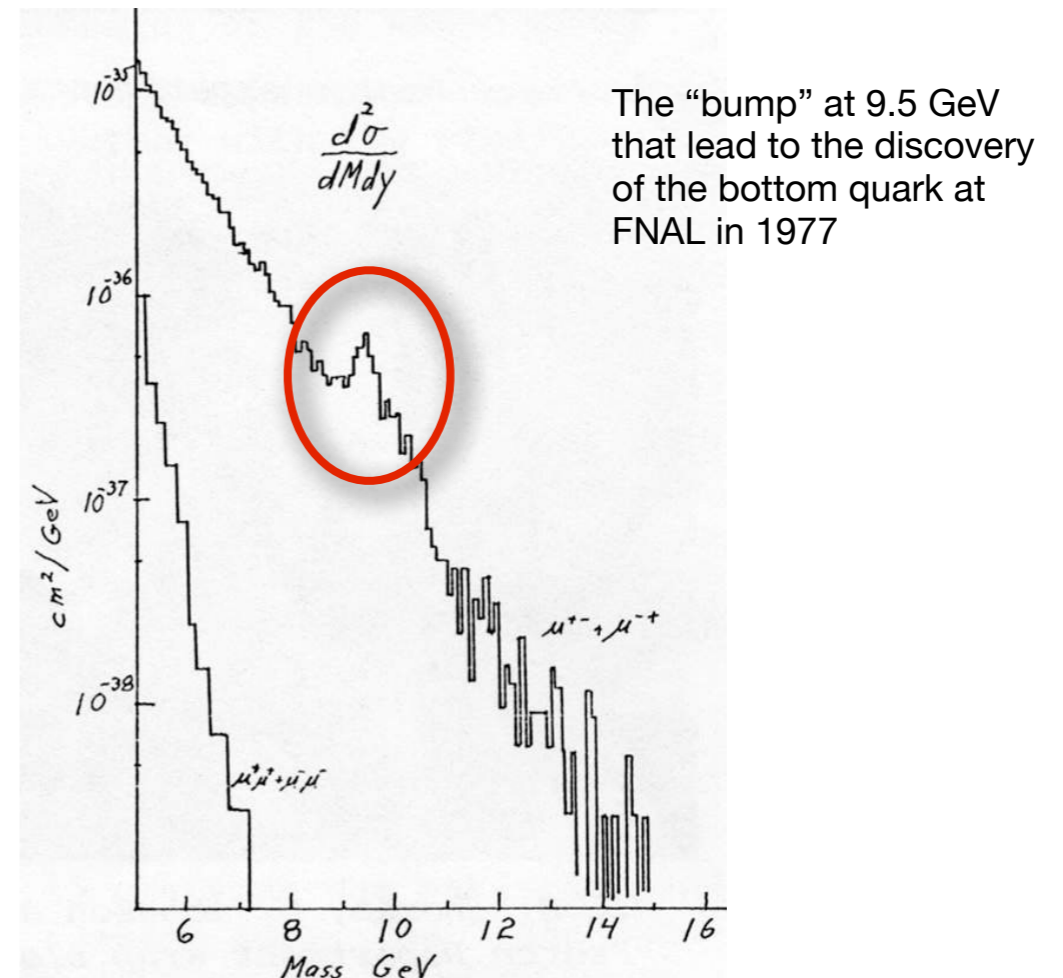
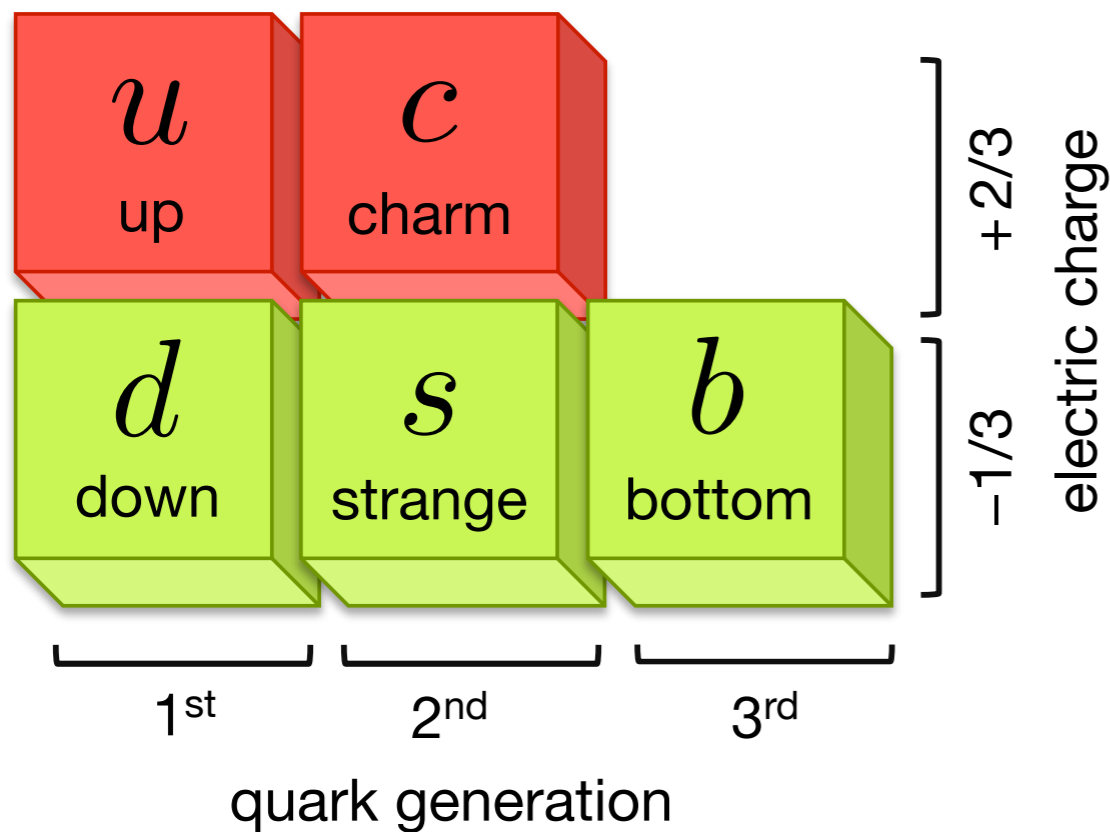


Unitarity triangle measuring the amount of CP violation in the Standard Model

- The bottom quark was postulated in 1973 by Kobayashi and Maskawa to describe the phenomenon of CP violation, which requires the existence of at least three generations of quarks in Nature (Nobel Prize 2008)

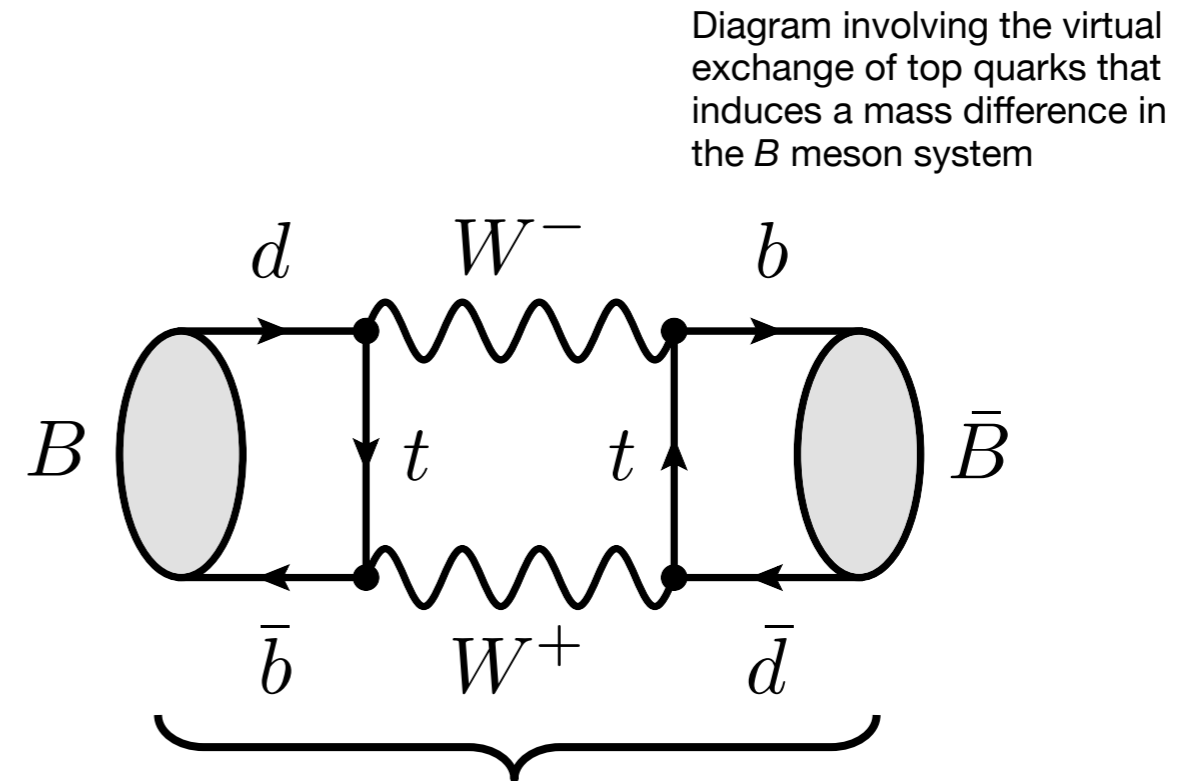
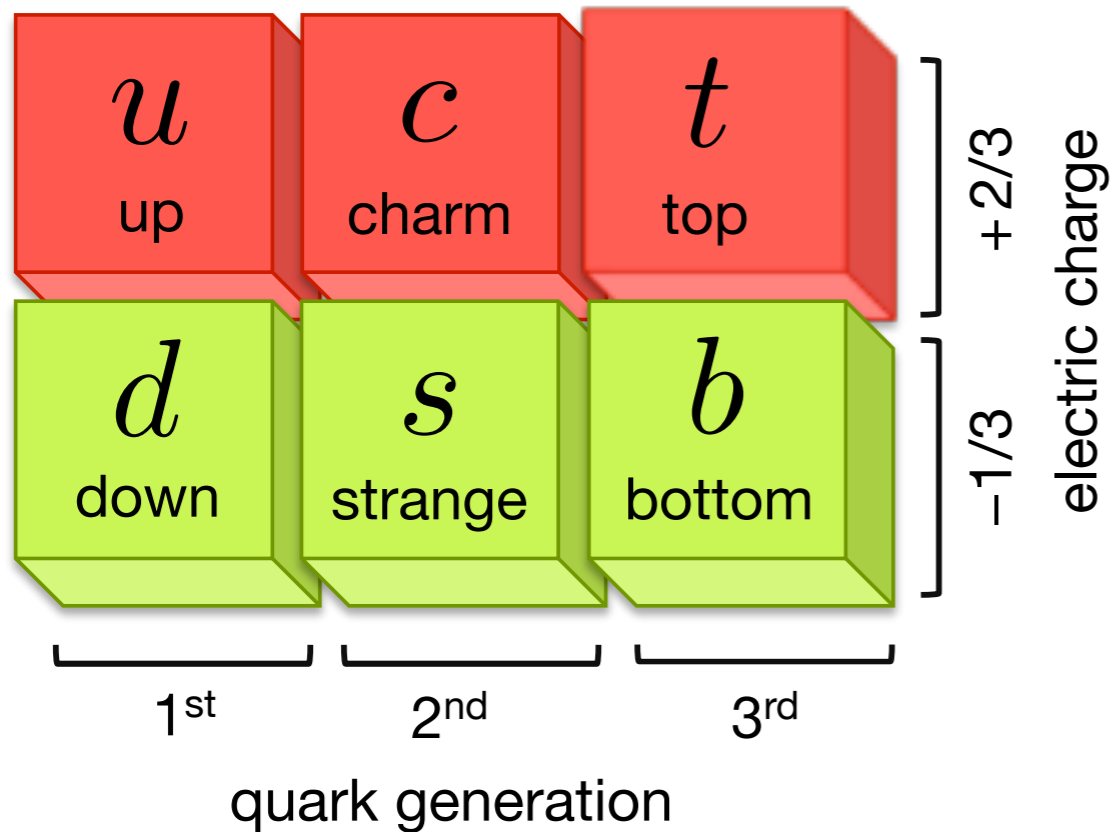
[M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49** (1973) 652]

# QCD matter sector



- In 1977, physicists working at the fixed target experiment E288 at FNAL discovered  $\Upsilon$  (Upsilon) meson. This discovery was eventually understood as the bound state of the bottom/anti-bottom (bottomonium)

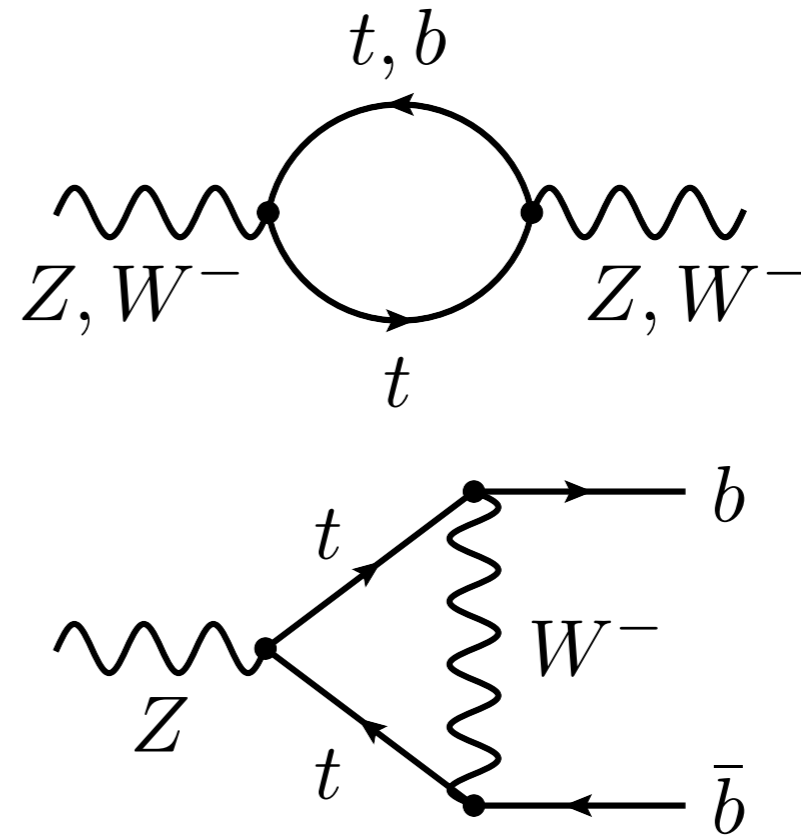
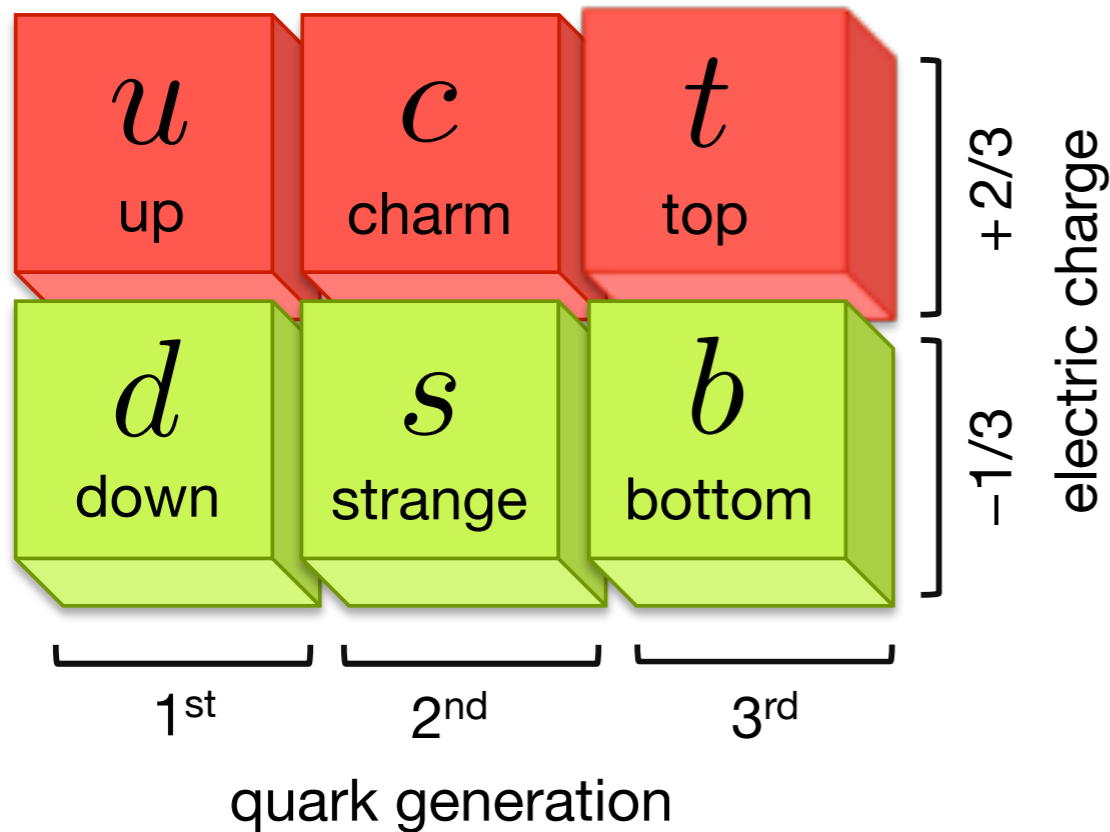
# QCD matter sector



$$\Delta M_B \propto G_F^2 m_B f_B^2 |V_{td}|^2 m_t^2$$

- The measurement of the oscillations of  $B$  mesons into its own anti-particles in 1987 by ARGUS led to the conclusion that the top-quark mass has to be larger than 50 GeV. This was a big surprise at that time, because in 1987 the top quark was generally believed to be much lighter

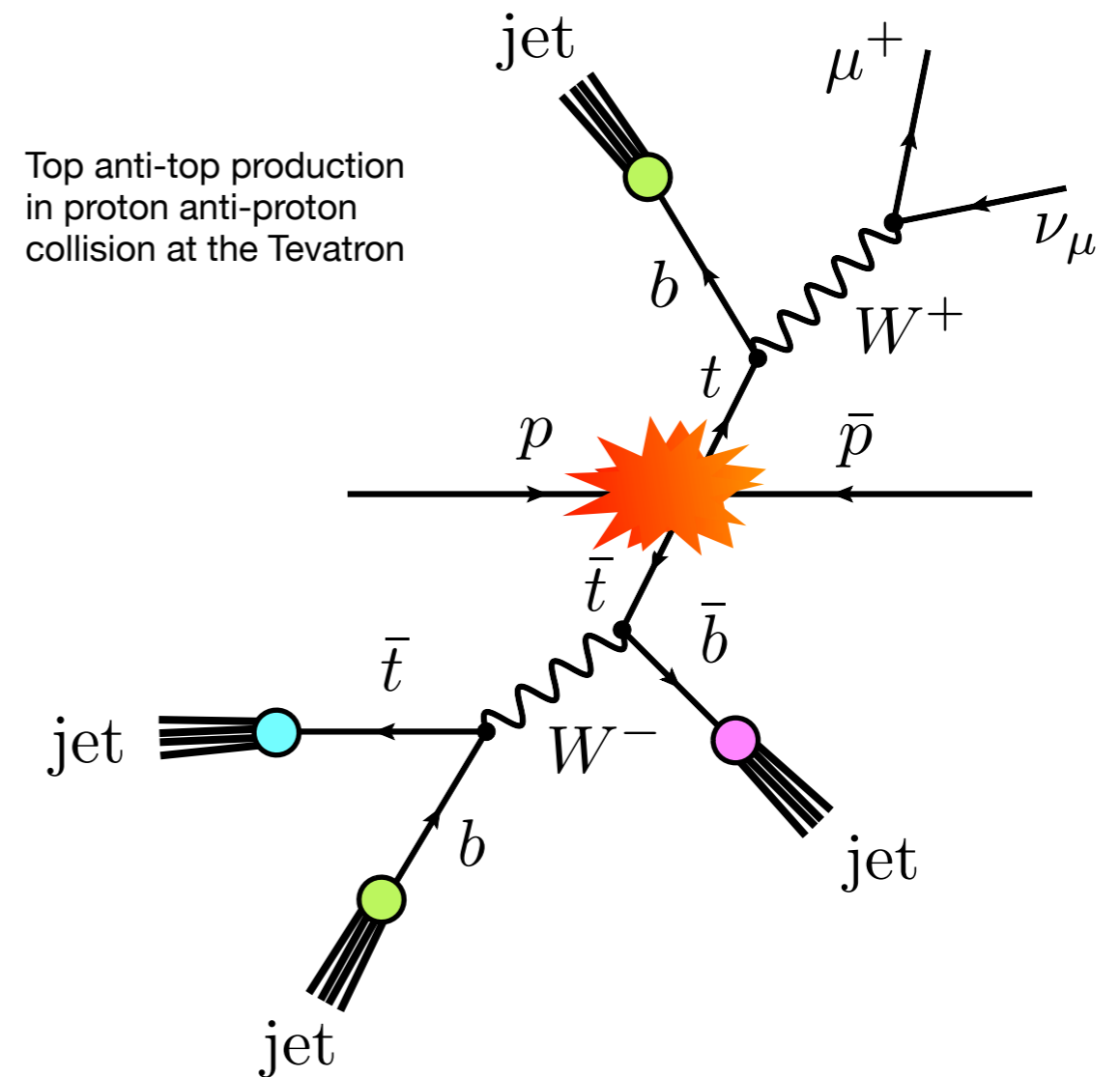
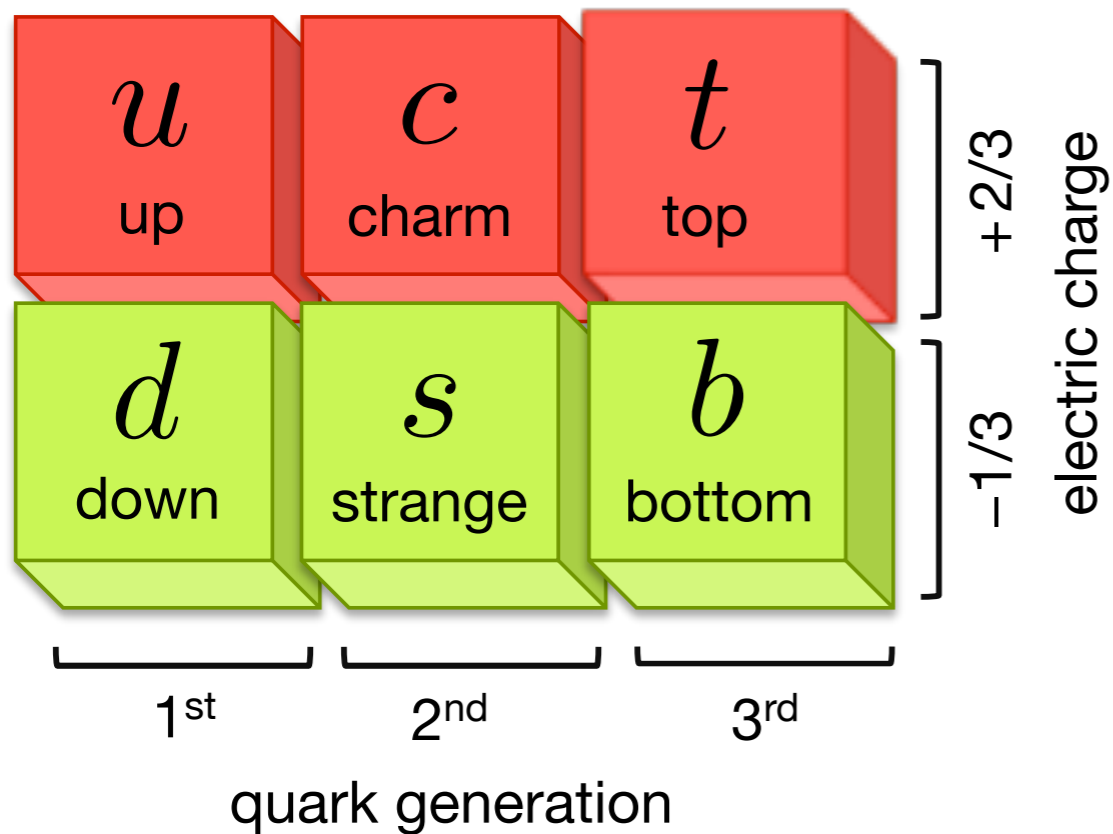
# QCD matter sector



Diagrams that feature a quadratic dependence on the top-quark mass

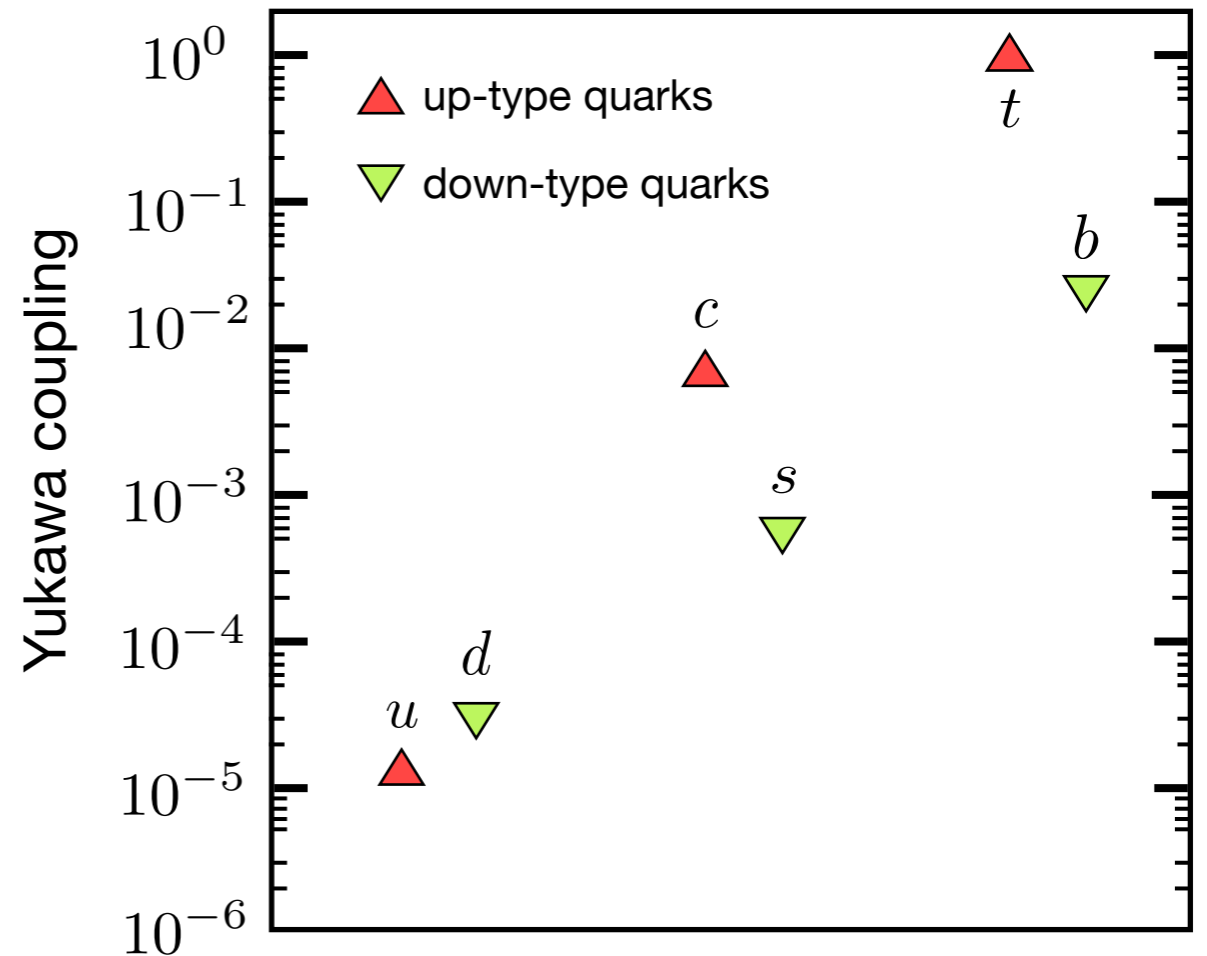
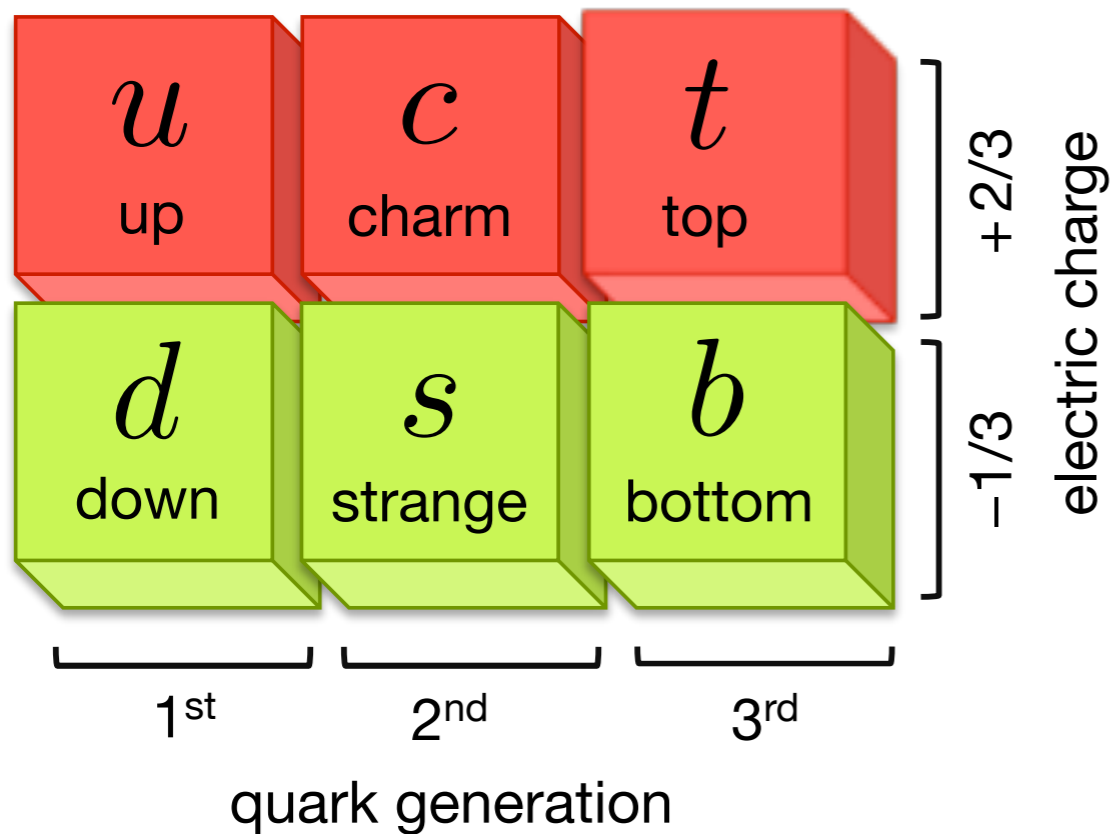
- It was also realized that certain precision measurements of the EW vector-boson masses and couplings are very sensitive to the mass of the top quark. By 1994 the precision of these indirect measurements led to a prediction of the top-quark mass between 145 GeV and 185 GeV

# QCD matter sector



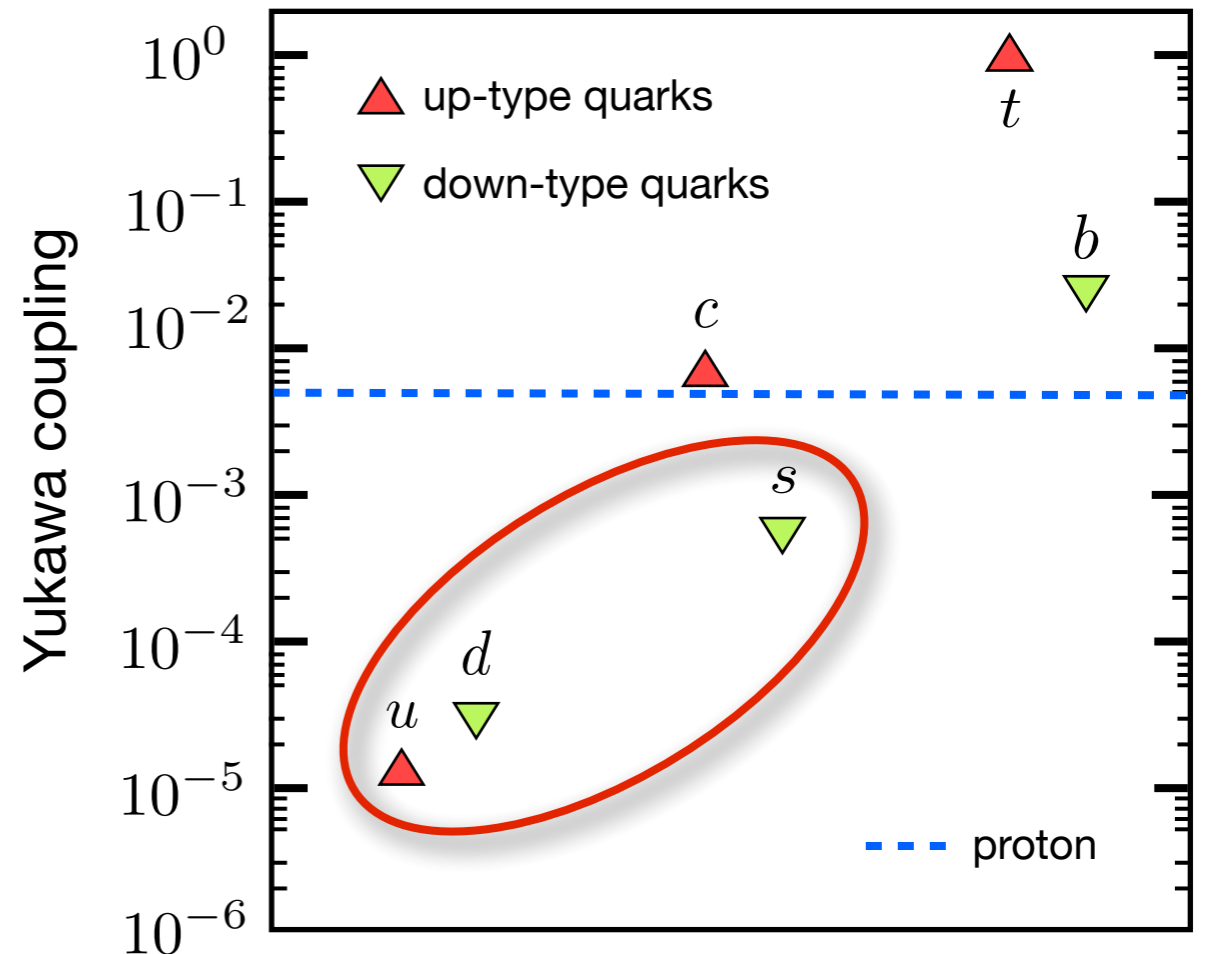
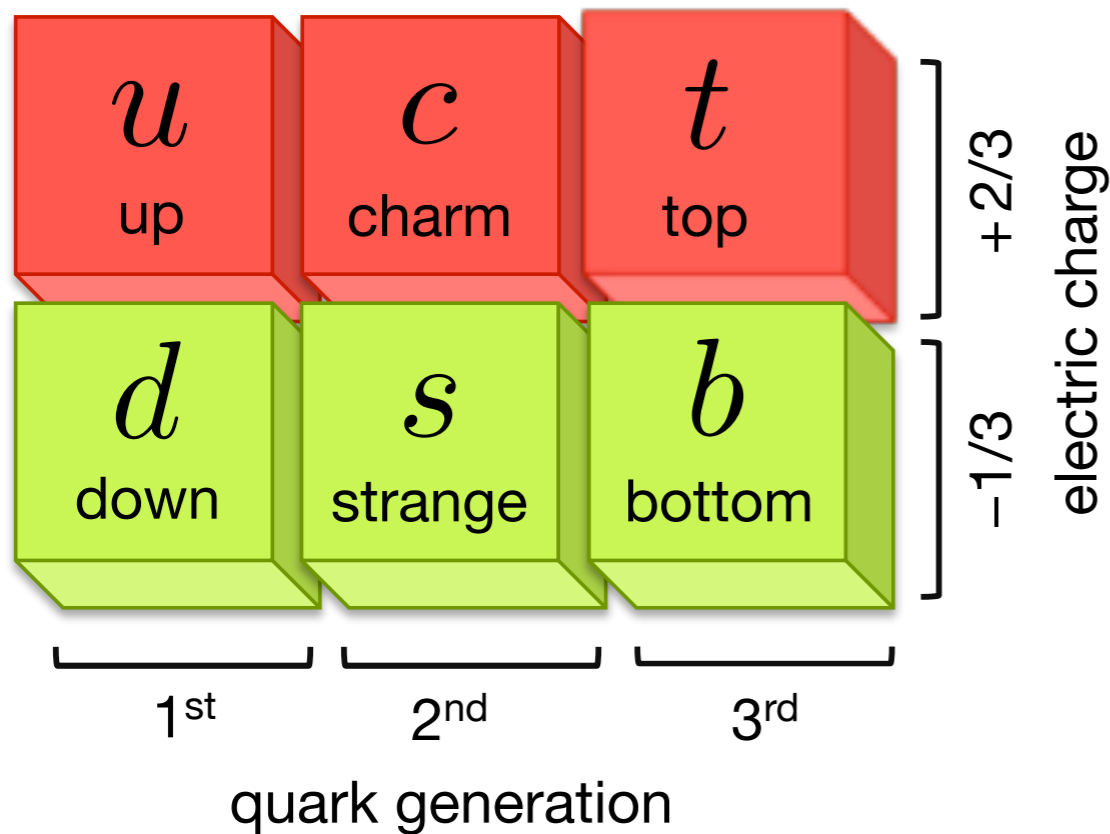
- The top quark was finally discovered in 1995 by CDF and D0 at FNAL. Its mass is today measured to be  $m_t = (172.3 \pm 0.9) \text{ GeV}$

# QCD matter sector



- The masses of the six different quarks range from 2 MeV for the up quark to 172 GeV for the top quark. Why these masses are split by almost six orders of magnitude is one of the big mysteries of particle physics

# QCD matter sector



- The up, down, and strange quark are much lighter than the proton. If one takes them to have an identical mass, the quarks become indistinguishable under QCD, and one obtains an effective  $SU(3)_f$  symmetry



# QED and QCD

- 📌 QED and QCD are very similar, yet very different theories
- 📌 quarks are a bit like leptons, but there are three of each
- 📌 gluons are a bit like photons, but there are eight of them
- 📌 gluons interact with themselves
- 📌 the QCD coupling is also small at collider energies, but larger than the QED one
- 📌 the similarities and differences are evident from the two Lagrangians

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So, let's start by looking at the QED Lagrangian

# The QED Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{QED}} &= \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{Maxwell}} + \mathcal{L}_{\text{int}} \\ &= \bar{\psi} (i\partial - m) \psi - \frac{1}{2} (F_{\mu\nu})^2 - e\bar{\psi}\gamma^\mu\psi A_\mu \\ &= \bar{\psi} (iD - m) \psi - \frac{1}{2} (F_{\mu\nu})^2\end{aligned}$$



electromagnetic vector potential  $A_\mu$



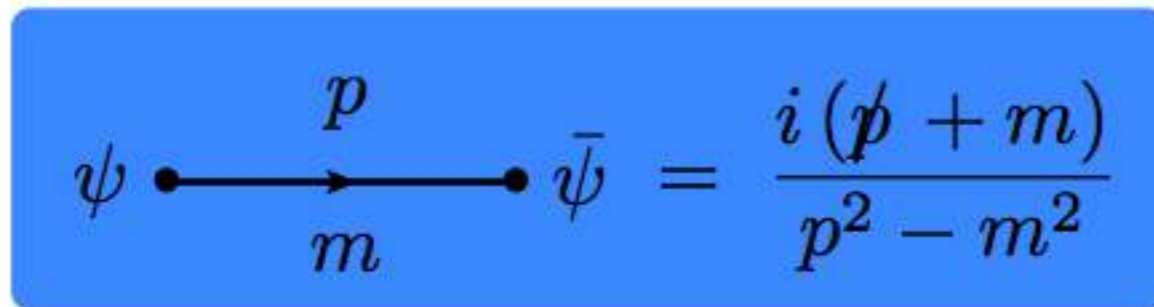
field strength tensor  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$



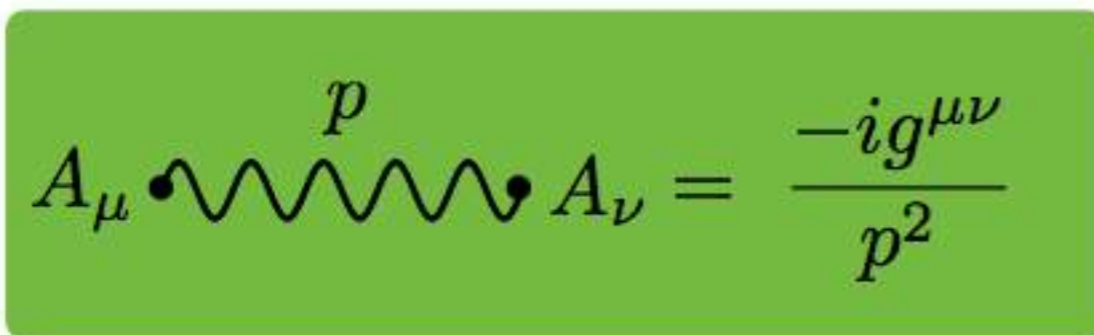
covariant derivative  $D_\mu = \partial_\mu + ieA_\mu$

# QED Feynman rules

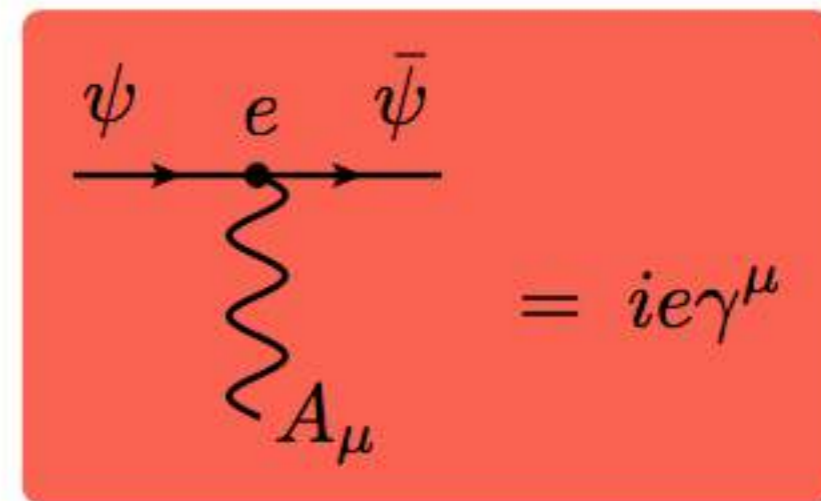
$$\begin{aligned}
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 &= \boxed{\bar{\psi} (i\not{\partial} - m) \psi} - \boxed{\frac{1}{2} (F_{\mu\nu})^2} - \boxed{e\bar{\psi}\gamma^\mu\psi A_\mu}
 \end{aligned}$$



$$\psi \xrightarrow[p]{p} \bar{\psi} = \frac{i(\not{p} + m)}{p^2 - m^2}$$



$$A_\mu \xrightarrow[p]{p} A_\nu = \frac{-ig^{\mu\nu}}{p^2}$$



$$\psi \xrightarrow[p]{p} \bar{\psi} \quad e \quad A_\mu = ie\gamma^\mu$$

# QED gauge invariance

$$\mathcal{L}_{\text{QED}} = \bar{\psi} (i\not{D} - m) \psi - \frac{1}{2} (F_{\mu\nu})^2$$

A crucial property of the QED Lagrangian is that it is invariant under

$$\psi(x) \rightarrow e^{i\alpha(x)} \psi(x), \quad A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{e} \partial_\mu \alpha(x)$$

which acts on the Dirac field as a local phase transformation

Exercise:

Check that the QED Lagrangian is invariant under the above transformations

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Exercise:

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Yang and Mills (1954) proposed that the local phase rotation in QED could be generalised to invariance under a continuous symmetry

[C. N. Yang and R. L. Mills, Phys. Rev. 96 (1954) 191]

# The QCD Lagrangian

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \sum_f \bar{\psi}_i^{(f)} (iD_{ij} - m_f \delta_{ij}) \psi_j^{(f)}$$

$$D_{ij}^\mu \equiv \partial^\mu \delta_{ij} + ig_s t_{ij}^a A_a^\mu,$$

$\Rightarrow$  covariant derivative

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

$\Rightarrow$  field strength

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- 📌 color matrices  $t_{ij}^a$  are the generators of SU(3)

# The QCD Lagrangian

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⇒ field strength

- 📌 only one QCD parameter  $g_s$  regulating the strength of the interaction (quark masses have EW origin)
- 📌 setting  $g_s = 0$  one obtains the free Lagrangian (free propagation of quarks and gluons without interaction)
- 📌 terms proportional to  $g_s$  in the field strength cause self-interaction between gluons (makes the difference w.r.t. QED)
- 📌 color matrices  $t_{ij}^a$  are the generators of SU(3)
- 📌 QCD flavour blind (differences only due to EW)

# The generators of $SU(N)$

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So, the fundamental representation of SU(N) has  $N^2 - 1$  generators  $t^a$ :  
 $N \times N$  traceless hermitian matrices  $\Rightarrow N^2 - 1$  gluons

$$U = e^{i\theta_a(x)t^a}$$

$$a = 1, \dots, N^2 - 1$$

# The Gell-Mann matrices

One explicit representation:  $t^A = \frac{1}{2}\lambda^A$

$\lambda^A$  are the Gell-Mann matrices

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix},$$
$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda^8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Standard normalization:  $\text{Tr}(t^a t^b) = T_R \delta^{ab} \quad T_R = \frac{1}{2}$

Notice that the first three Gell-Mann matrices contain the three Pauli matrices in the upper-left corner

# The generators of SU(N)

Infinitesimal transformations (close to the identity) give complete information about the group structure. The most important characteristic of a group is the commutator of two transformations:

$$\begin{aligned} [U(\delta_1), U(\delta_2)] &\equiv U(\delta_1)U(\delta_2) - U(\delta_2)U(\delta_1) \\ &= (i\delta_1^a)(i\delta_2^b)[t^a, t^b] + \mathcal{O}(\delta^3) \end{aligned}$$

The two matrices do not commute, therefore the transformations don't. Such a group is called **non-abelian**.

- Familiar abelian groups: translations, phase transformations U(1) ...
- Familiar non-abelian groups: 3D-rotations

# The generators of SU(N)

Consider the commutator

$$\text{Tr}([t_a, t_b]) = 0 \quad \Rightarrow \quad [t_a, t_b] = i f_{abc} t^c$$

The **Lie algebra** of the group is defined by the commutation relation of the generators of the group.  $f_{abc}$  are the **structure constants** of the SU(N<sub>c</sub>) algebra, they generate the adjoint representation of the algebra

Clearly,  $f_{abc}$  is anti-symmetric in (ab). It is easy to show that it is fully antisymmetric

$$i f_{abc} = 2 \text{Tr} ([t_a, t_b] t_c)$$

and that hence it is fully antisymmetric

$$f_{abc} = -f_{bac} = -f_{acb}$$

# Color algebra: fundamental identities

Fundamental representation 3:

$$i \longrightarrow j = \delta_{ij}$$

$$i \xrightarrow{\text{gluon}} j = t_{ij}^a$$

Adjoint representation 8:

$$a \text{---} b = \delta_{ab}$$

$$a \text{---} \text{gluon} \text{---} b = if_{abc}$$

Trace identities:

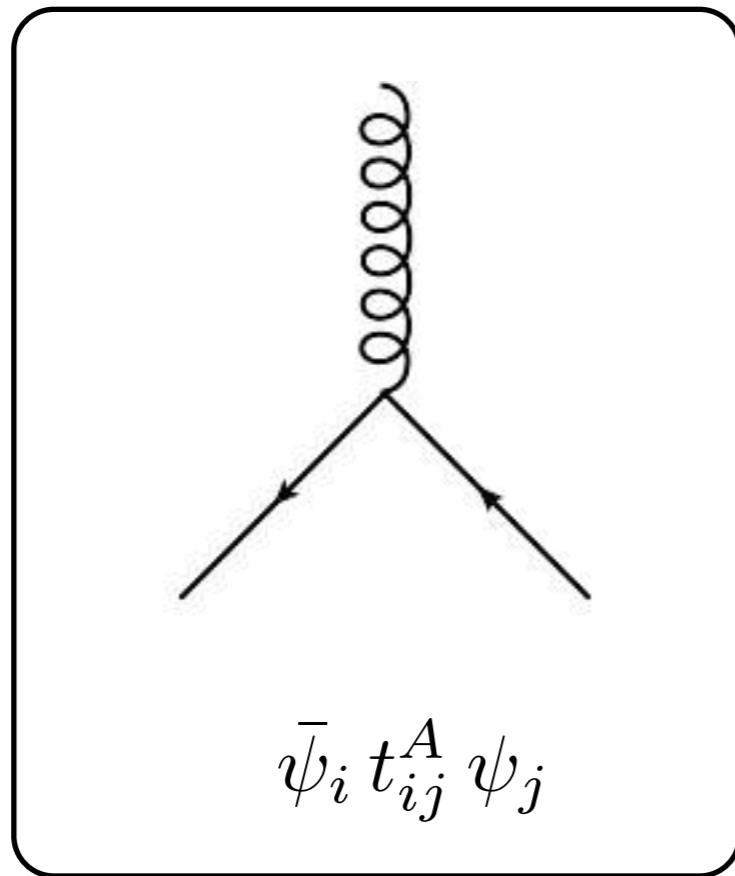
$$a \text{---} \text{loop} = 0$$

$$\text{Tr}(t^a) = 0$$

$$a \text{---} \text{loop} \text{---} b = T_R \text{---}$$

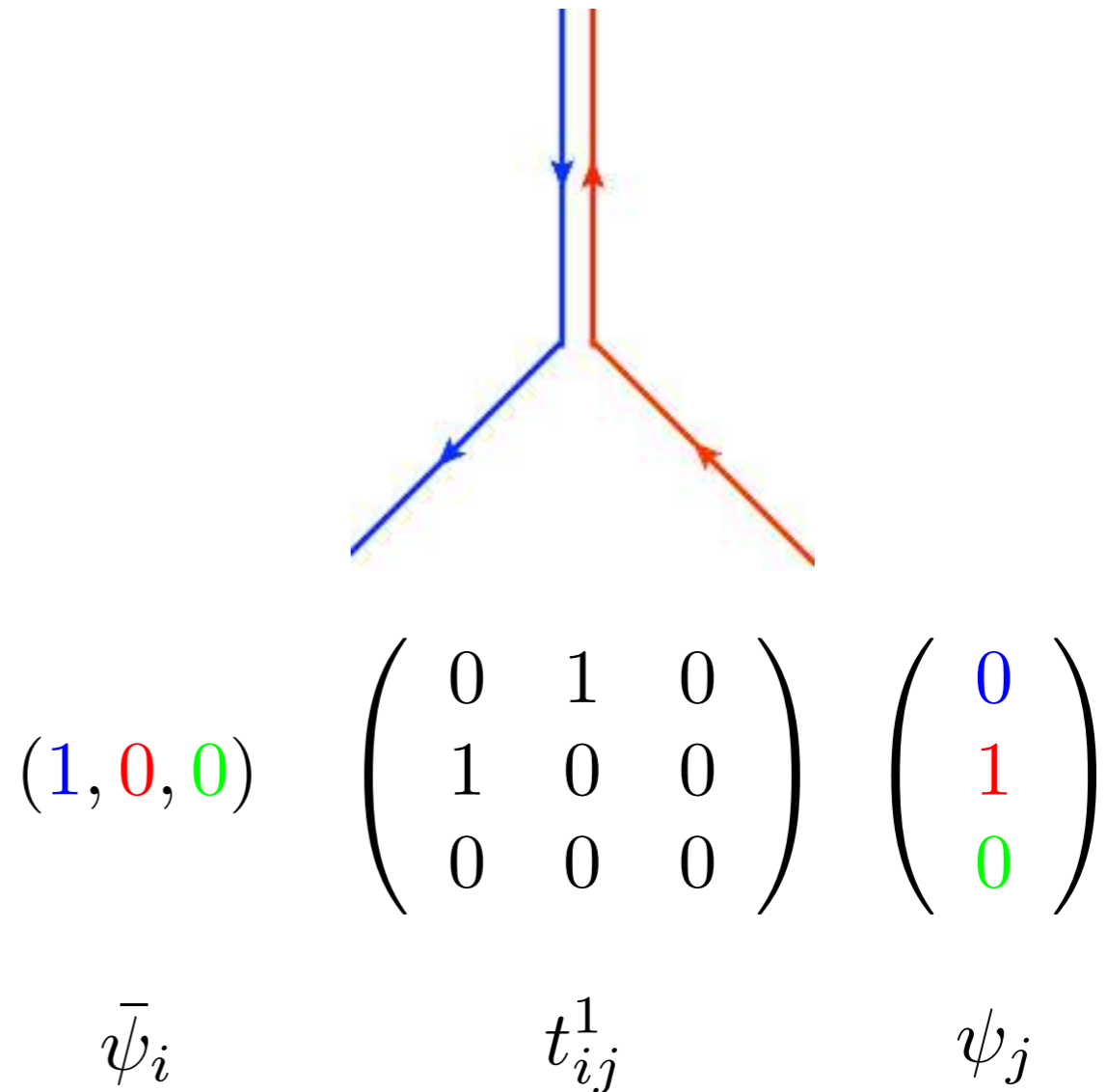
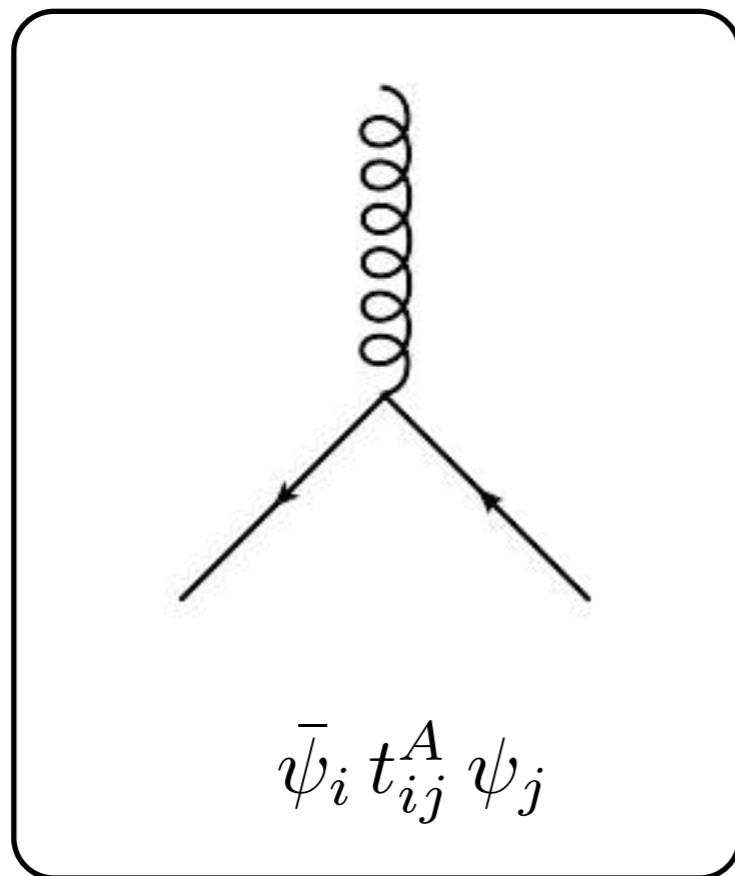
$$\text{Tr}(t^a t^b) = T_R \delta^{ab}$$

# What do color identities mean physically



What does this really mean?

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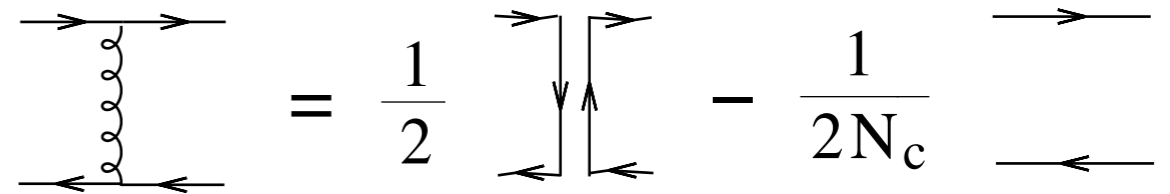
What does this really mean?

Gluons carry color and anti-color. They repaint quarks and other gluons.

# Color algebra: Casimirs & Fierz identity

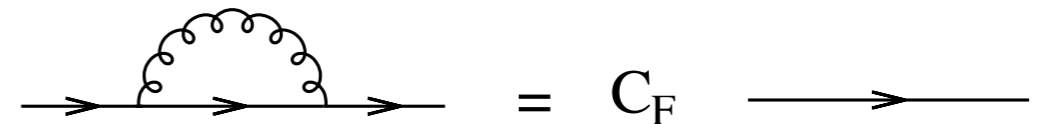
Fierz identity:

$$(t^a)_k^i (t^a)_j^l = \frac{1}{2} \delta_j^i \delta_k^l - \frac{1}{2N_c} \delta_k^i \delta_j^l$$



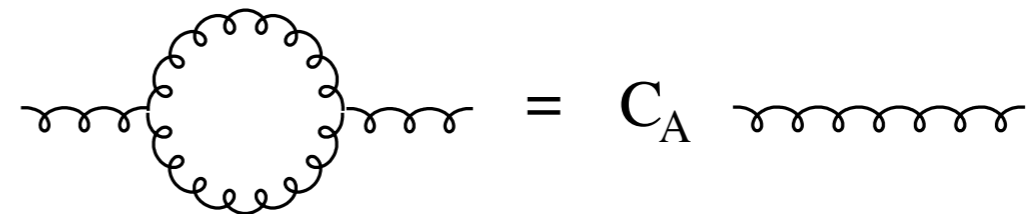
Fundamental representation 3:

$$\sum_a (t_{ij}^a)(t_{kj}^a) = C_F \delta_{ij} \quad C_F = \frac{N_c^2 - 1}{2N_c}$$



Adjoint representation 8:

$$\sum_{cd} f^{acd} f^{bdc} = C_A \delta^{ab} \quad C_A = N_c$$



## Exercises:

- 1) derive Fierz identity
- 2) use the Fierz identity to derive the value of  $C_F$  and  $C_A$



# Gauge invariance

The QCD Lagrangian is invariant under local gauge transformations, i.e. one can redefine the quark and gluon fields independently at every point in space and time without changing the physical content of the theory

- Gauge transformation for the quark field

$$\psi \rightarrow \psi' = U(x)\psi$$

- The **covariant** derivative  $(D_\mu)_{ij} = \partial_\mu \delta_{ij} + ig_s t_{ij}^a A_a^\mu$  must transform as (covariant = transforms “with” the field)

$$D_\mu \psi \rightarrow D'_\mu \psi' = U(x) D_\mu \psi$$

- From which one derives the transformation property of the gluon field

$$t^a A_a \rightarrow t^a A'_a = U(x) t^a A_a U^{-1}(x) + \frac{i}{g_s} (\partial U(x)) U^{-1}(x)$$

# Gauge invariance

The QCD Lagrangian is invariant under local gauge transformations, i.e. one can redefine the quark and gluon fields independently at every point in space and time without changing the physical content of the theory

- It follows that

$$\bar{\psi} \rightarrow \bar{\psi}' = \bar{\psi} U^\dagger(x)$$

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

e.g. because  $i g_s t^a F_{\mu\nu}^a = [D_\mu, D_\nu]$

- Therefore the QCD Lagrangian is indeed gauge invariant

$$-\frac{1}{4} F_a^{\prime\mu\nu} F_{\mu\nu}^{\prime a} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a$$

$$\sum_f \bar{\psi}_i^{\prime(f)} (iD'_{ij} - m_f \delta_{ij}) \psi_j^{\prime(f)} = \sum_f \bar{\psi}_i^{(f)} (iD_{ij} - m_f \delta_{ij}) \psi_j^{(f)}$$

# Gauge invariance

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## Remarks:

- the field strength alone is not gauge invariant in QCD (unlike in QED) because of self interacting gluons (carries of the force carry colour, unlike the photon)
- a gluon mass term violate gauge invariance and is therefore forbidden (as for the photon). On the other hand quark mass terms are gauge invariant.

$$\cancel{m^2 A_\mu A^\mu}$$

# Isospin symmetry

Isospin SU(2) symmetry: relates the content in terms of up and down quarks. **Isospin invariance means invariance under  $u \leftrightarrow d$**

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

- Proton has isospin  $I_3=1/2$ , while the neutron  $I_3=-1/2$ . Protons and neutrons form an iso-spin multiplet
- Pions have  $I_3=1$  ( $\pi^+ = ud$ ),  $I_3=0$  ( $\pi_0 = 1/\sqrt{2}(uu+dd)$ ),  $I_3=0$  ( $\pi^- = ud$ ). They are also in an iso-spin multiplet

Particles in the same isospin multiplet have very similar masses (proton and neutron, neutral and charged pions)

# Isospin symmetry

Isospin arises because QCD interactions are flavour blind and the accidental fact that up and down have very close masses

Check: the QCD Lagrangian has isospin symmetry if  $m_u = m_d$  or  $m_u, m_d \rightarrow 0$

In this limit of vanishing  $m_u, m_d$  masses, one can separate the fermion fields into left and right chiralities

$$\psi_L = P_L \psi, \quad \psi_R = P_R \psi, \quad P_{L/R} = \frac{1}{2} (1 \mp \gamma_5)$$

And the QCD Lagrangian becomes

$$\mathcal{L}_F = \sum_f \left( \bar{\psi}_L^{(f)} \not{D} \psi_L^{(f)} + \bar{\psi}_R^{(f)} \not{D} \psi_R^{(f)} \right) - \sum_f m_f \left( \bar{\psi}_R^{(f)} \psi_L^{(f)} + \bar{\psi}_L^{(f)} \psi_R^{(f)} \right)$$

So neglecting fermion masses the Lagrangian has the larger symmetry

$$SU_L(N_f) \times SU_R(N_f) \times U_L(1) \times U_R(1)$$

# Isospin symmetry

The fact that left-handed and right-handed terms in the Lagrangian are separately invariant is a direct consequence of the fact that the **chirality of massless fermions is conserved**

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

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

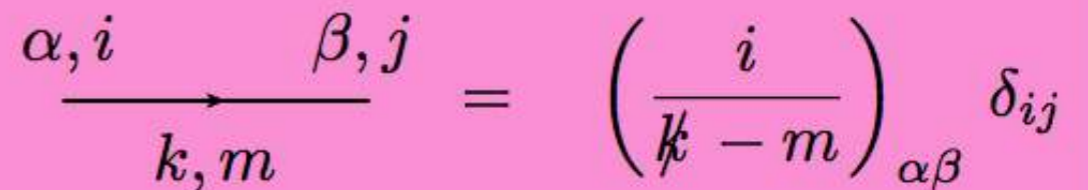
Similar mechanisms to the one that break the chiral symmetry in QCD have been proposed to explain why the Higgs boson so is light in composite Higgs scenarios ... but this is a topic for a different lecture!

# Feynman rules: propagators

Obtain quark/gluon propagators from free piece of the Lagrangian

Quark propagator: replace  $i\partial \rightarrow k$  and take the  $i \times$  inverse

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


$$\begin{array}{c} \alpha, i \\ \xrightarrow{\hspace{1cm}} \\ \beta, j \\ \text{\scriptsize } k, m \end{array} = \left( \frac{i}{\not{k} - m} \right)_{\alpha\beta} \delta_{ij}$$

Gluon propagator: replace  $i\partial \rightarrow k$  and take the  $i \times$  inverse ?

$$\mathcal{L}_{g,\text{free}} = \frac{1}{2} A^\mu (\square g_{\mu\nu} - \partial_\mu \partial_\nu) A^\nu$$

➡ **inverse does not exist, since**  $(\square g_{\mu\nu} - \partial_\mu \partial_\nu) \partial_\mu = \square \partial_\nu - \square \partial_\nu = 0$

How can one to define the propagator ?





# Ghosts

In covariant gauges gauge fixing term must be supplemented with **ghost term** to cancel unphysical longitudinal degrees of freedom which should not propagate

$$\mathcal{L}_{\text{ghost}} = \partial_\mu \eta^{a\dagger} D_{ab}^\mu \eta^b$$

$$\bar{u}^a \xrightarrow{k} u^b = \frac{i}{k^2} \delta^{ab}$$

$\eta$ : complex scalar field which obeys Fermi statistics

$$\sum_{\lambda=+1,-1,0} \left| \text{Diagram} \right|^2 - \left| \text{Diagram} \right|^2 = \sum_{\lambda=+1,-1} \left| \text{Diagram} \right|^2$$

# Axial gauges

Alternative: choose an axial gauge (introduce an arbitrary direction  $n$ )

$$\mathcal{L}_{\text{axial gauge}} = -\frac{1}{\xi} (n^\mu A_\mu^A)^2$$

The gluon propagator becomes

$$d_{\mu\nu} = \frac{i}{k^2} \left( -g_{\mu\nu} + \frac{n_\mu k_\nu + n_\nu k_\mu}{n \cdot k} + \frac{(n^2 + \xi k^2) k_\mu k_\nu}{(n \cdot k)^2} \right) \delta_{ab}$$

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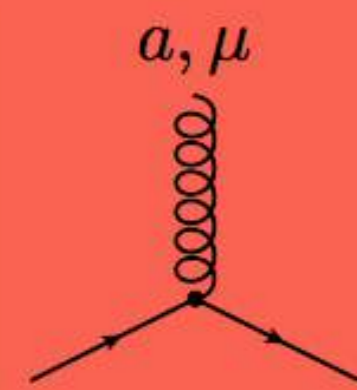
Light cone gauge:  $n^2 = 0$  and  $\xi = 0$

Axial gauges for  $k^2 \rightarrow 0$

$$d_{\mu\nu} k^\mu = d_{\mu\nu} n^\mu = 0$$

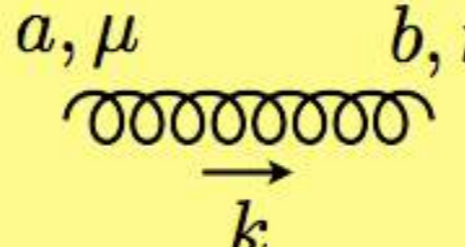
i.e. only two physical polarizations propagate, that's why often the term physical gauge is used

# QCD Feynman rules: the vertices



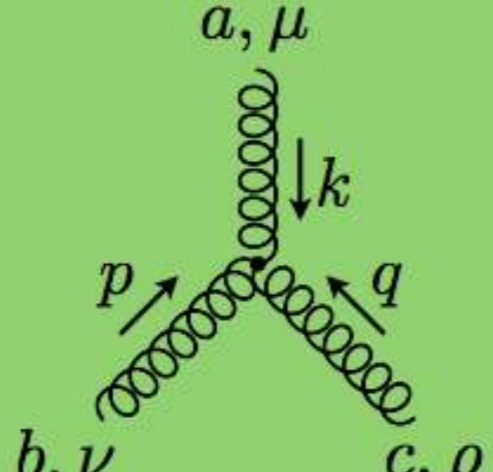
A Feynman diagram showing a quark line (represented by a straight line with an arrow) entering from the bottom left and exiting from the bottom right. A gluon line (represented by a wavy line) enters from the top and meets the quark line at a vertex. The gluon line is labeled with  $a, \mu$ .

$$= ig_s \gamma^\mu t^a$$



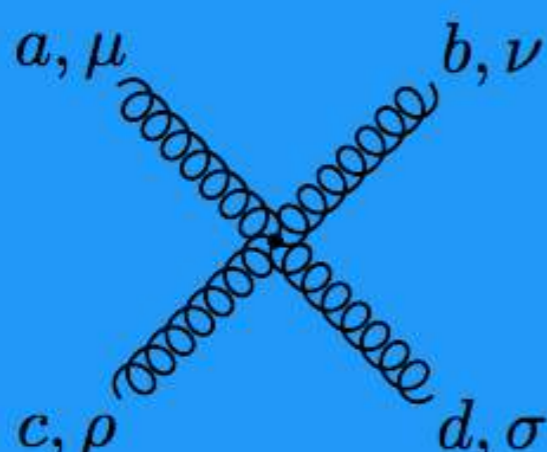
A Feynman diagram showing a three-gluon vertex. Three wavy lines meet at a central point. The top-left line is labeled  $a, \mu$ , the top-right line is labeled  $b, \nu$ , and the bottom line is labeled  $k$  with an arrow pointing downwards.

$$= \left( \frac{-ig_{\mu\nu}}{k^2} \right) \delta^{ab}$$



A Feynman diagram showing a four-gluon vertex. Four wavy lines meet at a central point. The top line is labeled  $a, \mu$  with a downward arrow and  $k$  below it. The bottom-left line is labeled  $b, \nu$  with an upward arrow and  $p$  to its left. The bottom-right line is labeled  $c, \rho$  with an upward arrow and  $q$  to its right.

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



A Feynman diagram showing a four-gluon vertex with two crossed gluon lines. The top-left line is labeled  $a, \mu$ , the top-right line is labeled  $b, \nu$ , the bottom-left line is labeled  $c, \rho$ , and the bottom-right line is labeled  $d, \sigma$ .

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

# Recap

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

- Describe the hadron spectrum
- Explain experimentally observed symmetries in the strong interaction
- Avoid mixing between strong and weak interactions
- Obtain a field-theoretical description of the strong force, opening the path to a unified formalism of all fundamental interactions

As we will see, the perturbative description of QCD is very predictive but we understand much less the regime governed by strong dynamics.