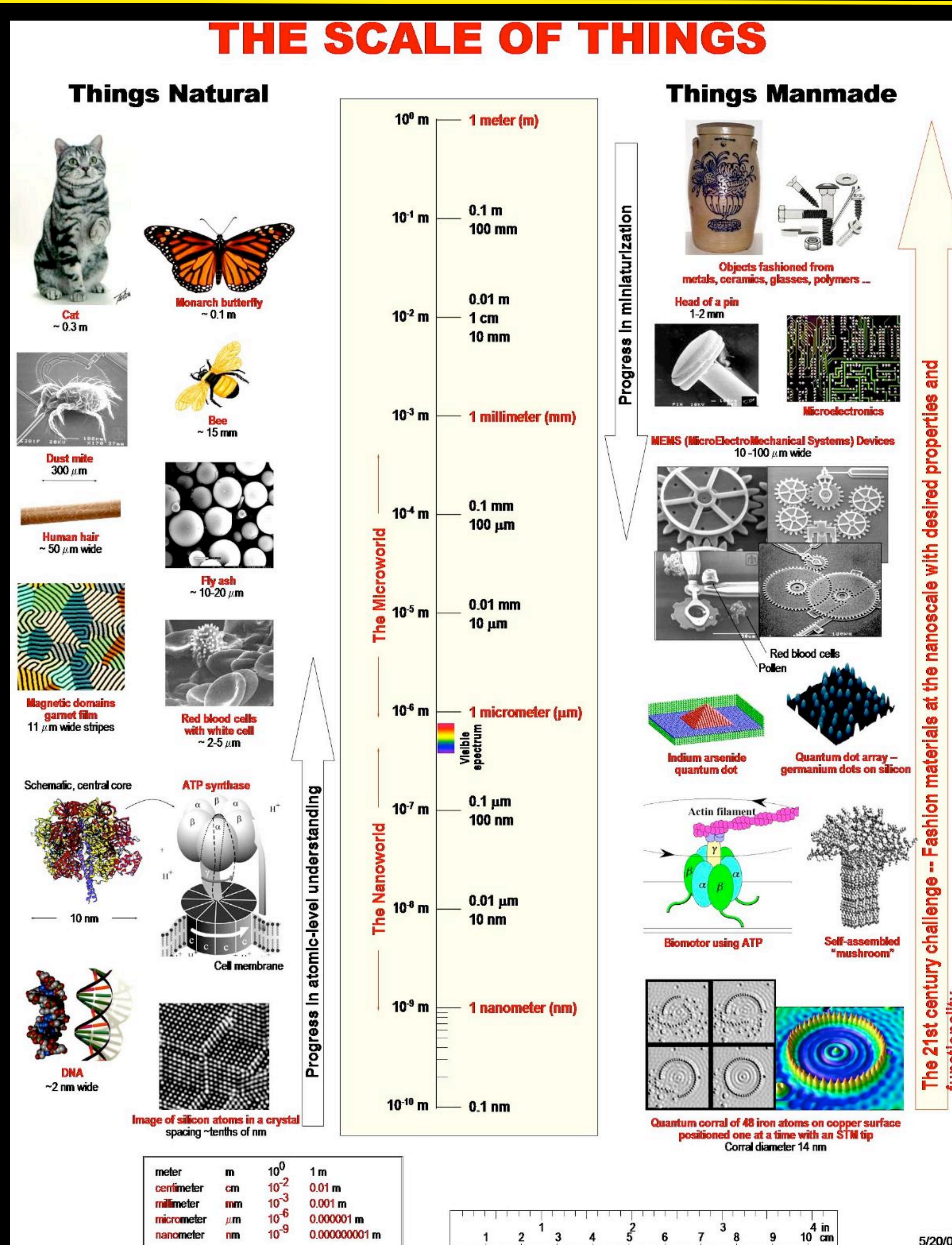
Nikhef

The Particle zoo

Panos Christakoglou

Nikhef and Utrecht University

About the different scales…



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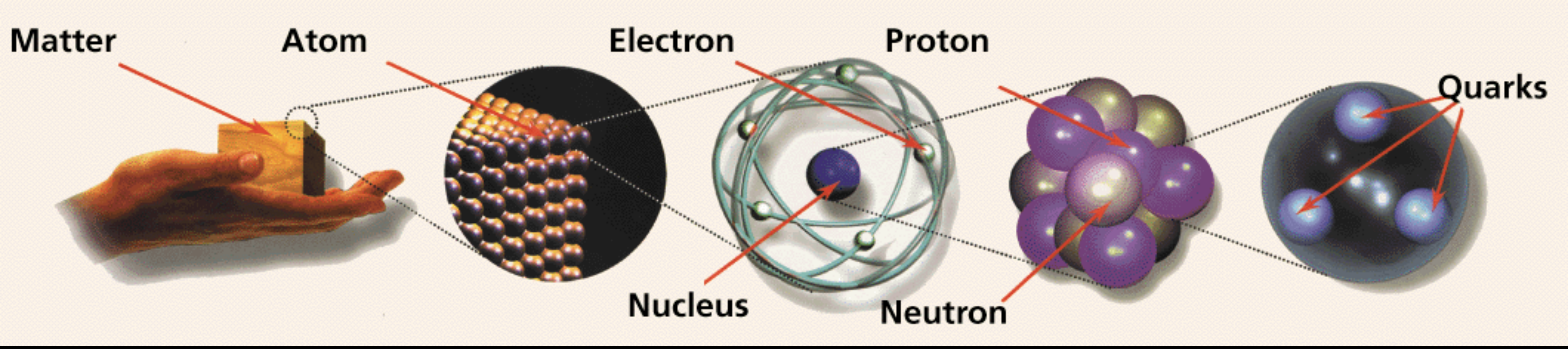
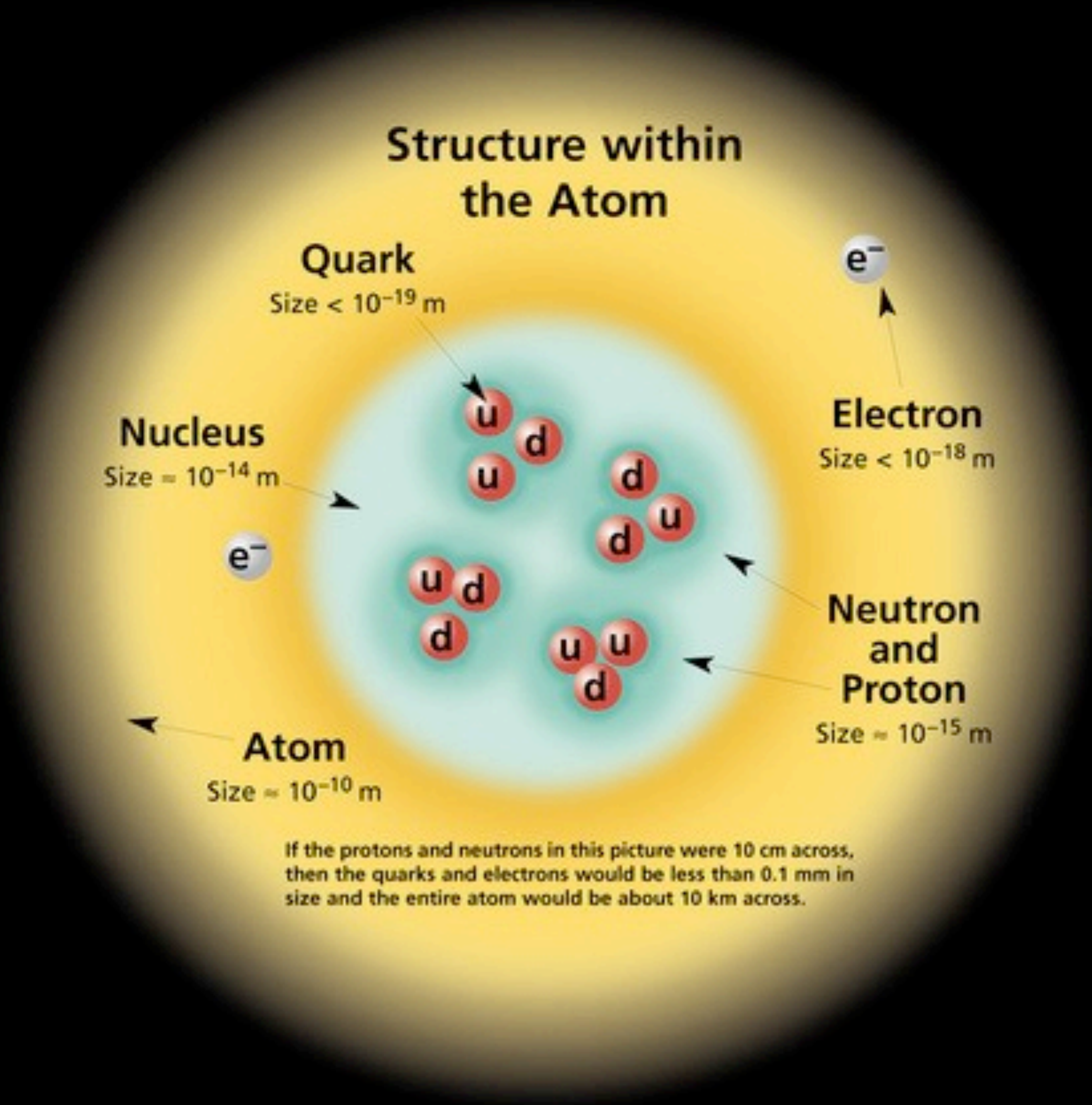
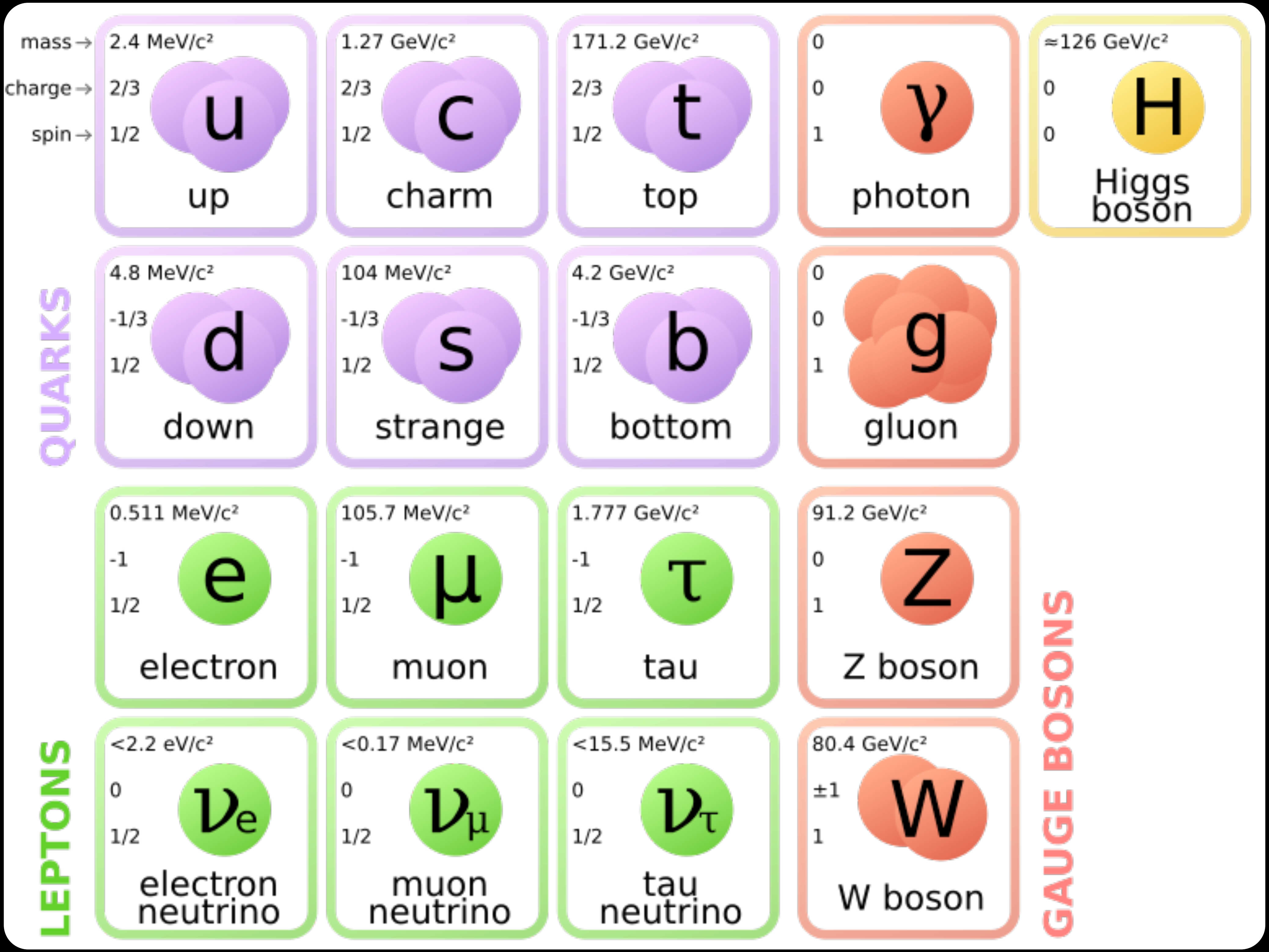


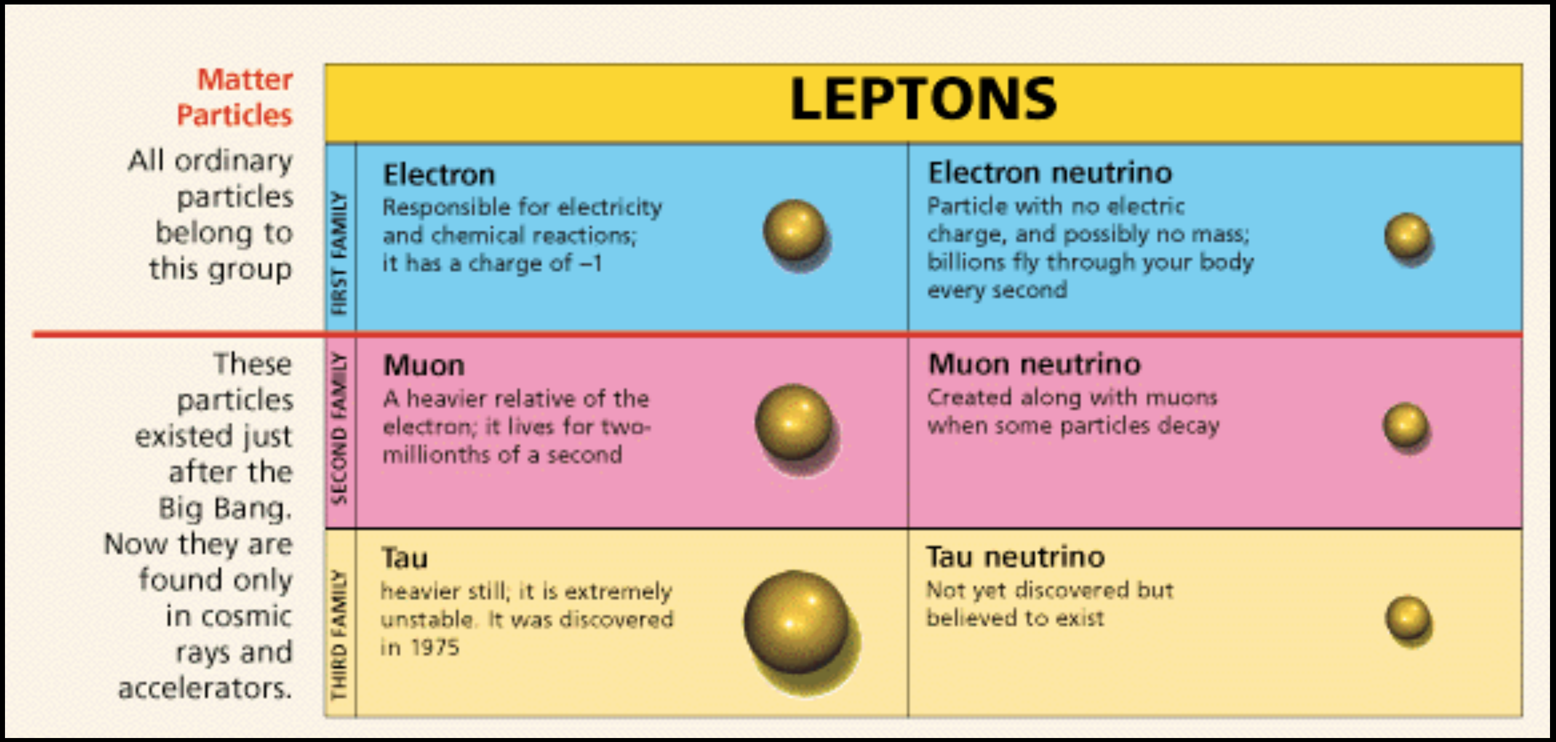
The world of subatomic particles



Periodic table of particle physics



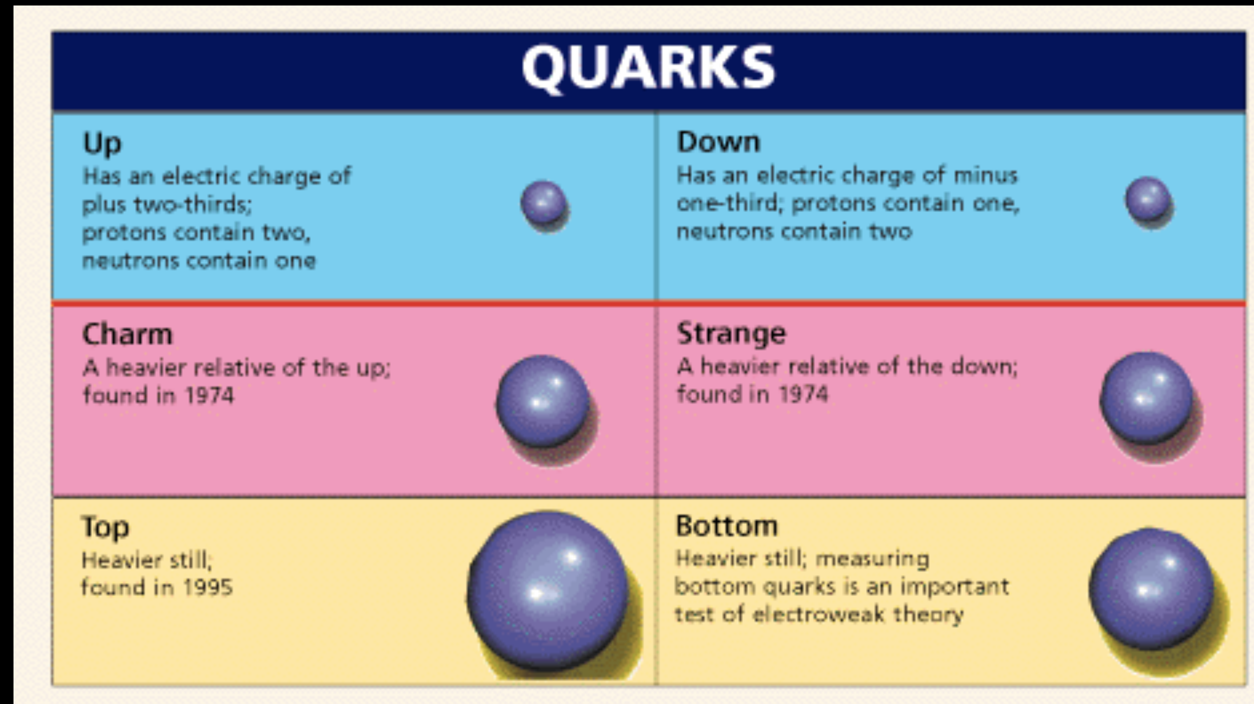
Leptons of the Standard Model



Particle	Mass (MeV)	Q/e	L_e	L_μ	L_τ
ν_e	$\leq 2\times 10^{-6}$	0	1	0	0
$\overline{\nu}_e$	$\leq 2\times 10^{-6}$	0	-1	0	0
e^-	0.511	-1	1	0	0
e^+	0.511	1	-1	0	0
ν_μ	≤ 0.19	0	0	1	0
$\overline{\nu}_\mu$	≤ 0.19	0	0	-1	0
μ^-	105.66	-1	0	1	0
μ^+	105.66	1	0	-1	0
ν_τ	≤ 18.2	0	0	0	1
$\overline{\nu}_\tau$	≤ 18.2	0	0	0	-1
τ^-	1777	-1	0	0	1
τ^+	1777	1	0	0	-1

Table 1.1: The basic properties of the Standard Model leptons.

Quarks of the Standard Model

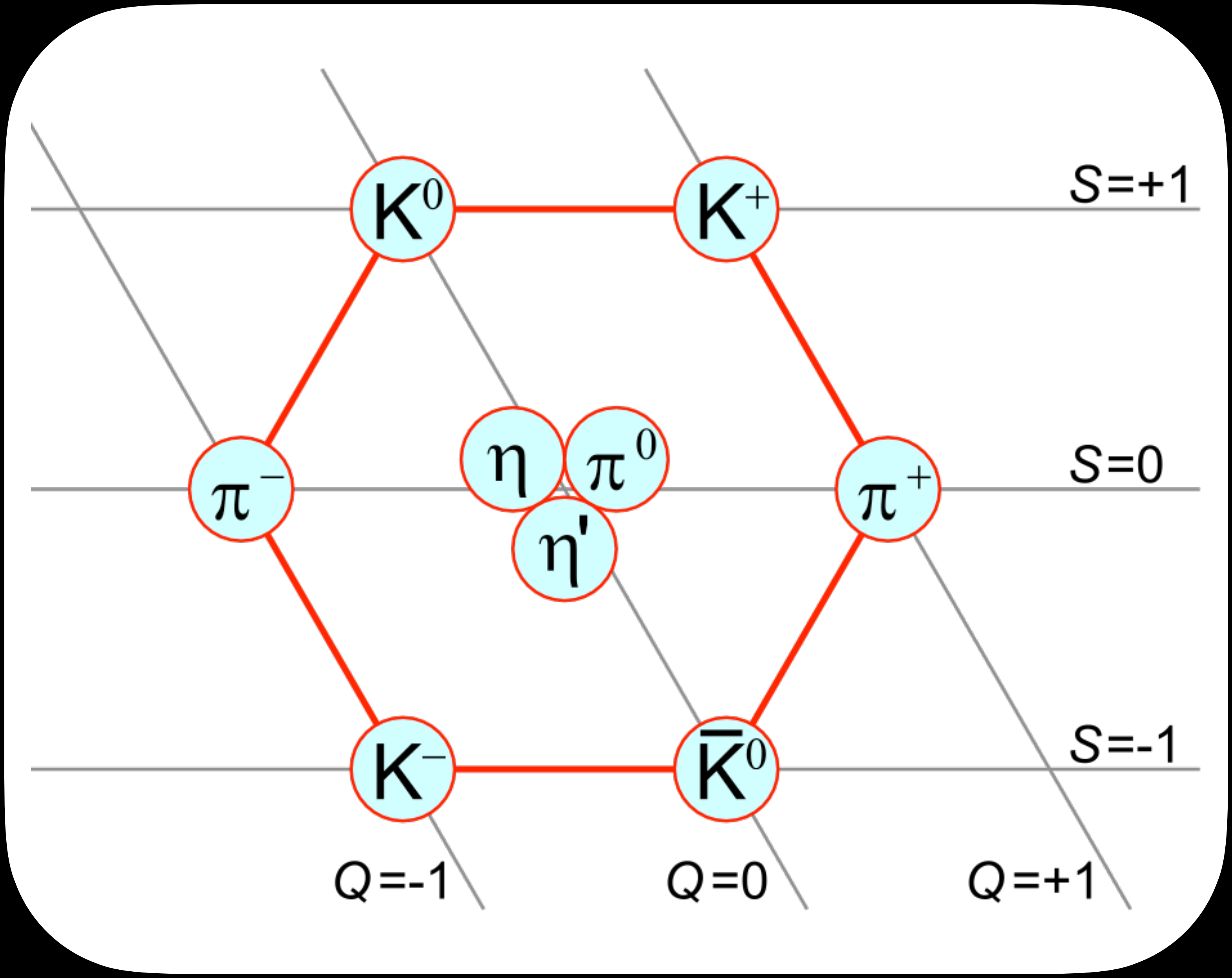


Particle	Mass (MeV)	Q/e	Strangeness	Charm	Beauty	Topness
u	2	2/3	0	0	0	0
$\bar{u}$	2	-2/3	0	0	0	0
d	5	-1/3	0	0	0	0
$\bar{d}$	5	1/3	0	0	0	0
c	1200	2/3	0	1	0	0
$\bar{c}$	1200	-2/3	0	-1	0	0
s	100	-1/3	-1	0	0	0
$\bar{s}$	100	1/3	1	0	0	0
t	174000	2/3	0	0	0	1
$\bar{t}$	174000	-2/3	0	0	0	-1
b	4200	-1/3	0	0	-1	0
$\bar{b}$	4200	1/3	0	0	1	0

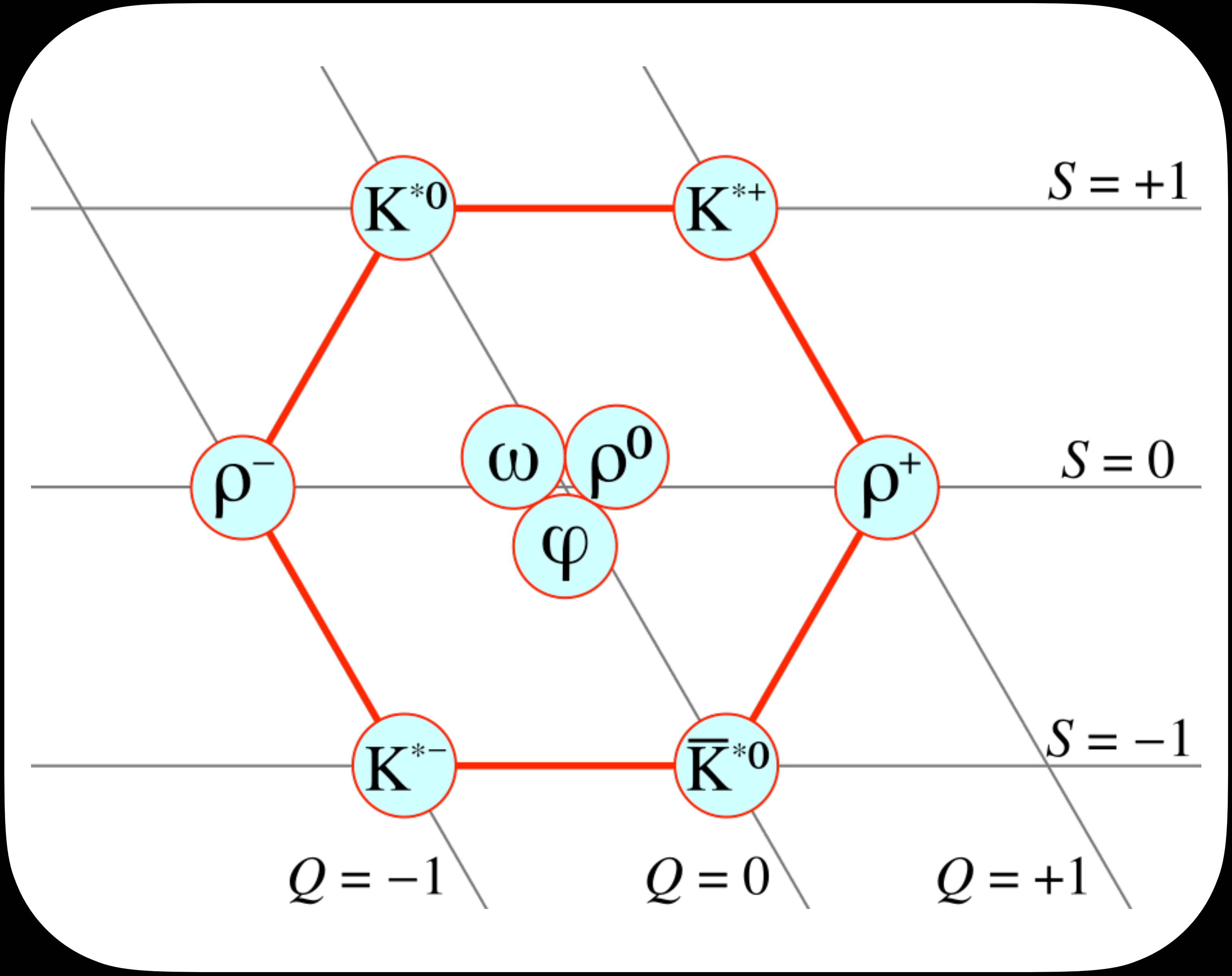
Table 1.2: The basic properties of the quarks of the Standard Model.

Panos.Christakoglou@nikhef.nl

But there are more…the mesons



But there are more…the mesons



A lot more…mesons

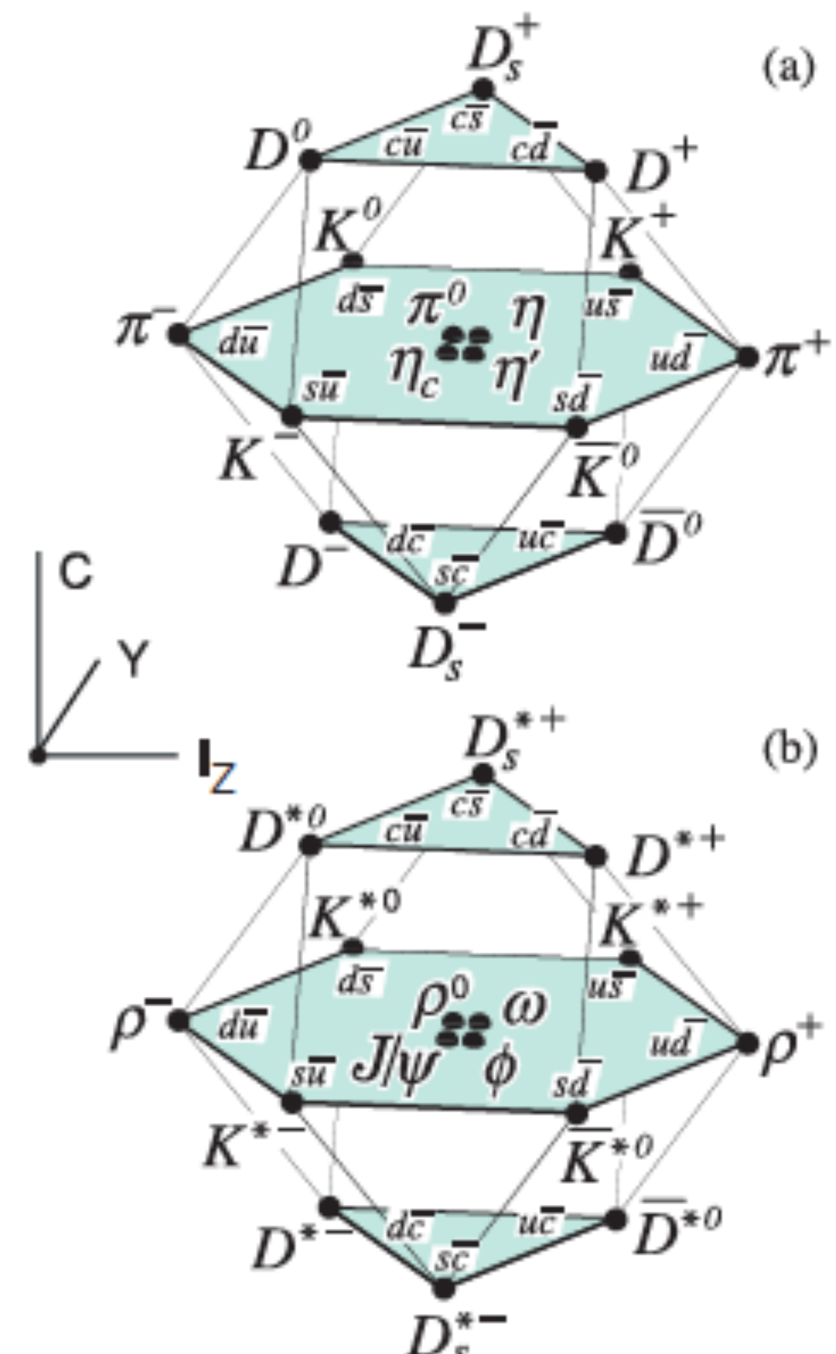
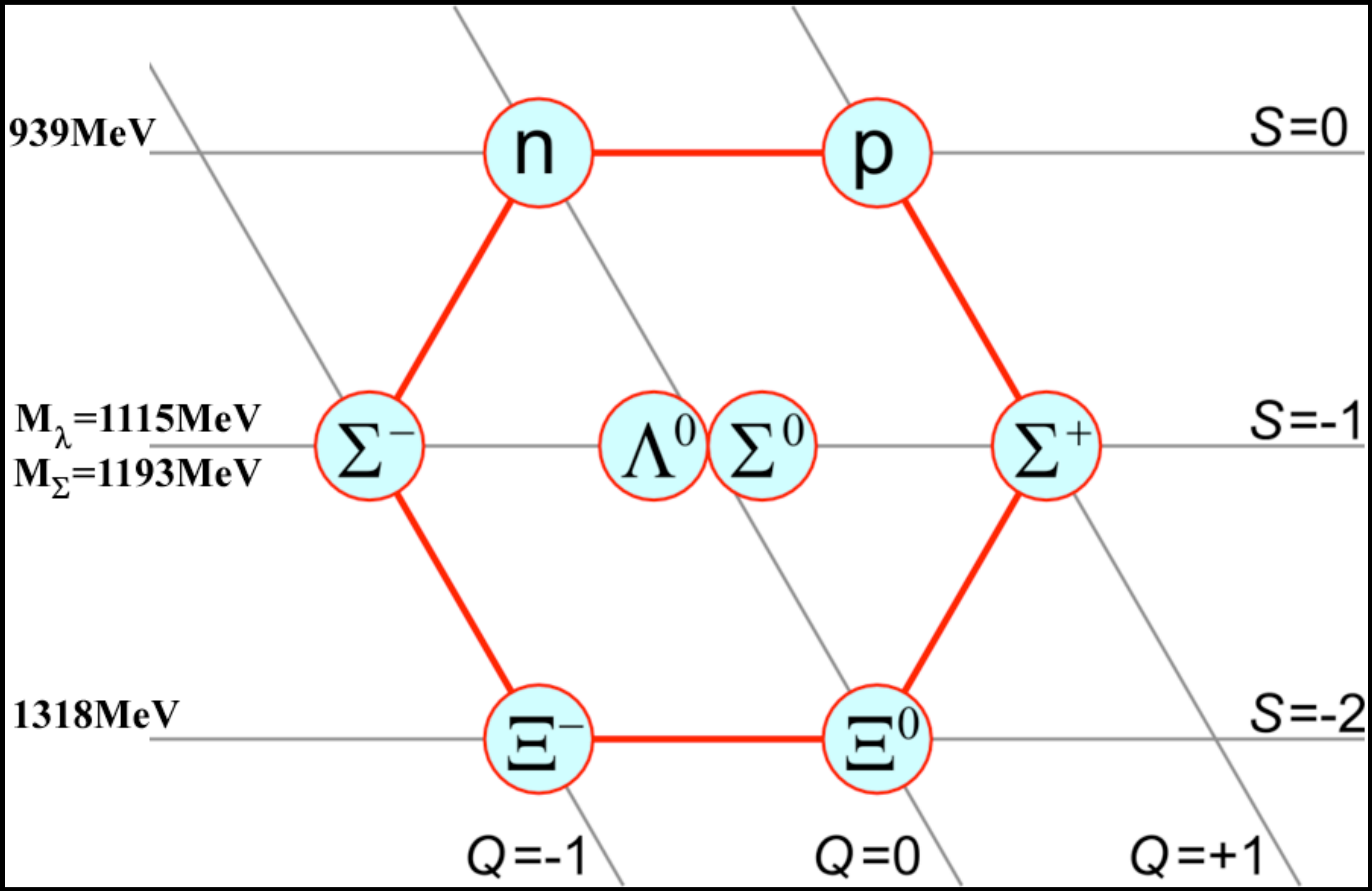
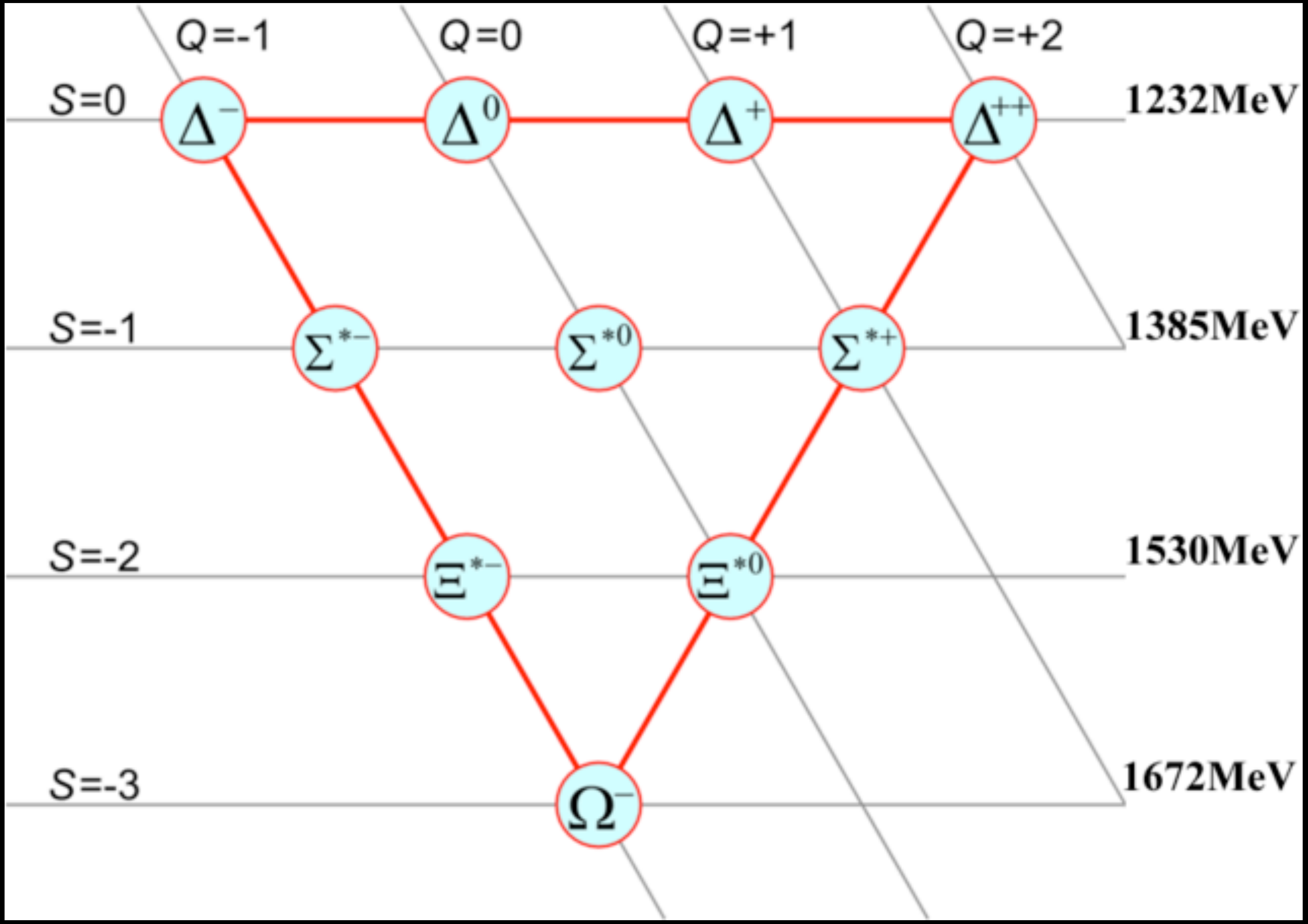


Figure 15.1: SU(4) weight diagram showing the 16-plets for the pseudoscalar (a) and vector mesons (b) made of the u, d, s, and c quarks as a function of isospin I_z, charm C, and hypercharge $Y = \mathcal{B} + S - \frac{C}{3}$. The nonets of light mesons occupy the central planes to which the $c\bar{c}$ states have been added.

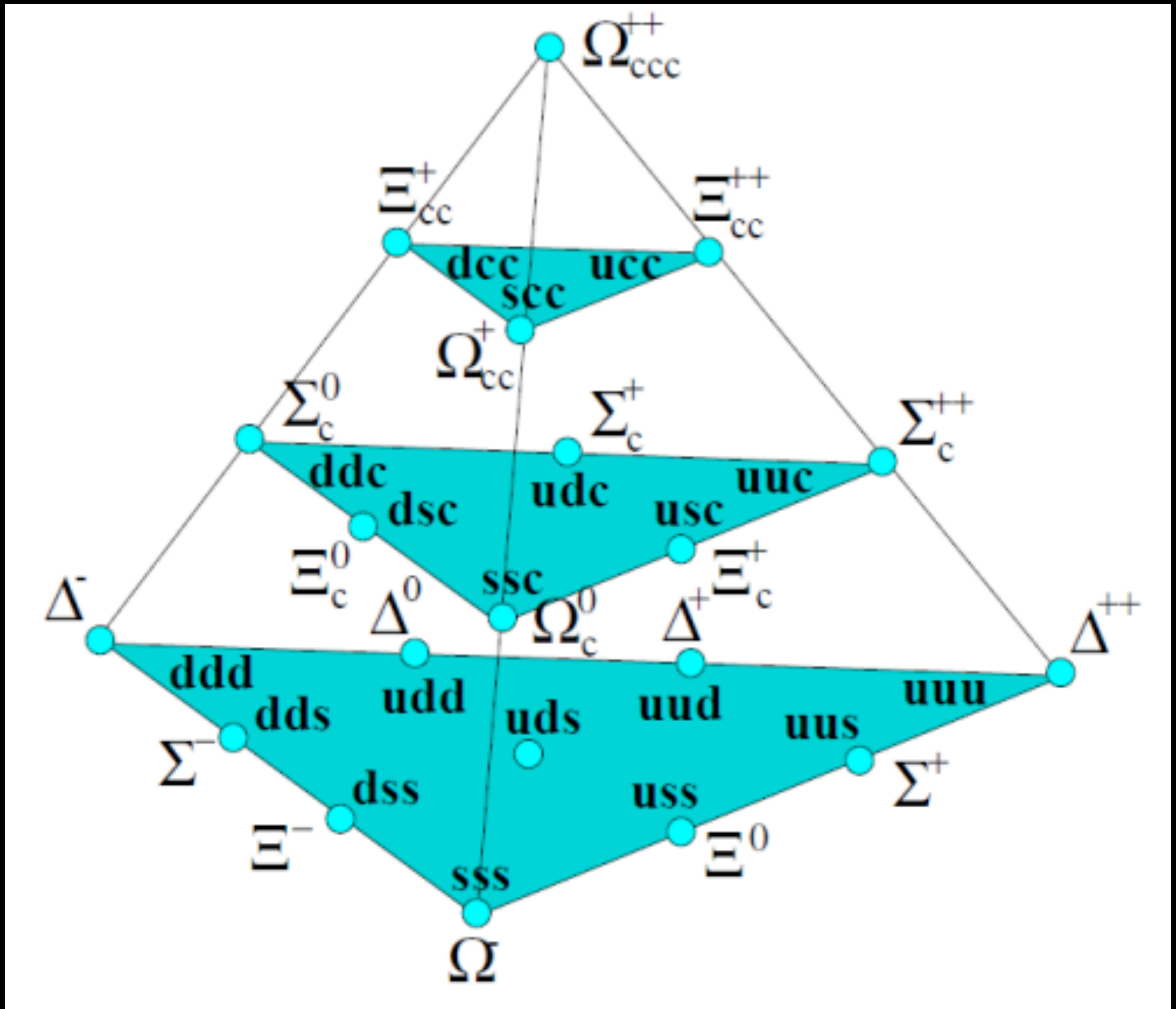
But there are more…the baryons



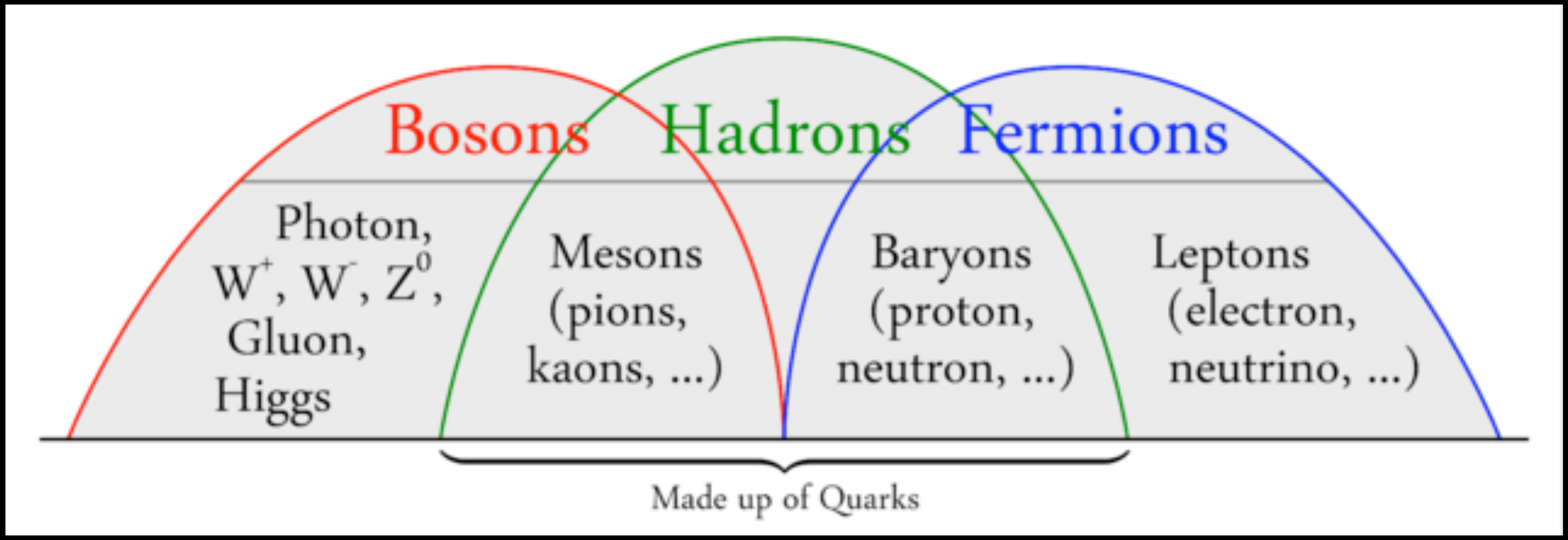
But there are more…the baryons



A lot more…baryons



Categories of particles



Based on which properties do we categorise them?

Particle mass

- A particle in the presence of an external force field, feels a force that accelerates it

$$m=\frac{|\vec{F}|}{|\vec{a}|}$$

- Atomic mass unit: 1/12 of the mass of an unbound neutral atom of ^{12}C in its ground state

$$1u=1.660539040(20)\cdot 10^{-27}kg$$

- Particles differ in masses by orders of magnitude
- Exited states are not given by their mass but by the excitation energy (MeV above ground state).
- For particles, we use eV/c^2, KeV/c^2, MeV/c^2, GeV/c^2 as mass units
  - it represents the amount of energy that it takes for a charge of a single electron to move across an electric potential difference of one volt

Particle mass (cont.)

eV ⇒ J conversion

$$1eV = 1V \cdot 1.602\times10^{-19}C$$
$$= 1\frac{J}{C}\cdot 1.602\times10^{-19}C$$
$$= 1.602\times10^{-19}J$$

eV ⇒ Kg conversion

$$1eV/c^2 = \frac{1.602\times10^{-19}J}{(2.9979\times10^8 m/s)^2} = 1.783\times10^{-36}Kg$$

electron/proton mass

$$m_e \simeq 0.511MeV/c^2 = 0.911\times10^{-30}Kg$$

$$m_p \simeq 1GeV/c^2 (0.938GeV/c^2) = 1.783\times10^{-27}Kg$$

atomic mass

$$1u = 1.660539040(20)\cdot10^{-27}kg$$

$$1u = 0.931GeV/c^2$$

Panos.Christakoglou@nikhef.nl

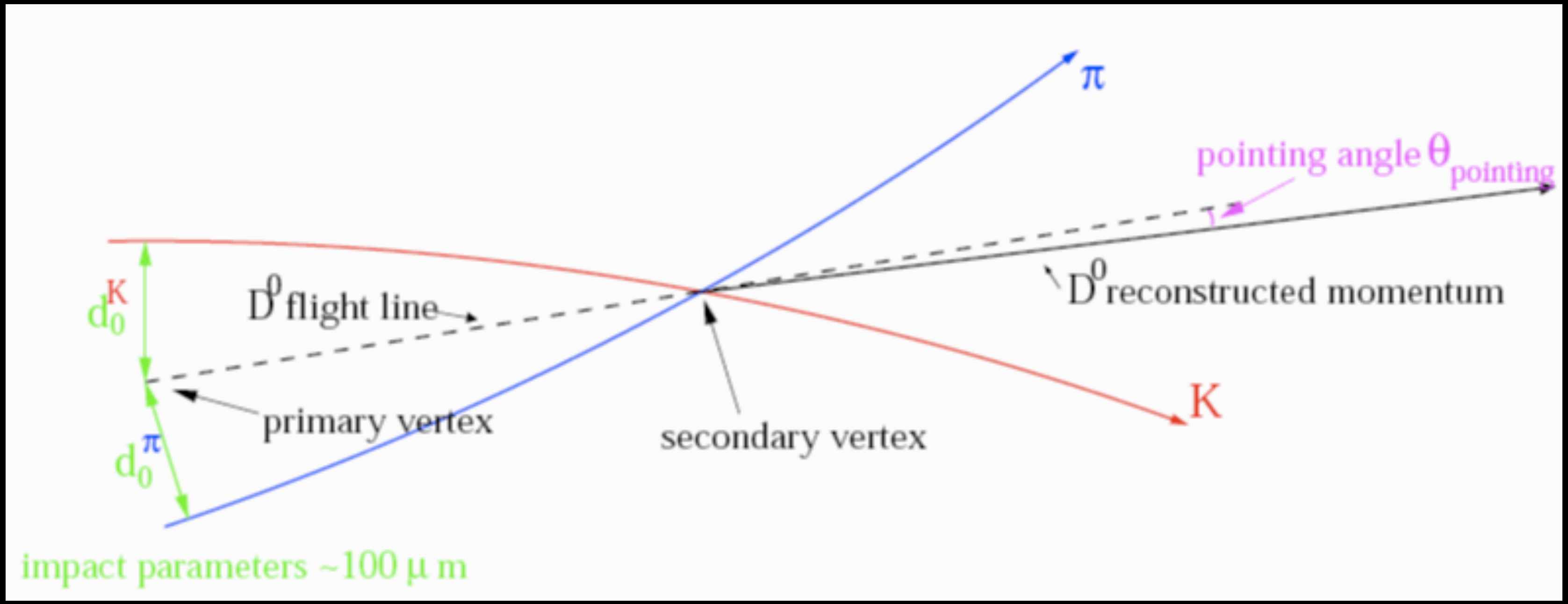
Particle mass (cont.)

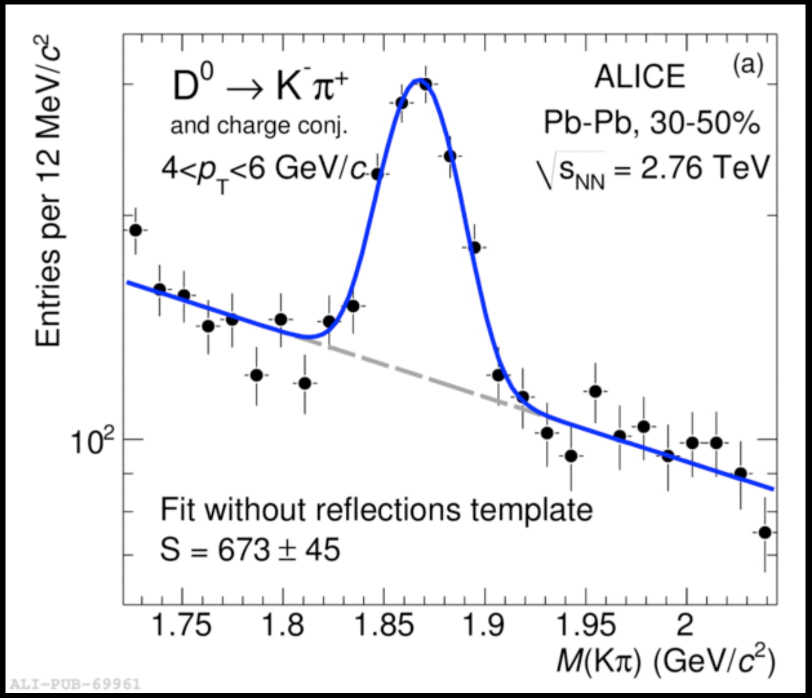
- The mass of a particle can be calculated by measuring at the same time its energy and momentum or velocity

$$E^2 = P^2c^2 + m^2c^4 \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = \frac{v}{c}$$

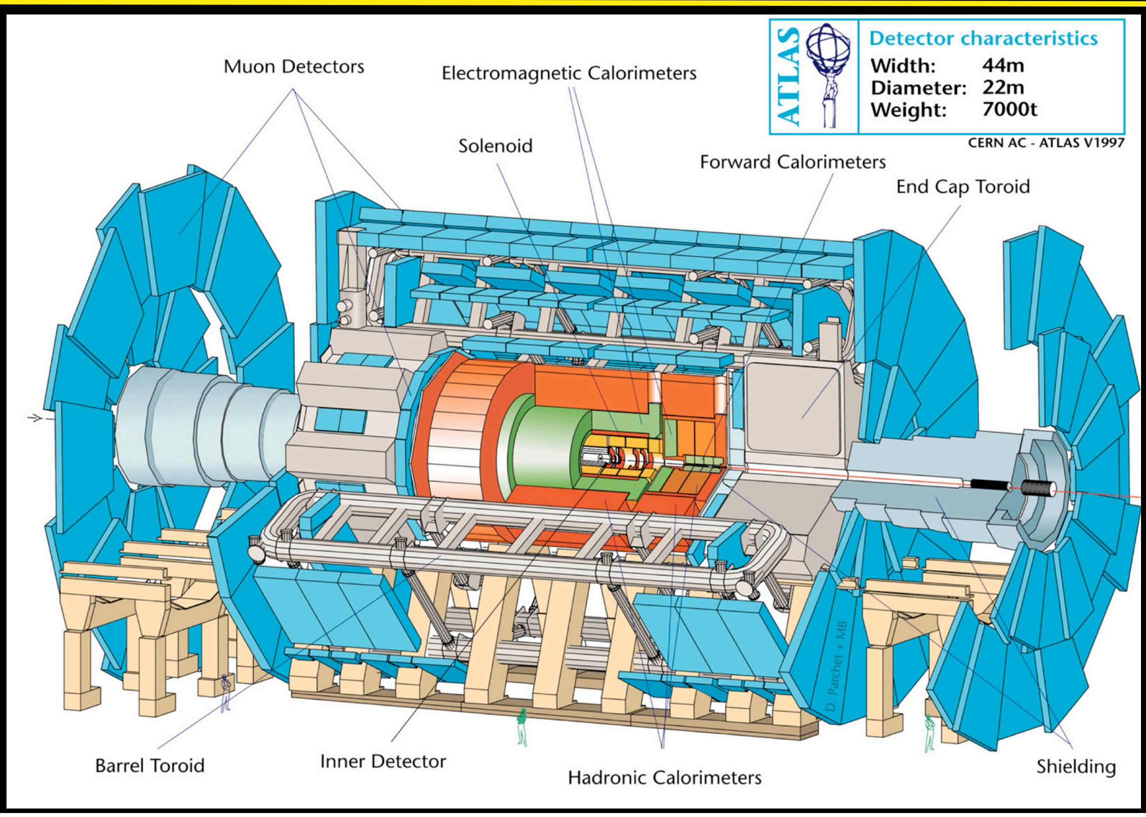
$$\vec{P} = m\gamma\vec{v}$$

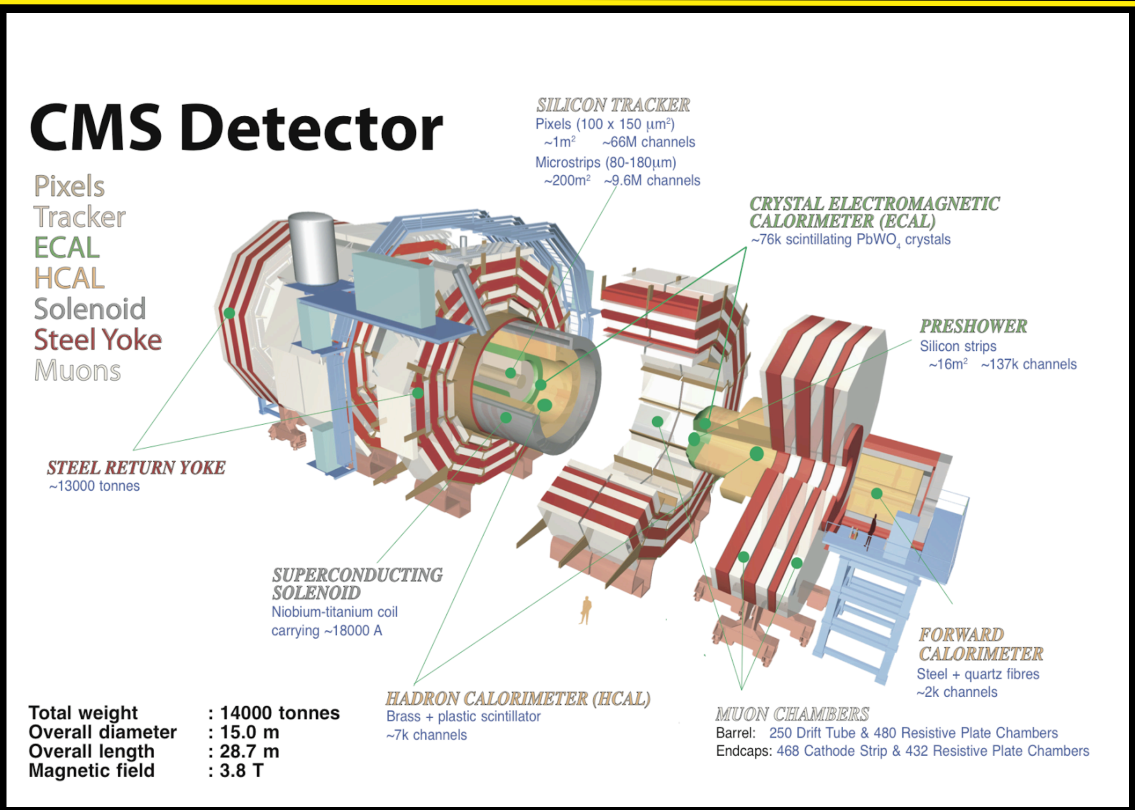
- Particle detectors are used for this reason
  - they are successful in measuring the mass of charged particles when these detectors are embedded in external magnetic fields
  - this method fails for neutral particles and for particles whose lifetime is short so that momentum and energy can not be measured → **Resonances**

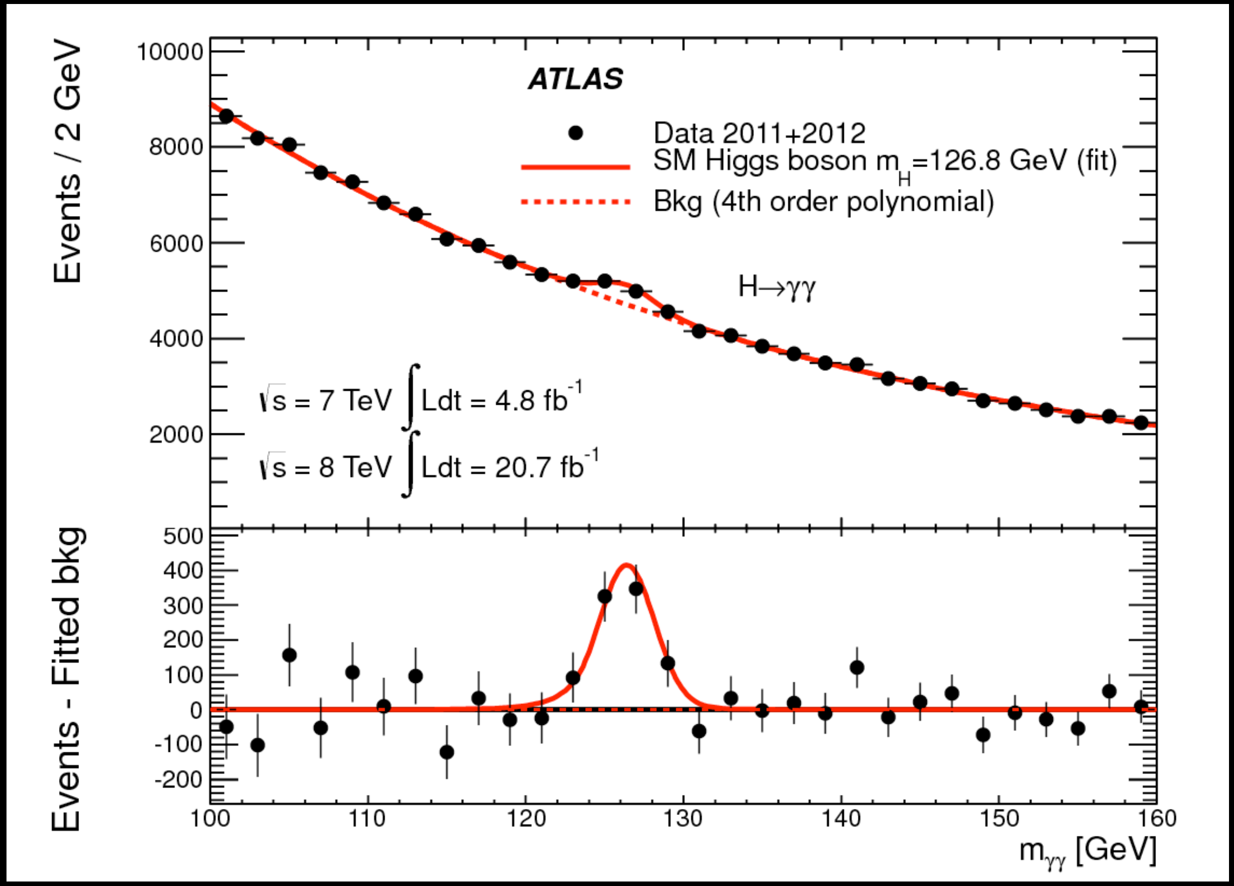


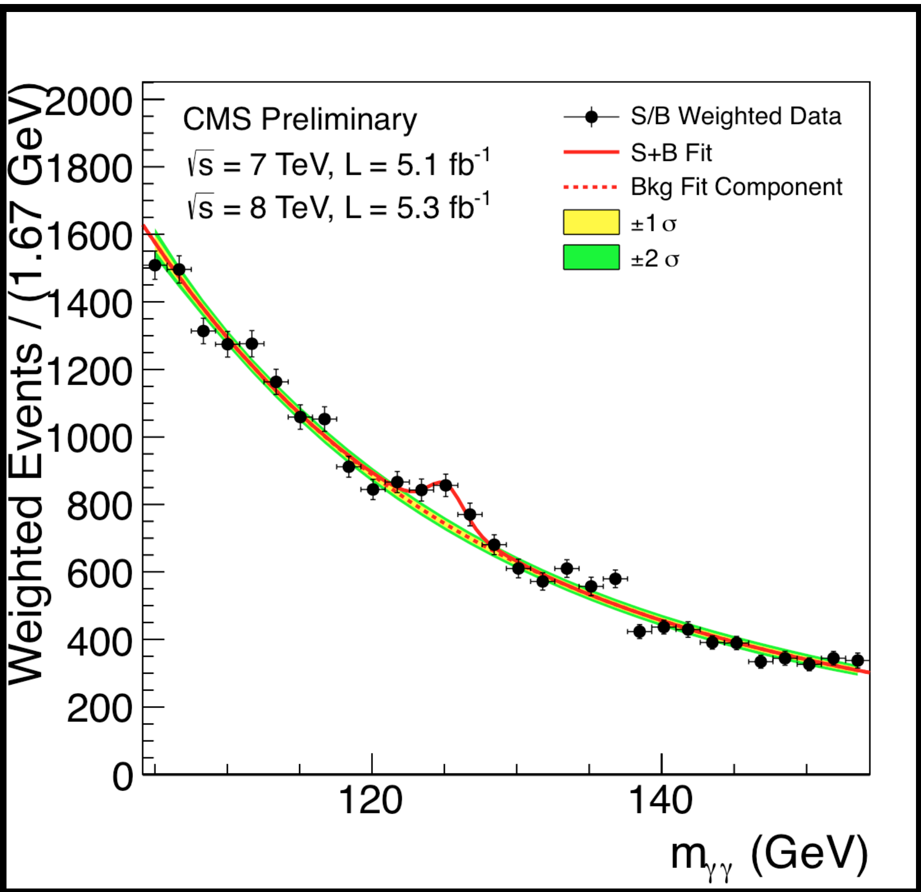


Particle mass (cont.)

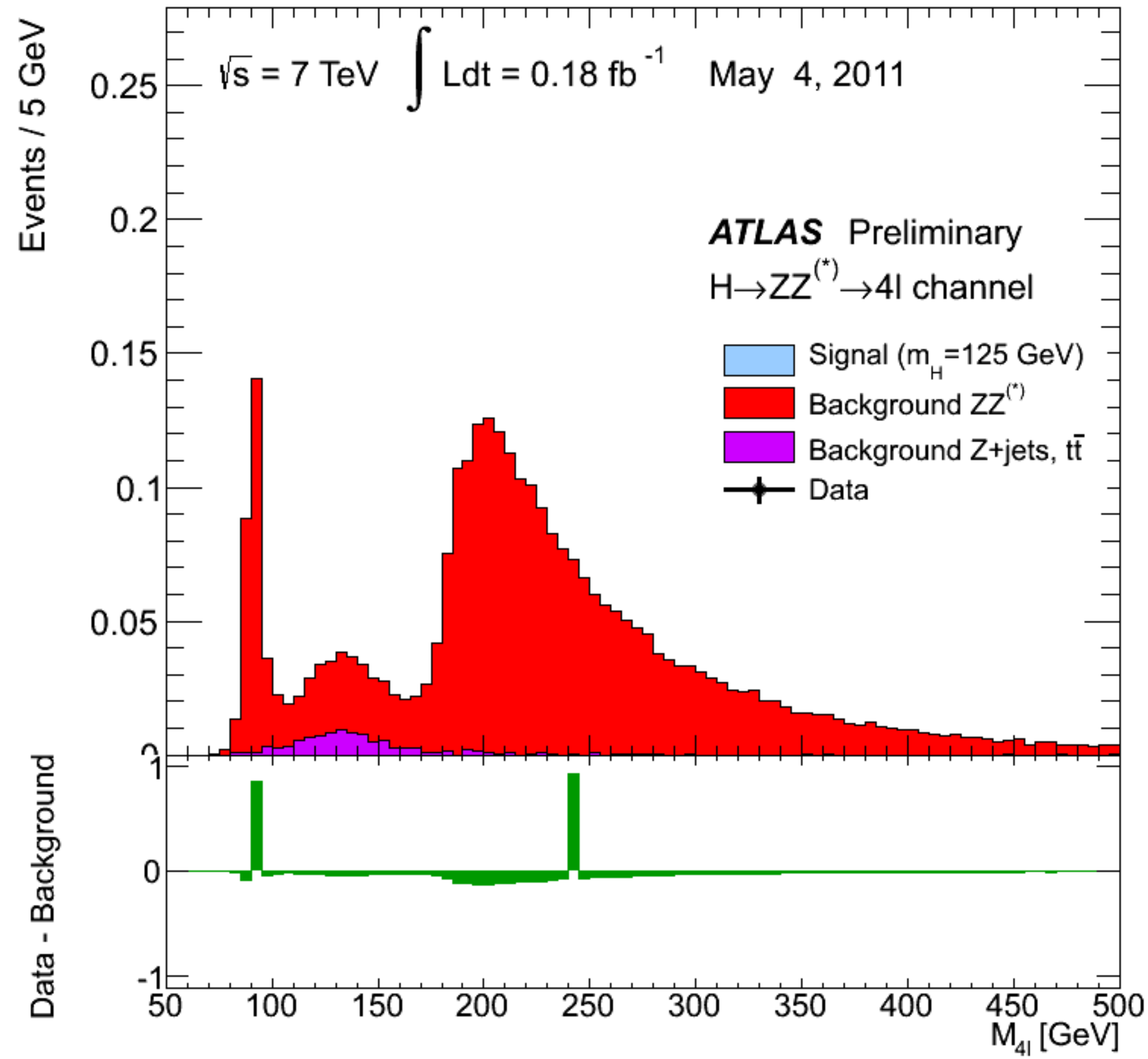








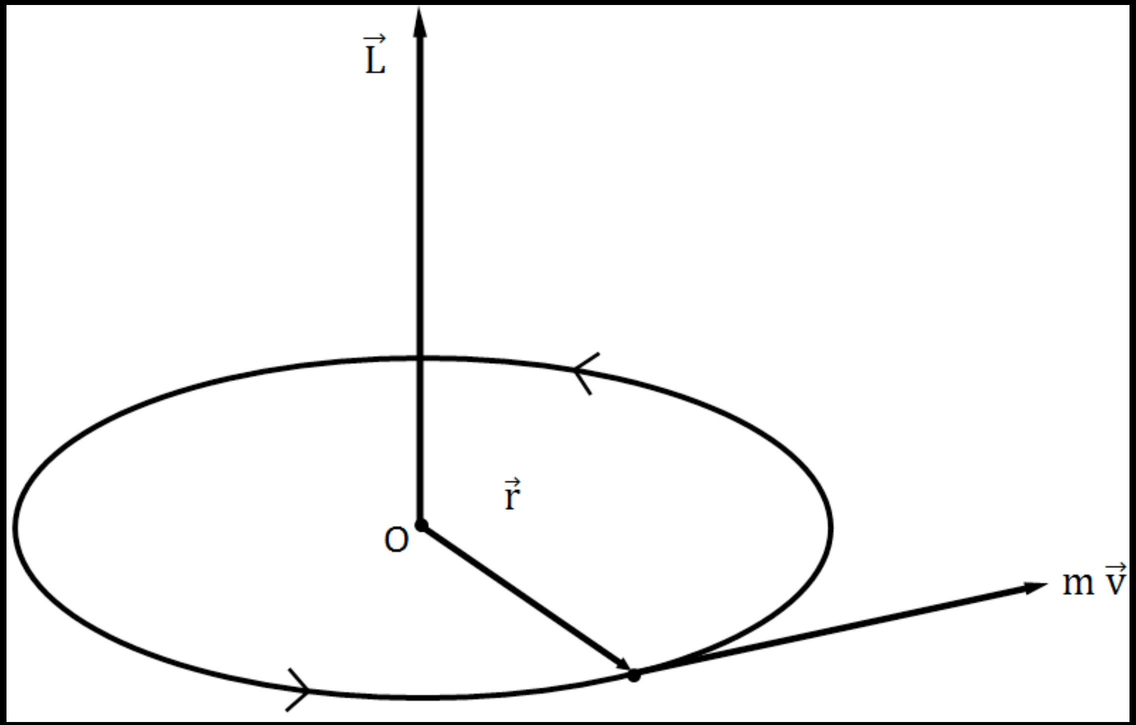
H → ZZ* → 4l signal = f(luminosity)



Orbital angular momentum

- Classically orbital angular momentum is defined by the cross product of the momentum and position vectors
- Classically L can take any value
- In quantum mechanics (QM), L is quantised and can only take discrete values
- In QM, each observable can be associated with an operator

$$\vec{L} = \vec{r} \times \vec{P}$$



$$\vec{r} \rightarrow \vec{r} = (x\hat{i}, y\hat{j}, z\hat{k})$$

$$\vec{P} \rightarrow \vec{P} = \left(-i\hbar\frac{\partial}{\partial x}\hat{i}, -i\hbar\frac{\partial}{\partial y}\hat{j}, -i\hbar\frac{\partial}{\partial z}\hat{k}\right) = -i\hbar\vec{\nabla}$$

$$\vec{L} \rightarrow \vec{L} = (L_x\hat{i}, L_y\hat{j}, L_z\hat{k})$$

$$L_x = -i\hbar\left(y\frac{\partial}{\partial z} - z\frac{\partial}{\partial y}\right)$$

$$L_y = -i\hbar\left(z\frac{\partial}{\partial x} - x\frac{\partial}{\partial z}\right)$$

$$L_z = -i\hbar\left(x\frac{\partial}{\partial y} - y\frac{\partial}{\partial x}\right)$$

Commutators

- The commutator of two elements a and b is given by

$$[a,b]=ab-ba$$

- For the components of the orbital angular momentum, the previous takes the form

$$\varepsilon_{ij}^{k}=\begin{cases} -1 & ,odd\ number\ of\ permutations\ (i,j,k) \\ 0 & i=j,\ or\ j=k,\ or\ k=i \\ 1 & ,even\ number\ of\ permutations\ (i,j,k) \end{cases}$$

$$[L_y,L_z]=L_yL_z-L_zL_y=i\hbar L_x$$

$$[L_z,L_x]=L_zL_x-L_xL_z=i\hbar L_y$$

$$[L_i,L_j]=i\hbar\varepsilon_{ij}^{k}L_k$$

Levi-Civita symbol

$$\varepsilon_{ij}^{k}=\begin{cases} -1 & ,odd\ number\ of\ permutations\ (i,j,k) \\ 0 & i=j,\ or\ j=k,\ or\ k=i \\ 1 & ,even\ number\ of\ permutations\ (i,j,k) \end{cases}$$

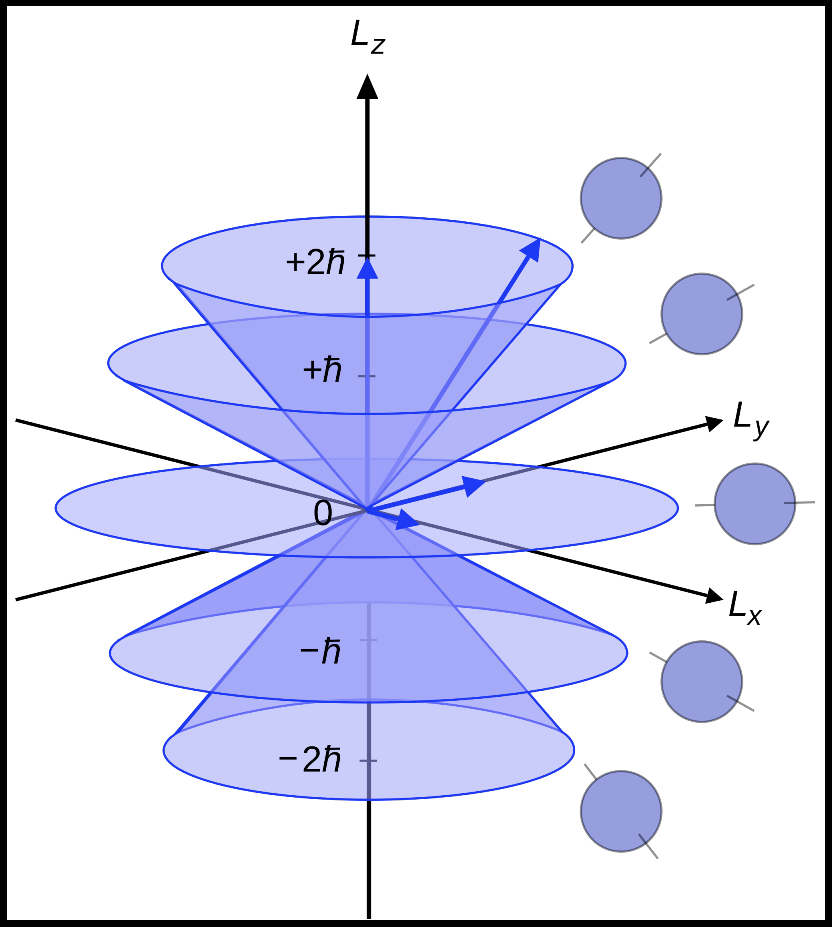
Orbital angular momentum

- In quantum mechanics we can not measure all components of angular momentum at the same time
  - We can measure its magnitude L^2 and its third component L_z
- Assuming that the wave function of a particle is given by |ψ> it can be chosen to be the eigenfunction of L^2 and L_z according to:

$$L^2 |\psi_{lm_l}\rangle = l(l+1)\hbar^2 |\psi_{lm_l}\rangle$$

$$L_z |\psi_{lm_l}\rangle = m_l \hbar |\psi_{lm_l}\rangle$$

  - The quantum numbers l and m_l are integers and ml can take any value from -l, -l+1,…,0,…,l-1,l (2l+1) values

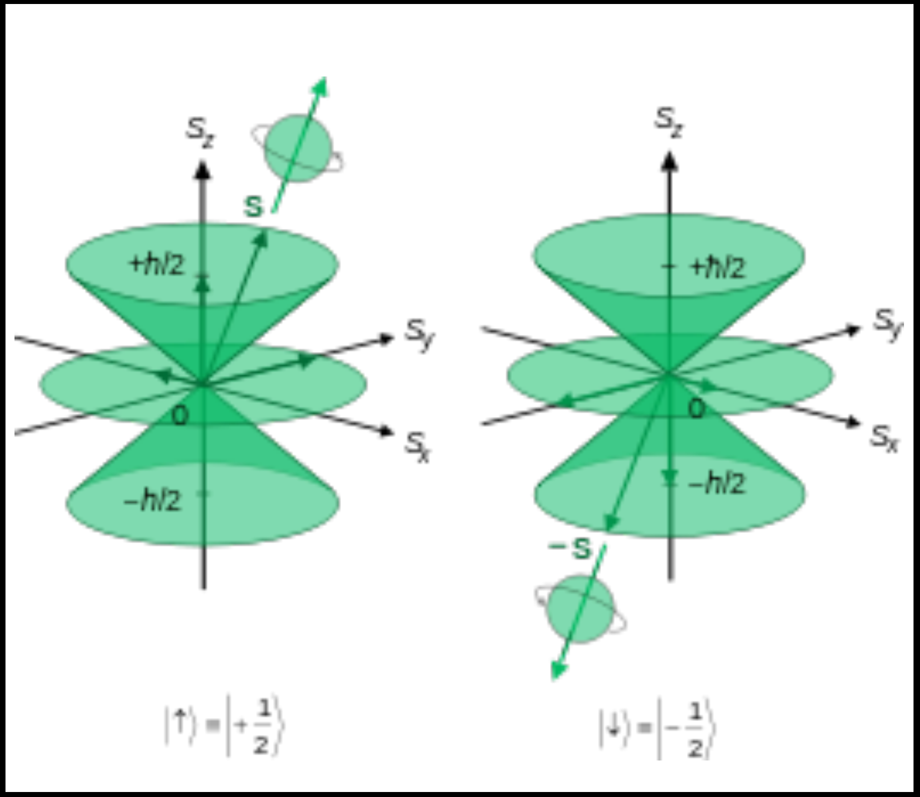


Spin

- Intrinsic angular momentum ➡ spin
- Has no classical counterpart
- Even particles with zero rest mass have spin (e.g. γ)
- The spin operator is denoted by S and satisfies the following

$$S^2 |\psi_{sm_s}\rangle = s(s+1)\hbar^2 |\psi_{sm_s}\rangle$$

$$S_z |\psi_{sm_s}\rangle = m_s \hbar |\psi_{sm_s}\rangle$$

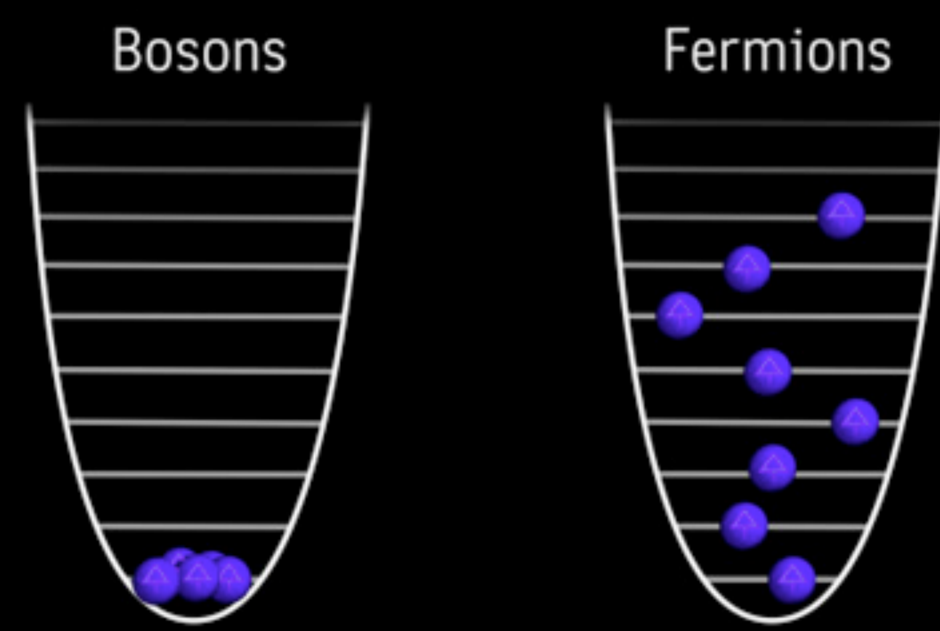


- The allowed values for s are not only integers but also half-integers: 0, 1/2, 1, 3/2, 2, 5/2…
- The allowed values for m_s are (2s+1): -s, -s+1,… 0,…, s-1, s

Fermions vs Bosons

Fermions		Bosons	
Leptons and Quarks	Spin = $\frac{1}{2}$	Spin = 1*	Force Carrier Particles
Baryons (qqq)	Spin = $\frac{1}{2}$, $\frac{3}{2}, \frac{5}{2}$...	Spin = 0, 1, 2...	Mesons ($q\bar{q}$)

- ✓ A fermion is any particle that has an odd half-integer (like 1/2, 3/2, and so forth) spin.
  - Quarks and leptons are fermions with spin-1/2
  - Baryons are composite particles, consisting of three quarks (anti-baryons consist of three anti-quarks) are fermions with spin 1/2, 3/2, 5/2,…
- ✓ Bosons are those particles which have an integer spin (0, 1, 2...).
  - All the force carrier particles are bosons w spin-1
  - Mesons are composite particles consisting a quark and an anti-quark are also meson with spin 0, 1, 2,…



Fermions vs Bosons

$$\Psi = \Psi(space) \cdot \Psi(flavour) \cdot \Psi(spin)$$

- Consider a set of two particles with the same quantum numbers, including spin, but different S_z
  - The wave function of the system is then $\psi(\vec{r}_1, S_z^1, \vec{r}_2, S_z^2) \equiv \psi(1,2)$
- If we interchange the two particles then the wave function becomes $\psi(2,1)$
  - This wave function can be symmetric or anti-symmetric wrt the initial one

$$\psi(2,1) = \begin{cases} \psi(1,2) \\ -\psi(1,2) \end{cases}$$

symmetric: Bosons

anti-symmetric: Fermions

- The wave function of the system is then given by $\psi = \frac{1}{\sqrt{2}}[\psi(1,2) + \psi(2,1)]$
  - ψ = 0 for fermions!

Pauli principle

- If two particles have the same quantum numbers, they are in the same state
- If these two particles are fermions then the wave function vanishes

A system can not exist with two or more fermions in the same state

Spin 1/2 particles

spin-up

$$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$|\uparrow\rangle = \left|\frac{1}{2}, +\frac{1}{2}\right\rangle$$

spin-down

$$\begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$|\downarrow\rangle = \left|\frac{1}{2}, -\frac{1}{2}\right\rangle$$

General representation

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \alpha \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \beta \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

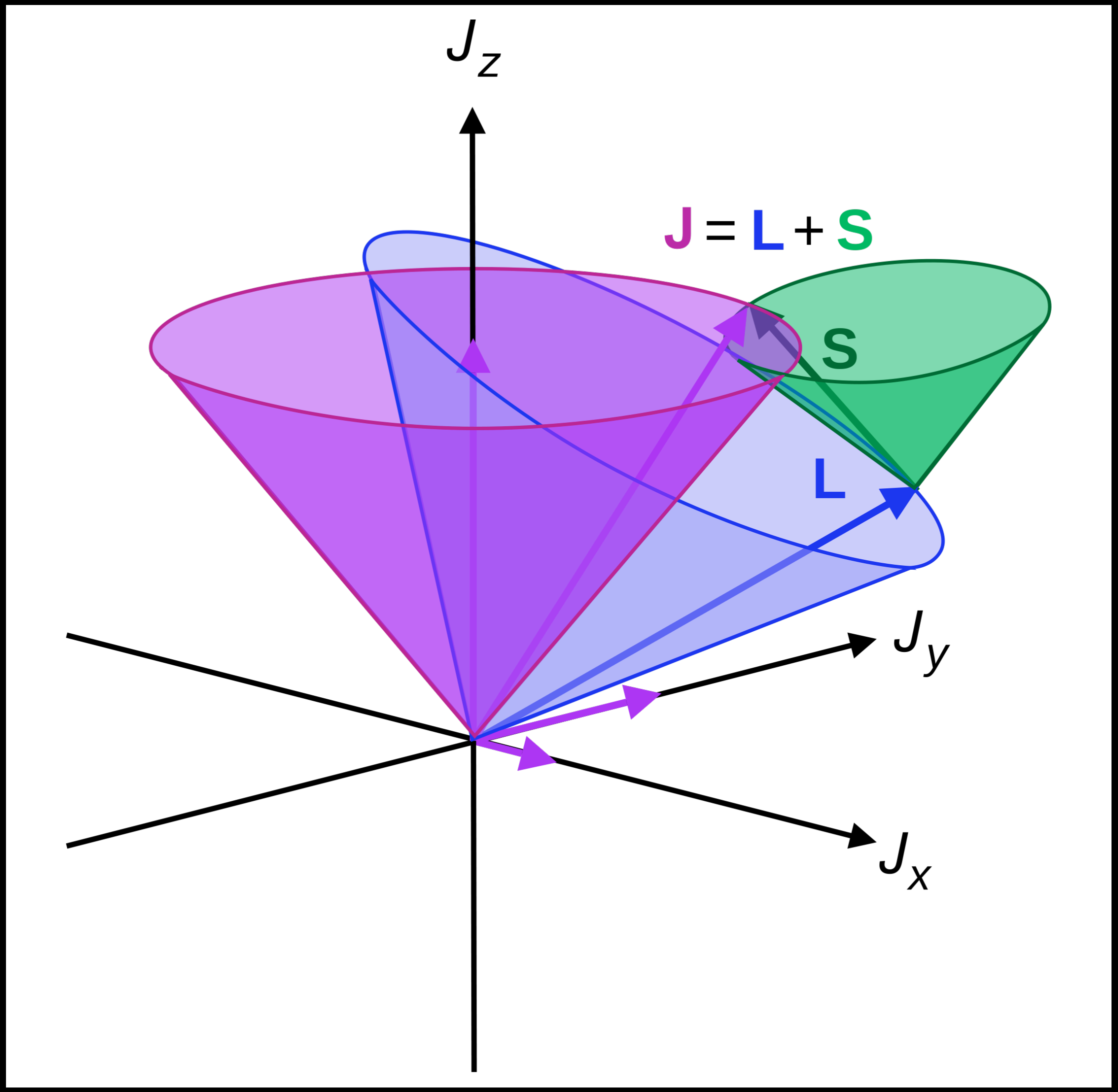
$|\alpha|^2$: probability to have s_z=+1/2
$|\beta|^2$: probability to have s_z=-1/2

Total angular momentum

$$\vec{J} = \vec{L} + \vec{S}$$

$$J^2 |\psi_{jm_j}\rangle = j(j+1)\hbar^2 |\psi_{jm_j}\rangle$$

$$J_z |\psi_{jm_j}\rangle = m_j \hbar |\psi_{jm_j}\rangle$$



Angular momentum and spin of a system

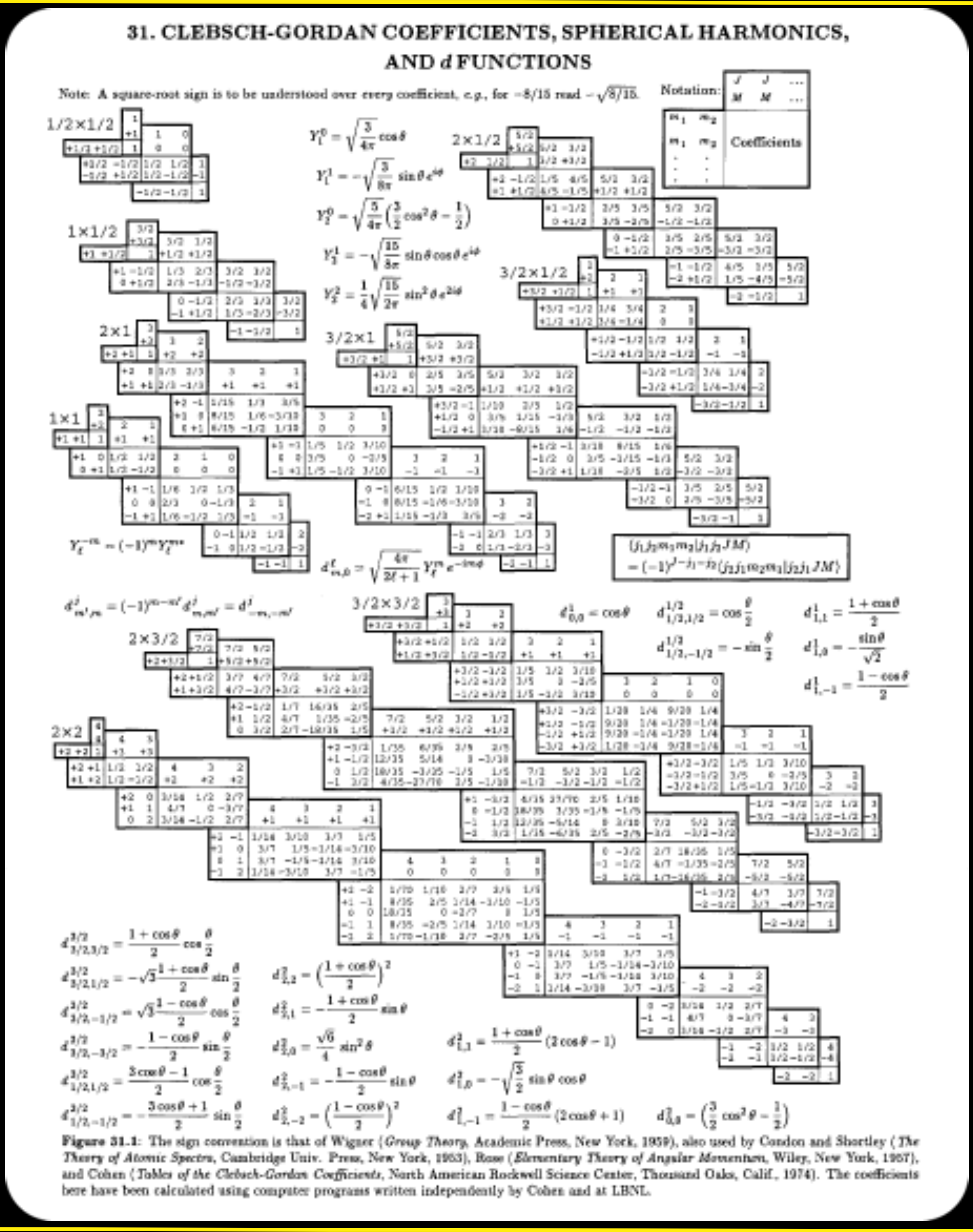
$$|s_1,m_{s1}\rangle \oplus |s_2,m_{s2}\rangle = |s,m\rangle$$

- Sz adds up $m_s = m_{s1} + m_{s2}$
- S can be anywhere between $|s_1-s_2|$ and s_1+s_2 $s = |s_1-s_2|, |s_1-s_2|+1, \ldots, s_1+s_2-1, s_1+s_2$

$$|s,m_s\rangle = \sum_{m_s=m_{s1}+m_{s2}} C^{s,s_1,s_2}_{m_s,m_{s1},m_{s2}} |s_1,m_{s1}\rangle\, |s_2,m_{s2}\rangle$$

Clebsch-Gordan coefficients

Clebsch-Gordan coefficients



31. CLEBSCH-GORDAN COEFFICIENTS, SPHERICAL HARMONICS, AND d FUNCTIONS

Note: A square-root sign is to be understood over every coefficient, e.g., for $-8/15$ read $-\sqrt{8/15}$.

Notation: J, M; m_1 m_2 – Coefficients

$$Y_1^0 = \sqrt{\frac{3}{4\pi}}\cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}}\sin\theta\, e^{i\phi}$$

$$Y_2^0 = \sqrt{\frac{5}{4\pi}}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta\, e^{i\phi}$$

$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{2i\phi}$$

$$Y_\ell^{-m} = (-1)^m Y_\ell^{m*}$$

$$d^\ell_{m,0} = \sqrt{\frac{4\pi}{2\ell+1}}\, Y_\ell^m\, e^{-im\phi}$$

$$\langle j_1 j_2 m_1 m_2 | j_1 j_2 J M\rangle = (-1)^{J-j_1-j_2}\langle j_2 j_1 m_2 m_1 | j_2 j_1 J M\rangle$$

$$d^j_{m',m} = (-1)^{m-m'} d^j_{m,m'} = d^j_{-m,-m'}$$

$$d^1_{0,0} = \cos\theta \qquad d^{1/2}_{1/2,1/2} = \cos\frac{\theta}{2} \qquad d^{1/2}_{1/2,-1/2} = -\sin\frac{\theta}{2}$$

$$d^1_{1,1} = \frac{1+\cos\theta}{2} \qquad d^1_{1,0} = -\frac{\sin\theta}{\sqrt{2}} \qquad d^1_{1,-1} = \frac{1-\cos\theta}{2}$$

$$d^{3/2}_{3/2,3/2} = \frac{1+\cos\theta}{2}\cos\frac{\theta}{2} \qquad d^{3/2}_{3/2,1/2} = -\sqrt{3}\frac{1+\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3/2}_{3/2,-1/2} = \sqrt{3}\frac{1-\cos\theta}{2}\cos\frac{\theta}{2} \qquad d^{3/2}_{3/2,-3/2} = -\frac{1-\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3/2}_{1/2,1/2} = \frac{3\cos\theta-1}{2}\cos\frac{\theta}{2} \qquad d^{3/2}_{1/2,-1/2} = -\frac{3\cos\theta+1}{2}\sin\frac{\theta}{2}$$

$$d^2_{2,2} = \left(\frac{1+\cos\theta}{2}\right)^2 \qquad d^2_{2,1} = -\frac{1+\cos\theta}{2}\sin\theta \qquad d^2_{2,0} = \frac{\sqrt{6}}{4}\sin^2\theta$$

$$d^2_{2,-1} = -\frac{1-\cos\theta}{2}\sin\theta \qquad d^2_{2,-2} = \left(\frac{1-\cos\theta}{2}\right)^2$$

$$d^2_{1,1} = \frac{1+\cos\theta}{2}(2\cos\theta-1) \qquad d^2_{1,0} = -\sqrt{\frac{3}{2}}\sin\theta\cos\theta \qquad d^2_{1,-1} = \frac{1-\cos\theta}{2}(2\cos\theta+1)$$

$$d^2_{0,0} = \left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

Figure 31.1: The sign convention is that of Wigner (*Group Theory*, Academic Press, New York, 1959), also used by Condon and Shortley (*The Theory of Atomic Spectra*, Cambridge Univ. Press, New York, 1953), Rose (*Elementary Theory of Angular Momentum*, Wiley, New York, 1957), and Cohen (*Tables of the Clebsch-Gordan Coefficients*, North American Rockwell Science Center, Thousand Oaks, Calif., 1974). The coefficients here have been calculated using computer programs written independently by Cohen and at LBNL.

Clebsch-Gordan coefficients (cont.)

1/2×1/2

m_1 m_2	J=1, M=+1	J=1, M=0	J=0, M=0	J=1, M=−1
+1/2 +1/2	1			
+1/2 −1/2		1/2	1/2	
−1/2 +1/2		1/2	−1/2	
−1/2 −1/2				1

1×1/2

m_1 m_2	J=3/2, M=+3/2	J=3/2, M=+1/2	J=1/2, M=+1/2	J=3/2, M=−1/2	J=1/2, M=−1/2	J=3/2, M=−3/2
+1 +1/2	1					
+1 −1/2		1/3	2/3			
0 +1/2		2/3	−1/3			
0 −1/2				2/3	1/3	
−1 +1/2				1/3	−2/3	
−1 −1/2						1

2×1

	3	3	2
	+3		

Y_1

Y

Y

Isospin

- Neutron and proton are quite similar apart from their charge
- Heisenberg proposed that they are regarded as the two states of the same particle
  - the nucleon
- Similar to the notation related to spin we can write p and n with a two component column matrix
- By direct analogy to spin we introduce isospin with coordinates in the isospin space:
  - I_1, I_2, I_3
  - they follow the same algebra as the components of spin
- Strong interactions are invariant under rotations in isospin space
  - Isospin is conserved
- Group theory wording:
  - Strong interactions are invariant under an internal symmetry of SU(2)

Panos.Christakoglou@nikhef.nl

Electric charge

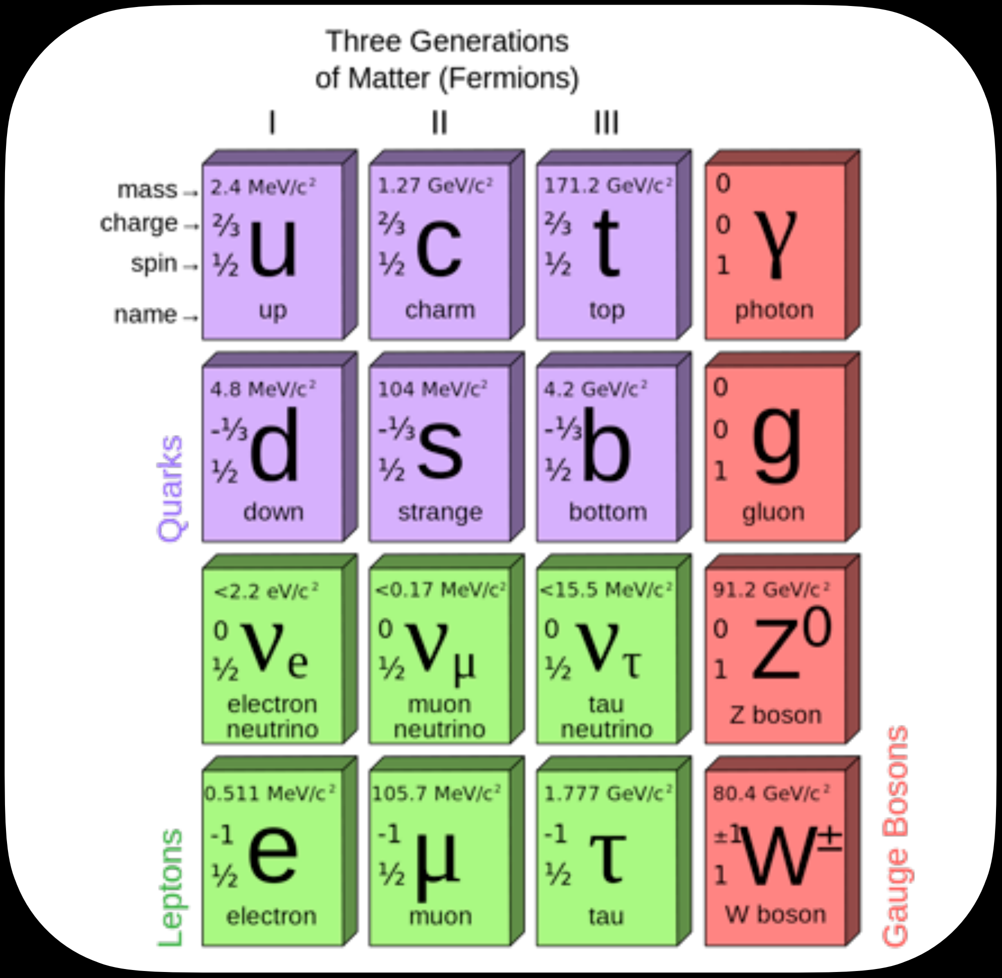
- A charged particle in the presence of an external electromagnetic field, feels a force given by

$$\vec{F} = q\left(\vec{E} + \frac{1}{c}\vec{v} \times \vec{B}\right)$$

- The total charge of a particle is not entirely characteristic of the particle itself since in nature only particles with integer multiples of the electron charge exist!

$$p(uud) \rightarrow q_p = -q_e = +1$$

$$p(uud) \rightarrow q_p = 2 \times q_u + 1 \times q_d = 2 \times \left(\frac{2}{3}\right) + 1 \times \left(-\frac{1}{3}\right) = 1$$

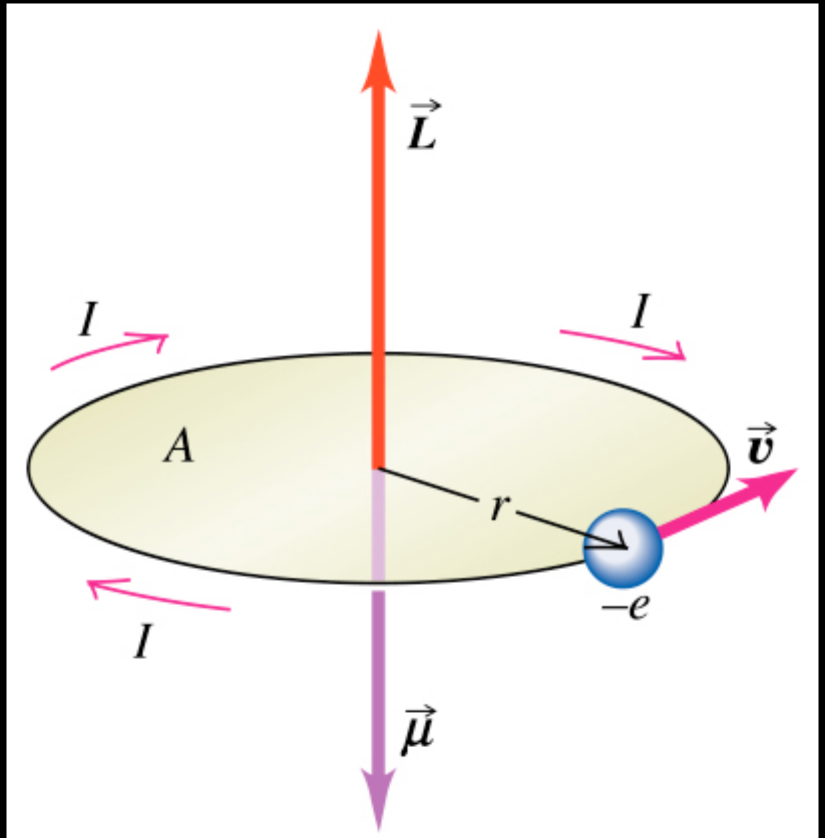


Magnetic moment

- Consider a particle with charge and spin contains currents and exhibits a magnetic dipole moment
- If the electric charge is distributed throughout a particle that also spins, it produces a magnetic moment that is given by

$$|\vec{\mu}| = \frac{1}{c} I \cdot A$$

- The direction of the magnetic moment vector is perpendicular to the plane of the loop
- Consider a particle of charge q, moving with a velocity v in a circular orbit of radius r
  - The particle revolves with a period T given by $T = \frac{2\pi r}{v}$
  - and produces a current given by $I = q\frac{v}{2\pi r}$
  - The connection between the magnetic moment and the orbital momentum is $\vec{\mu} = \frac{q}{2mc}\vec{L}$
    - the magnetic moment points to the direction of the angular momentum vector
    - the ratio of μ to L is (q/2mc) ~ the ratio of charge to mass



Magnetic moment (cont.)

- The operator of the magnetic moment is connected to the angular momentum by

$$\vec{\mu} = (const)\,\vec{J} \qquad (const) = g\left(\frac{e}{2mc}\right) \qquad \vec{\mu} = g\left(\frac{e}{2mc}\right)\vec{J}$$

- The parameter g measures the deviation of the magnetic moment from the simple value (e/2mc)

$$\vec{\mu} = g\left(\frac{e}{2mc}\right)\vec{J} = g\left(\frac{e\hbar}{2mc}\right)\frac{\vec{J}}{\hbar} = g\mu_0\frac{\vec{J}}{\hbar}$$

$$\mu_0 = \frac{e\hbar}{2mc}$$ Magneton: unit of magnetic moment

- In atomic physics and for electrons $m=m_e$ $\mu_0 \equiv \mu_B = \frac{e\hbar}{2m_e c}$ Bohr magneton

- In subatomic physics $\mu_0 \equiv \mu_N = \frac{e\hbar}{2m_p c}$ nuclear magneton

$$\mu_N \simeq 10^{-3}\mu_B$$

Magnetic moment (cont.)

- The energy levels of a particle with a magnetic moment **μ** positioned in an external magnetic field **B** are obtained from the Schrodinger equation

$$H|\psi\rangle = E|\psi\rangle$$

- The Hamiltonian H has the form

$$H = H_0 + H_{mag} = H_0 - \vec{\mu}\,\vec{B} = H_0 - \frac{g\mu_o}{\hbar}\vec{J}\,\vec{B}$$

- The spin independent Hamiltonian gives rise to the energy E_o, given by

$$H_0|\psi\rangle = E_0|\psi\rangle$$

- Assuming that the z-axis is aligned with the magnetic field

$$\vec{J}\,\vec{B} = J_z B_z = J_z B$$

- The energy values in the presence of a magnetic field are

$$E = E_o - g\mu_0 m_j B$$

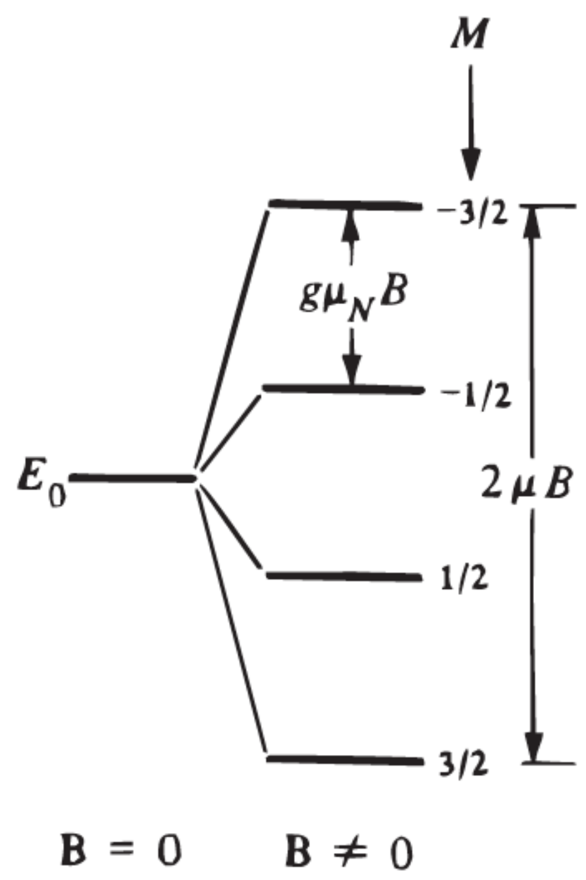
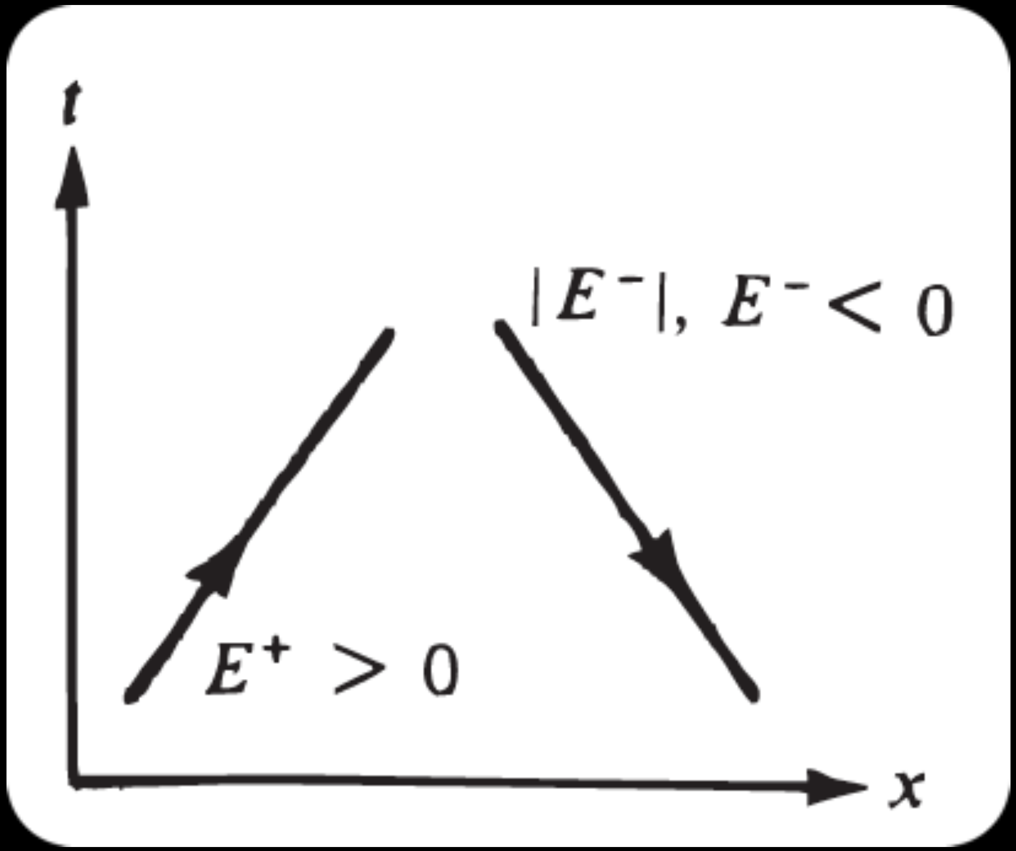
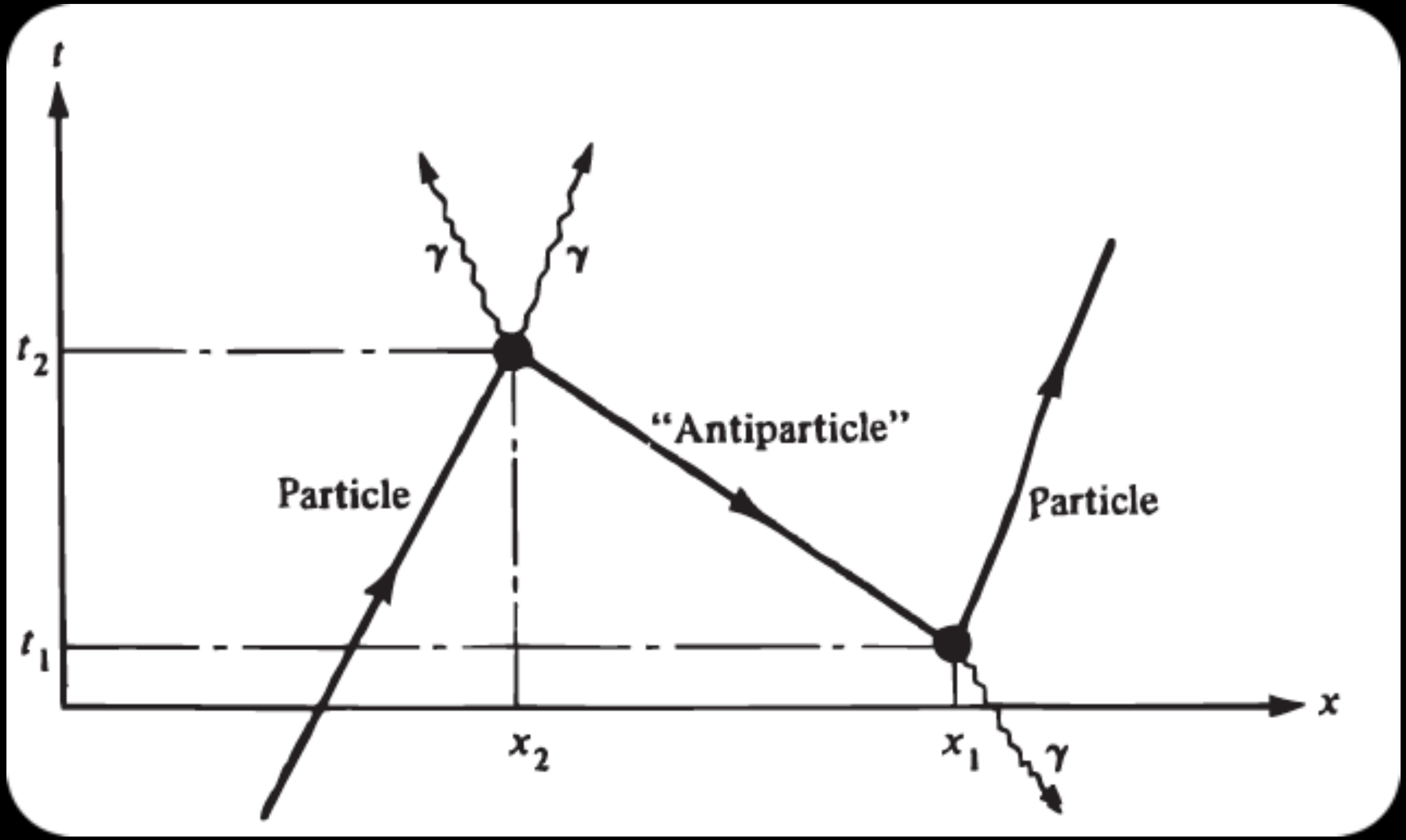


Figure 5.5: Zeeman splitting of the energy levels of a subatomic particle with spin J and g factor g in an external magnetic field $\boldsymbol{B}$. $\boldsymbol{B}$ is along the z axis, $g > 0$.

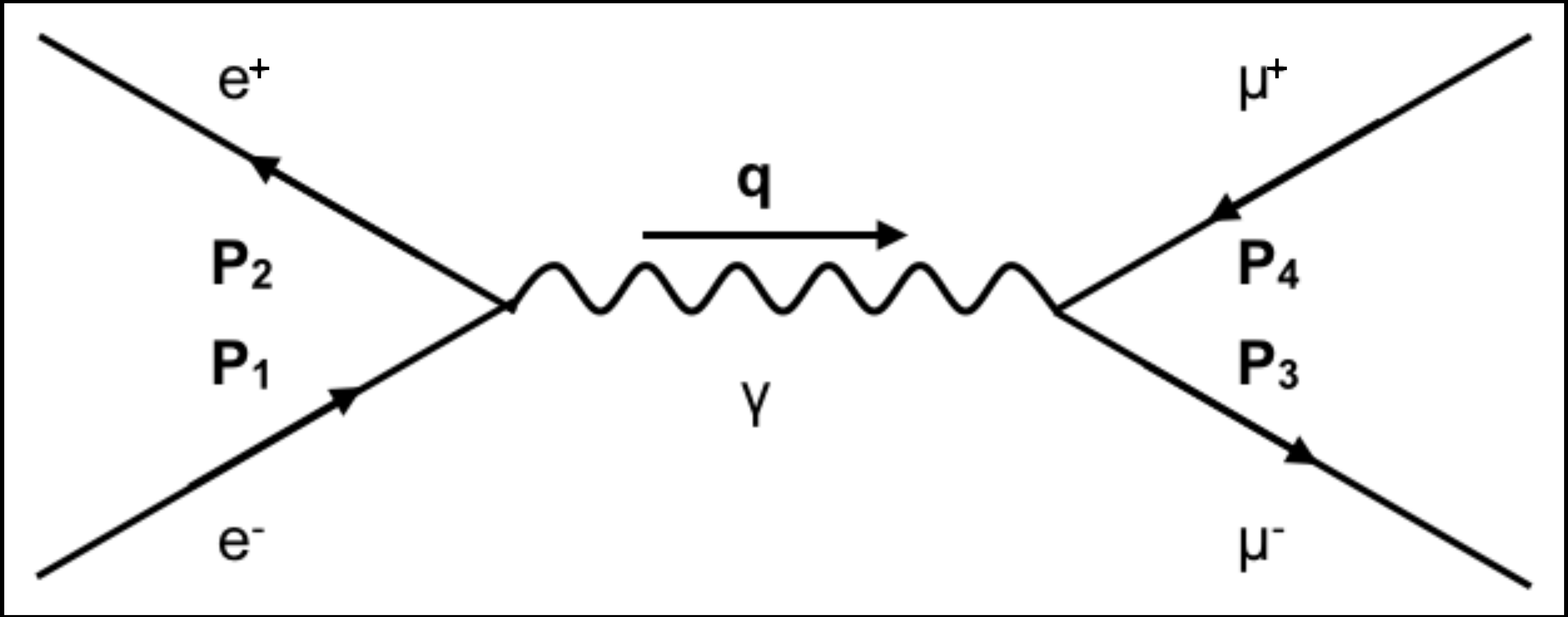
Particles vs antiparticles

$$E^{\pm} = \pm[(pc)^2 + (mc^2)^2]^{1/2}$$

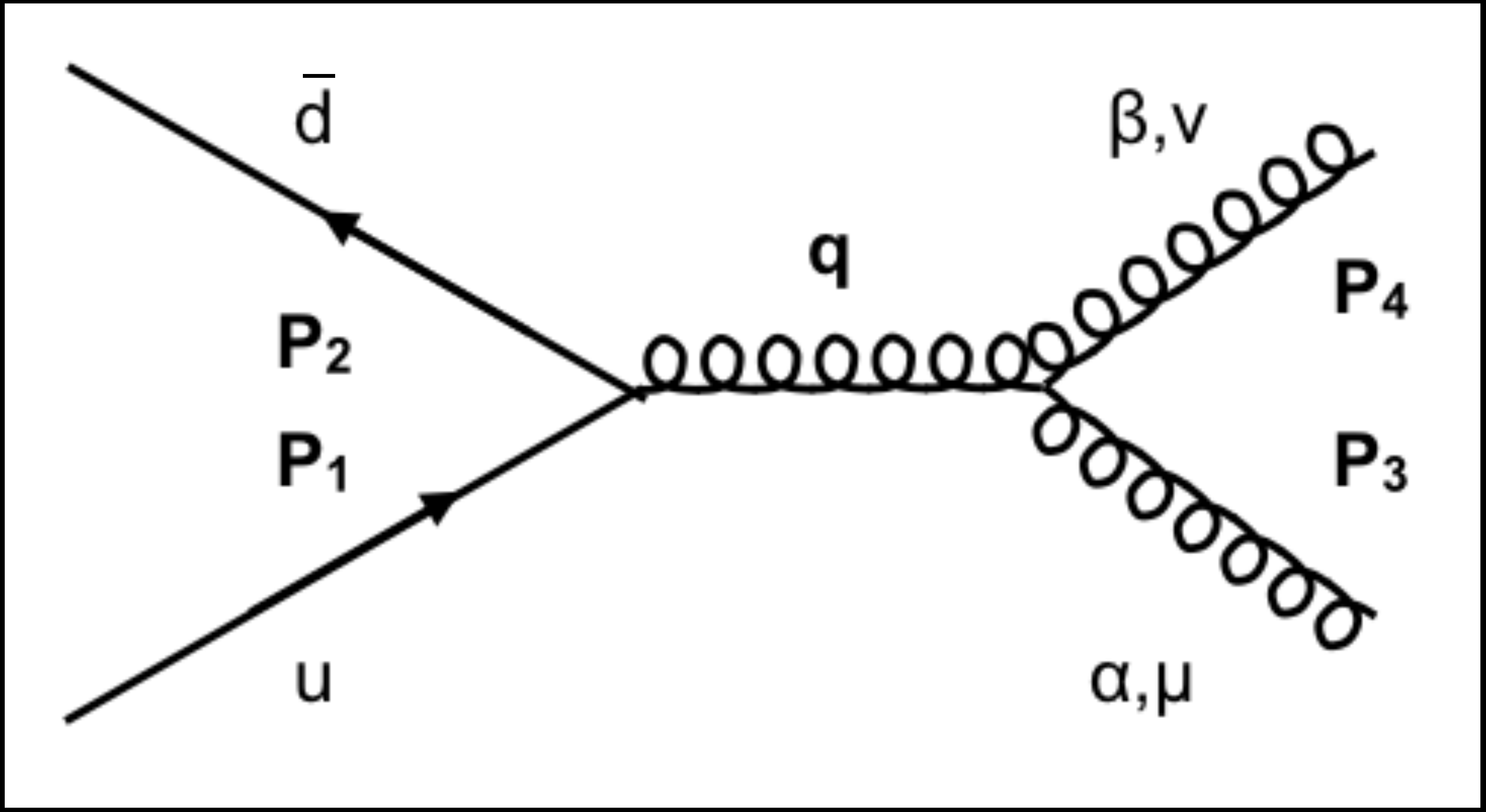




Particles vs antiparticles (cont.)

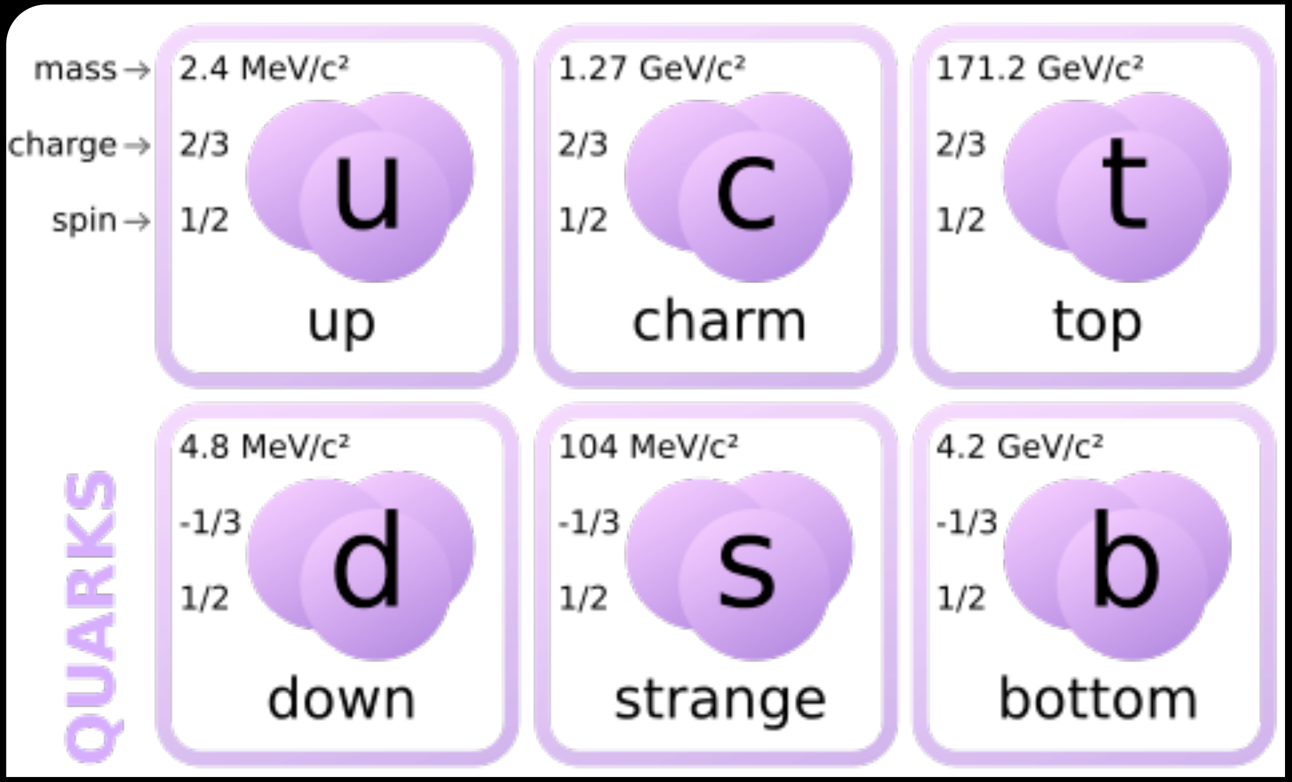


Particles vs antiparticles (cont.)



QUARK MODEL

Quarks


mass →
charge →
spin →
2.4 MeV/c²
2/3
1/2
u
up
1.27 GeV/c²
2/3
1/2
c
charm
171.2 GeV/c²
2/3
1/2
t
top
QUARKS
4.8 MeV/c²
-1/3
1/2
d
down
104 MeV/c²
-1/3
1/2
s
strange
4.2 GeV/c²
-1/3
1/2
b
bottom

Quarks

Table 15.1: Additive quantum numbers of the quarks.

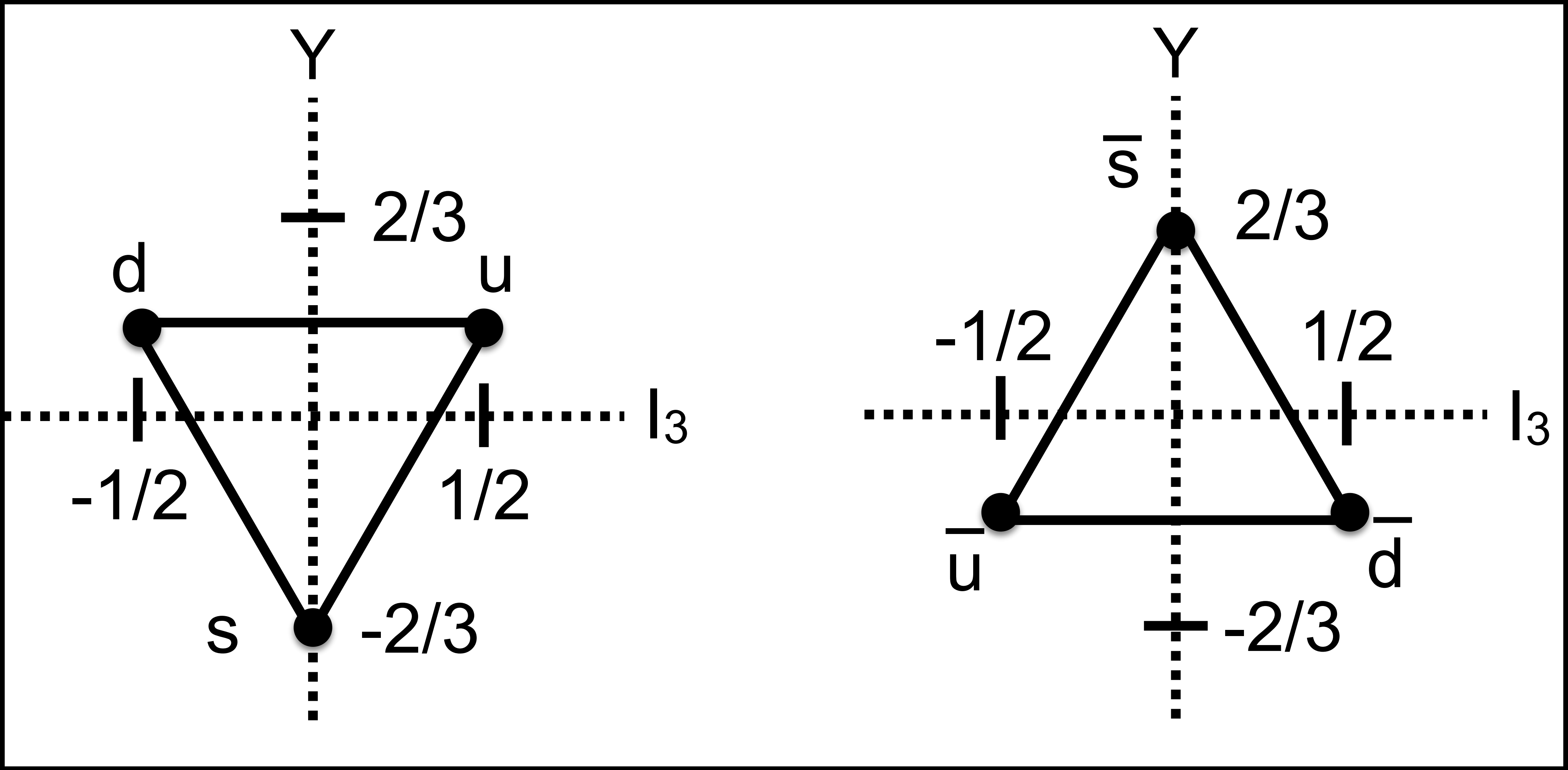
	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	$+1$	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	$+1$

Hypercharge

$$Y = S + C + B + T + BN$$

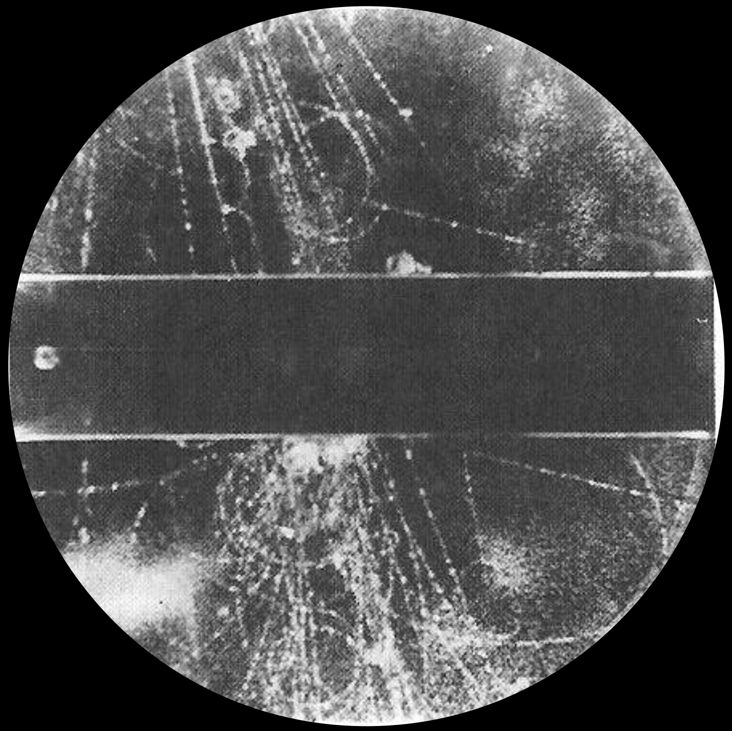
Quark model

- ✓ A pattern for classifying hadrons based on their quantum numbers
- ✓ All mesons are made of a combination of a quark and an anti-quark
- ✓ All baryons are made of a combination of three quarks
- ✓ The basic representation of SU(3) is a triplet

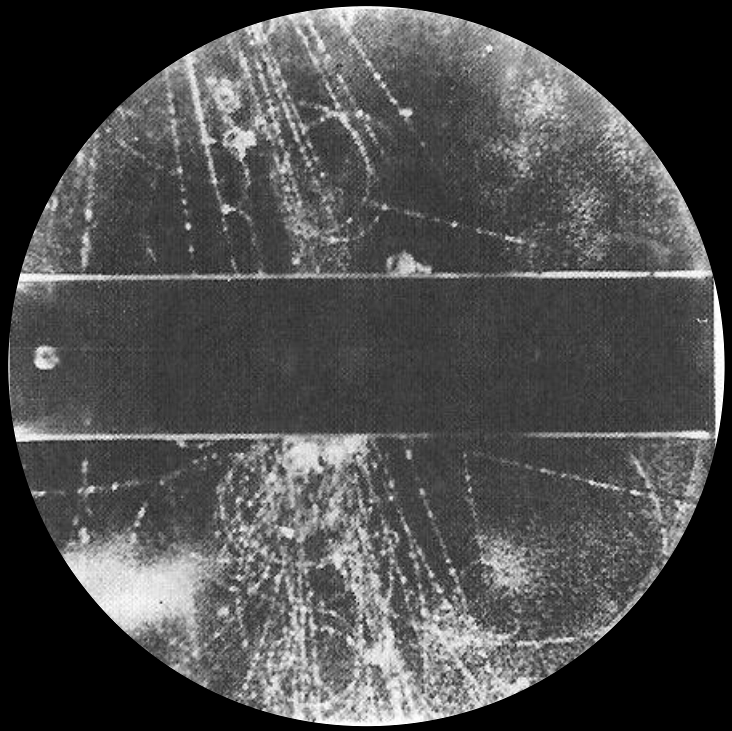


Discovery of strange particles

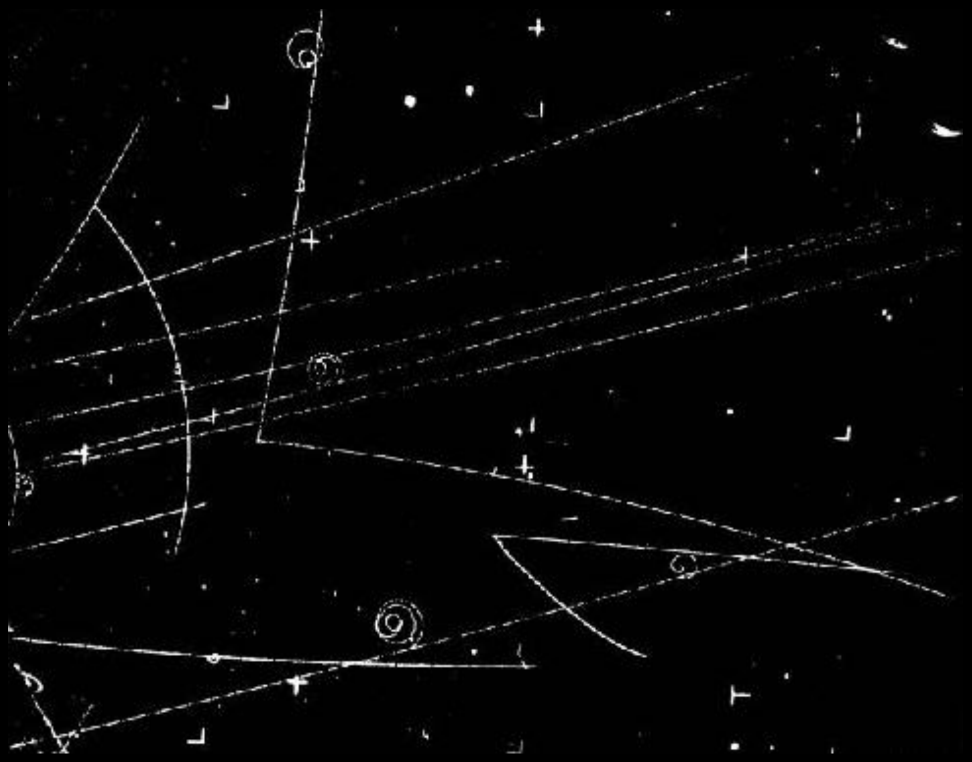
- Particles that had long life-time (typically 10^{-10}sec)
- Particles with large production cross-section (10^{-27}cm^2)
- Why are these particles behaving so strange???



Discovery of strange particles (cont.)

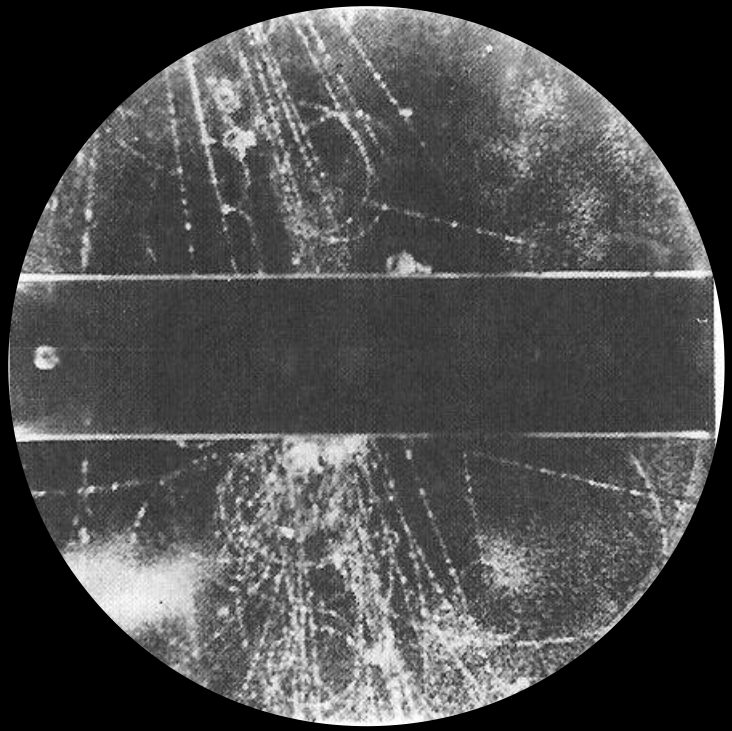


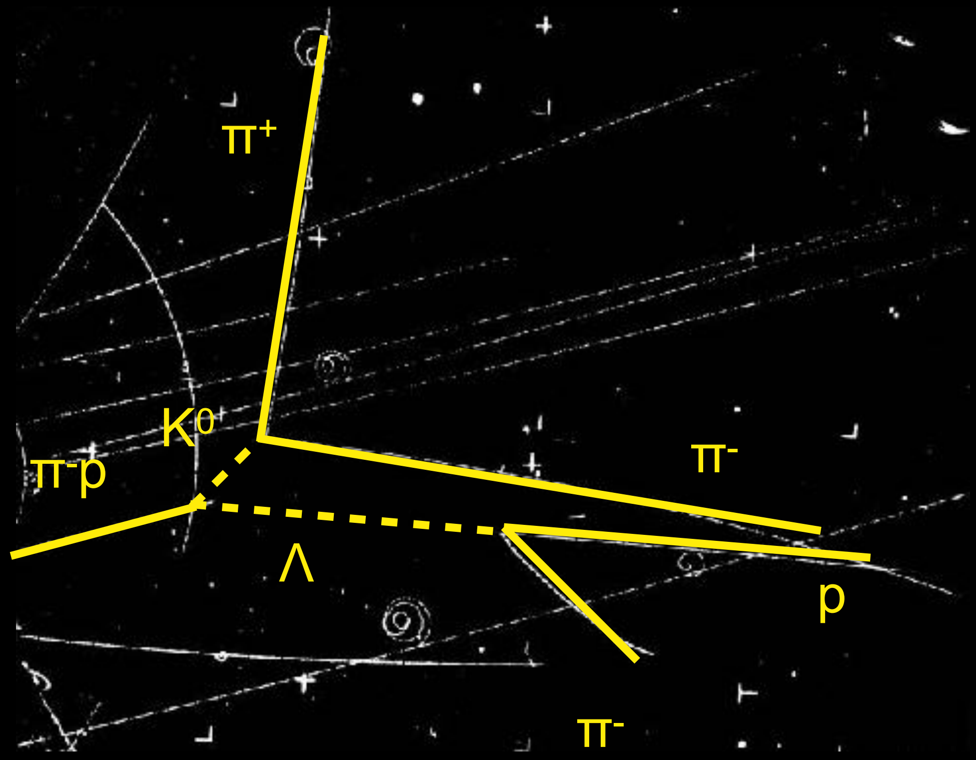
- ✓ Particles that had long life-time (typically 10^{-10}sec)
- ✓ Particles with large production cross-section (10^{-27}cm^2)
- ✓ Why are these particles behaving so strange???



Discovery of strange particles (cont.)

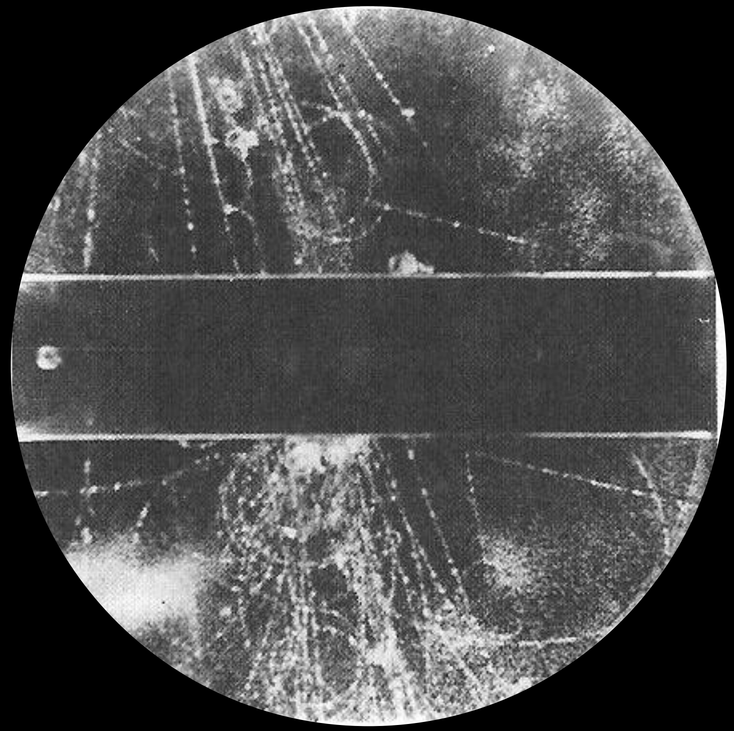
- ✓ Particles that had long life-time (typically 10^{-10}sec)
- ✓ Particles with large production cross-section ($10^{-27}cm^2$)
- ✓ Why are these particles behaving so strange???

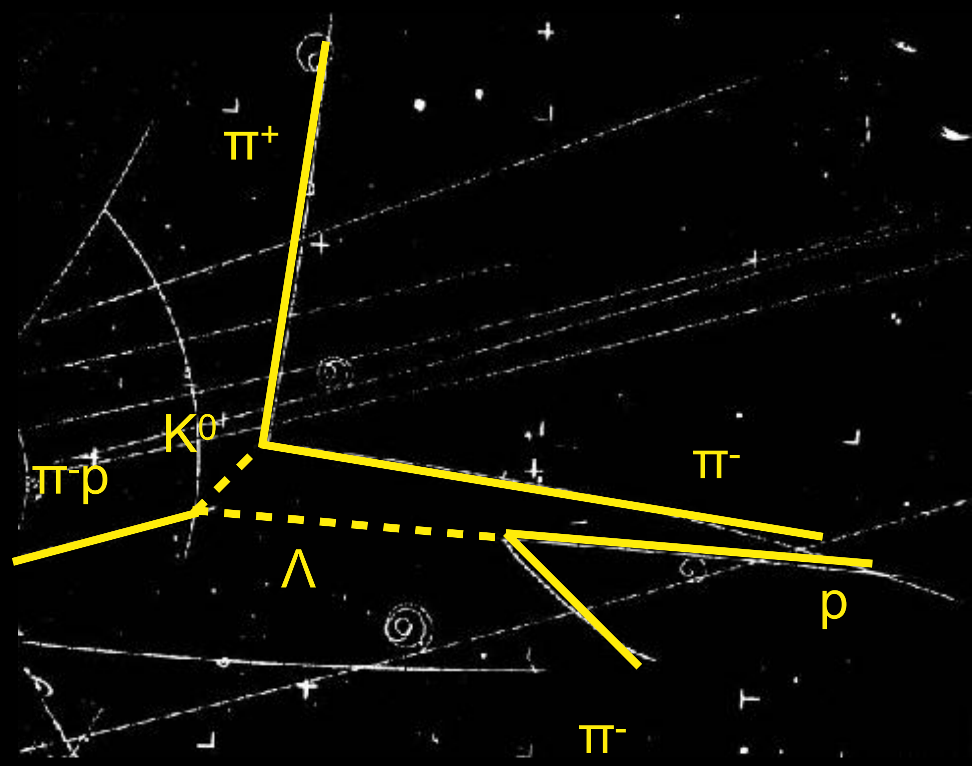




Discovery of strange particles (cont.)

- Particles that had long life-time (typically 10^{-10}sec)
- Particles with large production cross-section (10^{-27}cm^2)
- Why are these particles behaving so strange???





- New quantum number: **strangeness**
- Conserved in the strong and electromagnetic interactions
  - Particles with S=+1 and S=-1 produced simultaneously
- Not conserved in the weak interactions

Mesons

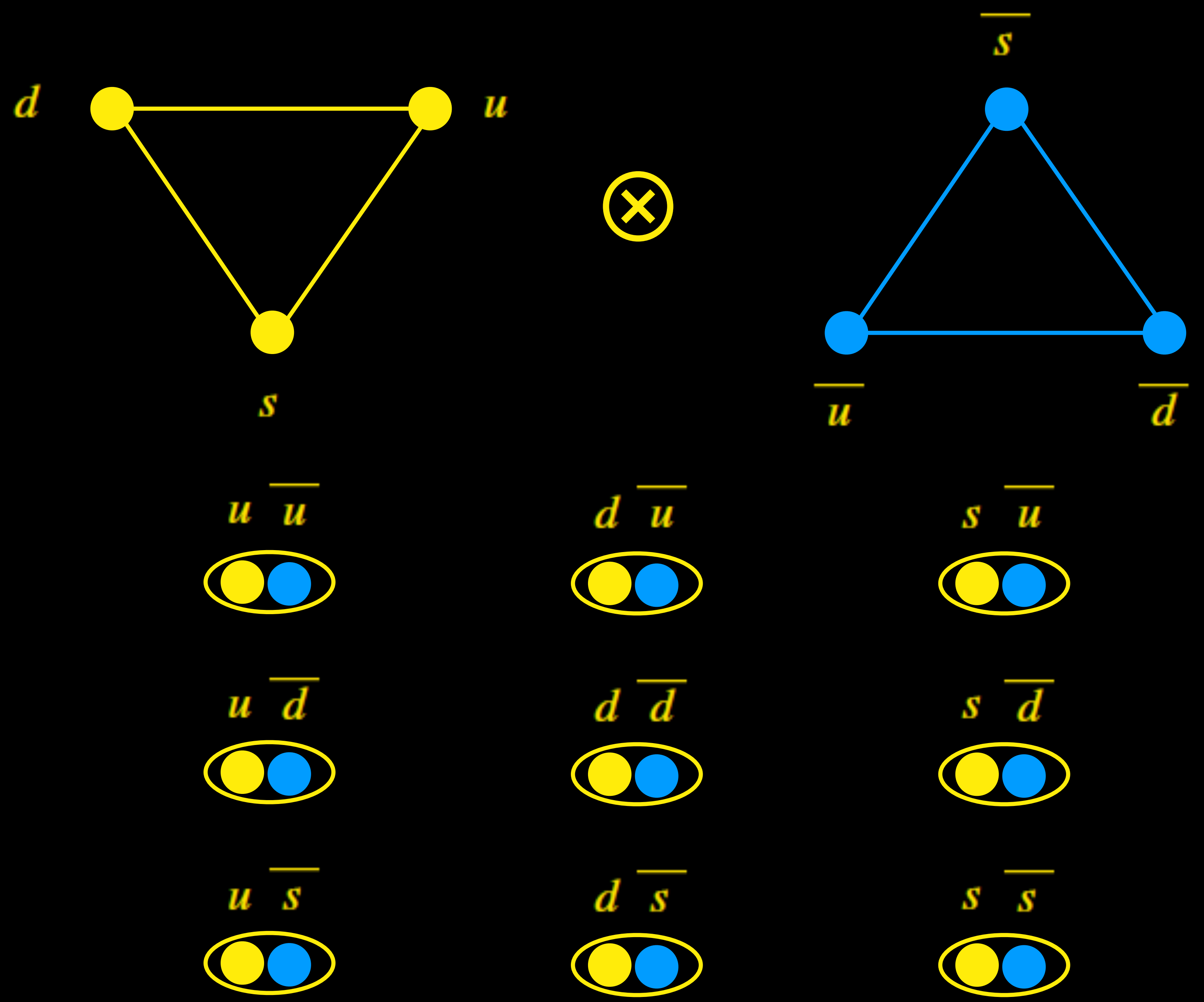
- Mesons are part of the hadron family, together with the baryons
- Mesons are particles composed of a combination of a quark and an antiquark
- Since they consist of an even combination of subatomic particles with spin 1/2, mesons are bosons

Particle	Mass (MeV/c^2)	Charge (e)	Mean Life (sec)
π^0	135.0	0	0.84×10^{-16}
$\pi^\pm$	139.6	$+, -$	2.60×10^{-8}
$K^\pm$	493.7	$+, -$	1.24×10^{-8}
K^0	497.7	0	Complicated
η	547.8	0	5.1×10^{-19}
$D^\pm$	1869	$+, -$	1.0×10^{-12}
D^0	1865	0	4.1×10^{-13}
$B^\pm$	5279	$+, -$	$\sim 1.7 \times 10^{-12}$
B^0	5279	0	$\sim 1.5 \times 10^{-12}$

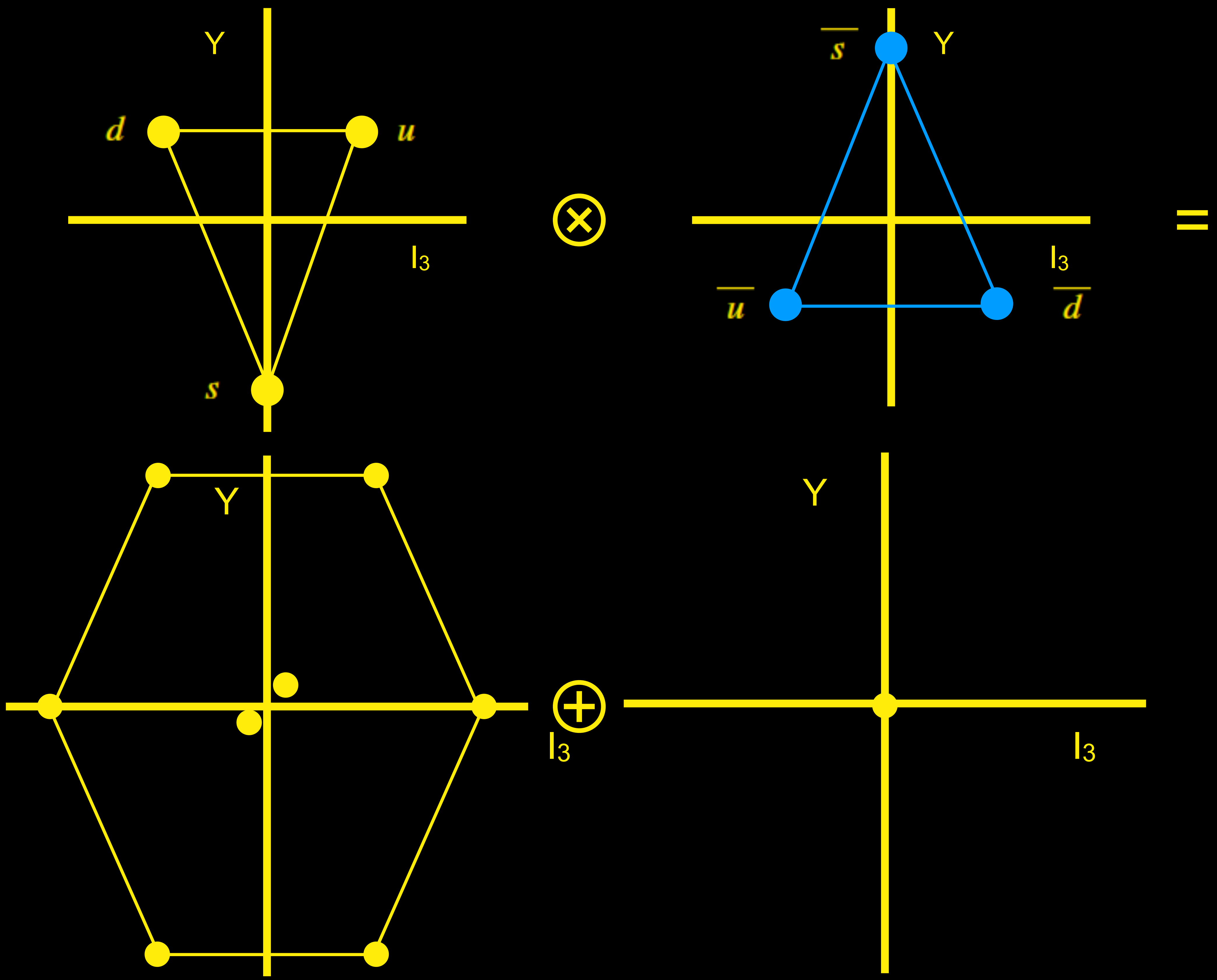
Panos.Christakoglou@nikhef.nl

Mesons (cont.)

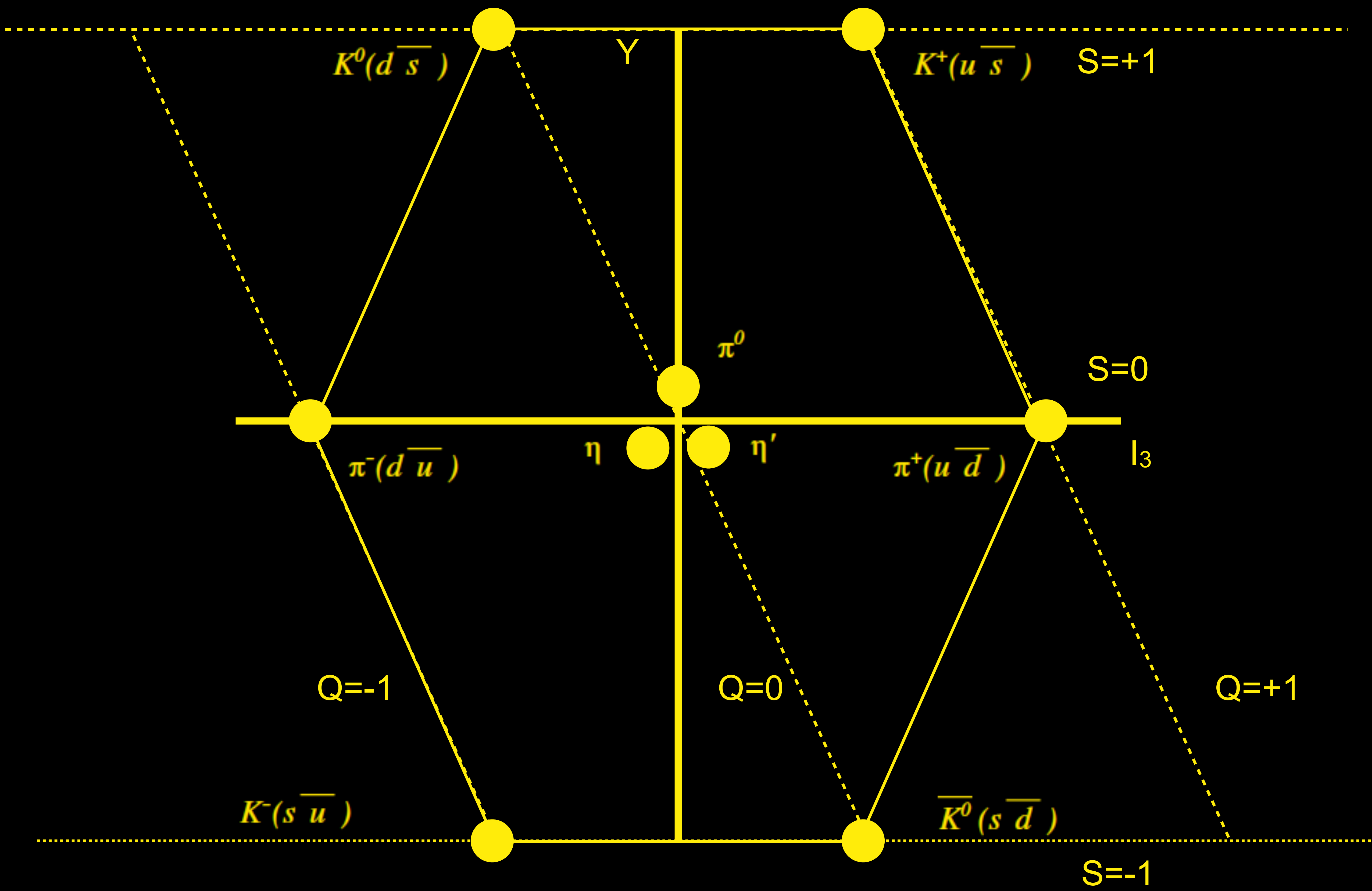
- Consider the three lightest (anti)quarks: u(bar), d(bar), s(bar)
- Which mesons can one form?



Mesons (cont.)



Mesons (cont.)



Panos.Christakoglou@nikhef.nl

(some of the) Mesons in the quark model

Table 15.2: Suggested $q\overline{q}$ quark-model assignments for some of the observed light mesons. Mesons in bold face are included in the Meson Summary Table. The wave functions f and f' are given in the text. The singlet-octet mixing angles from the quadratic and linear mass formulae are also given for the well established nonets. The classification of the 0^{++} mesons is tentative: The light scalars $a_0(980)$, $f_0(980)$, and $f_0(500)$ are often considered as meson-meson resonances or four-quark states, and are omitted from the table. Not shown either is the $f_0(1500)$ which is hard to accommodate in the nonet. The isoscalar 0^{++} mesons are expected to mix. See the "Note on Scalar Mesons" in the Meson Listings for details and alternative schemes.

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\overline{d}$, $\overline{u}d$, $\frac{1}{\sqrt{2}}(d\overline{d}-u\overline{u})$	I = $\frac{1}{2}$ $u\overline{s}$, $d\overline{s}$; $\overline{d}s$, $-\overline{u}s$	I = 0 f'	I = 0 f	θ_{quad} [°]	θ_{lin} [°]
$1\,^1S_0$	0^{-+}	$\boldsymbol{\pi}$	$\boldsymbol{K}$	$\boldsymbol{\eta}$	$\boldsymbol{\eta'(958)}$	−11.4	−24.5
$1\,^3S_1$	1^{--}	$\boldsymbol{\rho(770)}$	$\boldsymbol{K^*(892)}$	$\boldsymbol{\phi(1020)}$	$\boldsymbol{\omega(782)}$	39.1	36.4
$1\,^1P_1$	1^{+-}	$\boldsymbol{b_1(1235)}$	$\boldsymbol{K_{1B}}^\dagger$	$h_1(1380)$	$\boldsymbol{h_1(1170)}$		
$1\,^3P_0$	0^{++}	$\boldsymbol{a_0(1450)}$	$\boldsymbol{K_0^*(1430)}$	$\boldsymbol{f_0(1710)}$	$\boldsymbol{f_0(1370)}$		
$1\,^3P_1$	1^{++}	$\boldsymbol{a_1(1260)}$	$\boldsymbol{K_{1A}}^\dagger$	$\boldsymbol{f_1(1420)}$	$\boldsymbol{f_1(1285)}$		
$1\,^3P_2$	2^{++}	$\boldsymbol{a_2(1320)}$	$\boldsymbol{K_2^*(1430)}$	$\boldsymbol{f_2'(1525)}$	$\boldsymbol{f_2(1270)}$	32.1	30.5
$1\,^1D_2$	2^{-+}	$\boldsymbol{\pi_2(1670)}$	$\boldsymbol{K_2(1770)}^\dagger$	$\eta_2(1870)$	$\boldsymbol{\eta_2(1645)}$		
$1\,^3D_1$	1^{--}	$\boldsymbol{\rho(1700)}$	$\boldsymbol{K^*(1680)}$		$\boldsymbol{\omega(1650)}$		
$1\,^3D_2$	2^{--}		$\boldsymbol{K_2(1820)}$				
$1\,^3D_3$	3^{--}	$\boldsymbol{\rho_3(1690)}$	$\boldsymbol{K_3^*(1780)}$	$\boldsymbol{\phi_3(1850)}$	$\boldsymbol{\omega_3(1670)}$	31.8	30.8
$1\,^3F_4$	4^{++}	$\boldsymbol{a_4(2040)}$	$\boldsymbol{K_4^*(2045)}$		$\boldsymbol{f_4(2050)}$		
$1\,^3G_5$	5^{--}	$\rho_5(2350)$	$K_5^*(2380)$				
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		
$2\,^1S_0$	0^{-+}	$\boldsymbol{\pi(1300)}$	$K(1460)$	$\boldsymbol{\eta(1475)}$	$\boldsymbol{\eta(1295)}$		
$2\,^3S_1$	1^{--}	$\boldsymbol{\rho(1450)}$	$\boldsymbol{K^*(1410)}$	$\boldsymbol{\phi(1680)}$	$\boldsymbol{\omega(1420)}$		

† The $1^{+\pm}$ and $2^{-\pm}$ isospin $\frac{1}{2}$ states mix. In particular, the K_{1A} and K_{1B} are nearly equal (45°) mixtures of the $K_1(1270)$ and $K_1(1400)$. The physical vector mesons listed under 1^3D_1 and 2^3S_1 may be mixtures of 1^3D_1 and 2^3S_1, or even have hybrid components.

Mesons categories

- A meson contains a combination of a quark and an antiquark
  - The spin of a meson can be either 0 or 1
  - The orbital angular momentum and thus the total angular momentum can take many different values

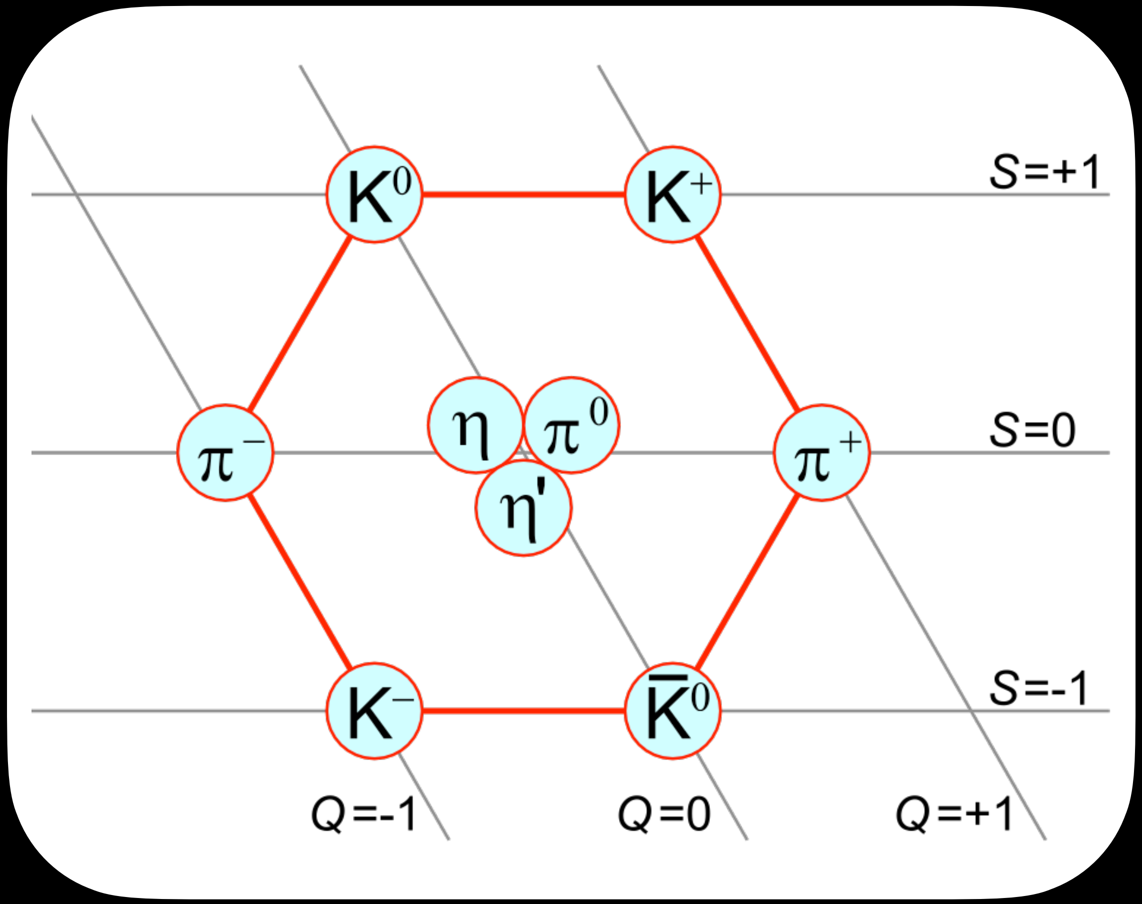
	S	L	J	$P \sim (-1)^{l+1}$	J^P
Pseudoscalar	0	0	0	-	0^-
Vector	1	0	1	-	1^-
Scalar	0	1	1	+	0^+
Pseudovector	1	1	1	+	1^+
Tensor	1	1	2	+	2^+

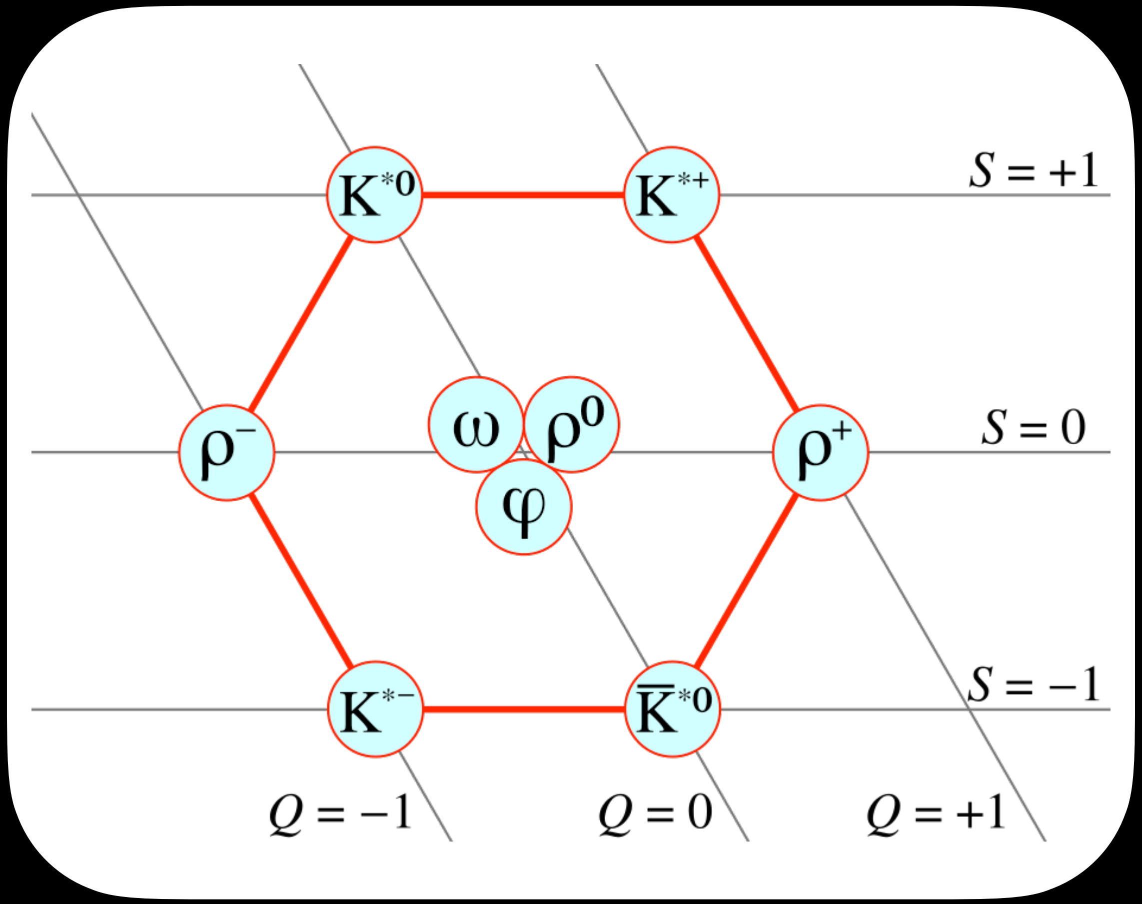
Panos.Christakoglou@nikhef.nl

Mesons categories (cont.)

Pseudoscalar mesons:
s = 0 and l = 0

Vector mesons:
s = 1 and l = 0





for meson junkies:

http://pdg.lbl.gov/2014/tables/rpp2014-qtab-mesons.pdf

(some of the) Mesons in the quark model (cont.)

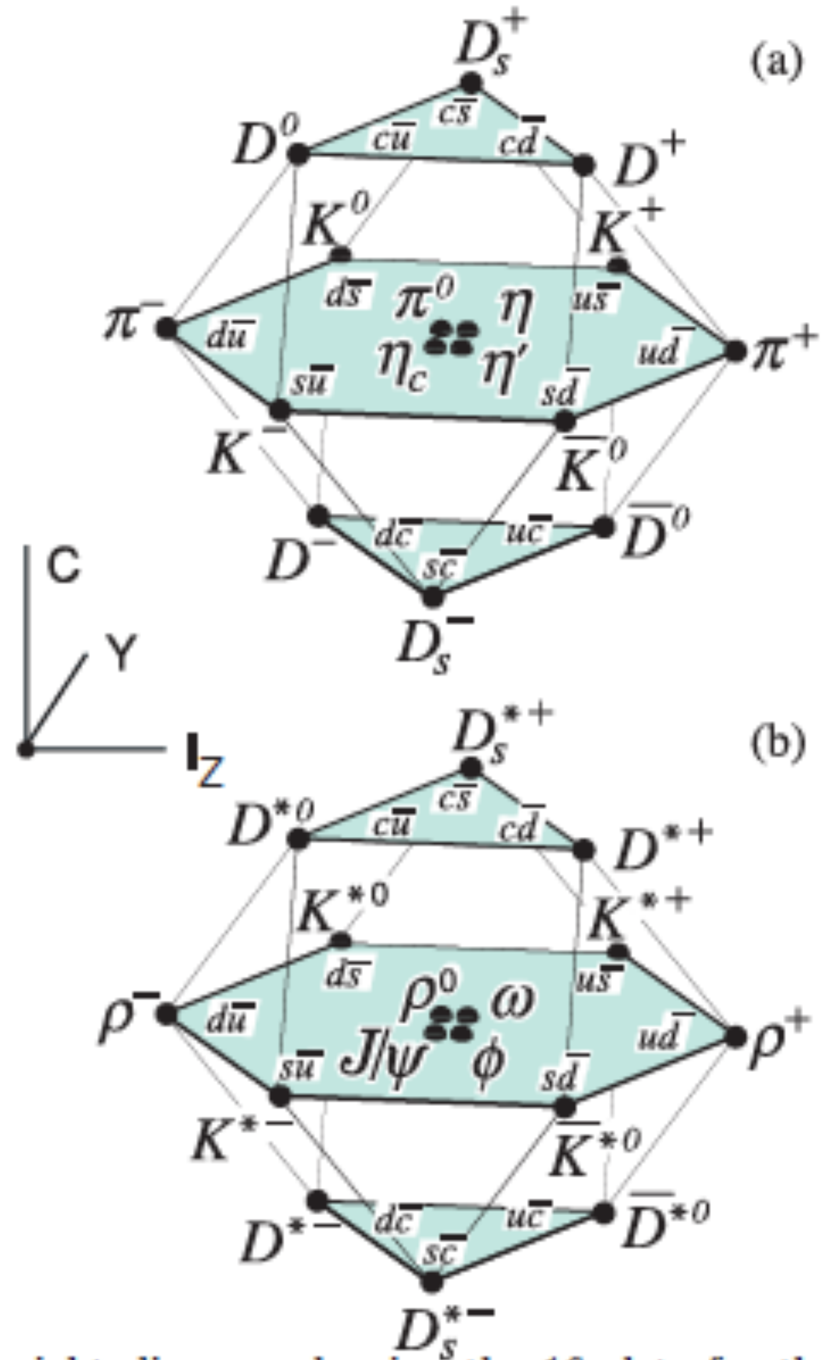


Figure 15.1: SU(4) weight diagram showing the 16-plets for the pseudoscalar (a) and vector mesons (b) made of the u, d, s, and c quarks as a function of isospin I_z, charm C, and hypercharge $Y = \mathcal{B} + S - \frac{C}{3}$. The nonets of light mesons occupy the central planes to which the $c\bar{c}$ states have been added.

Baryons

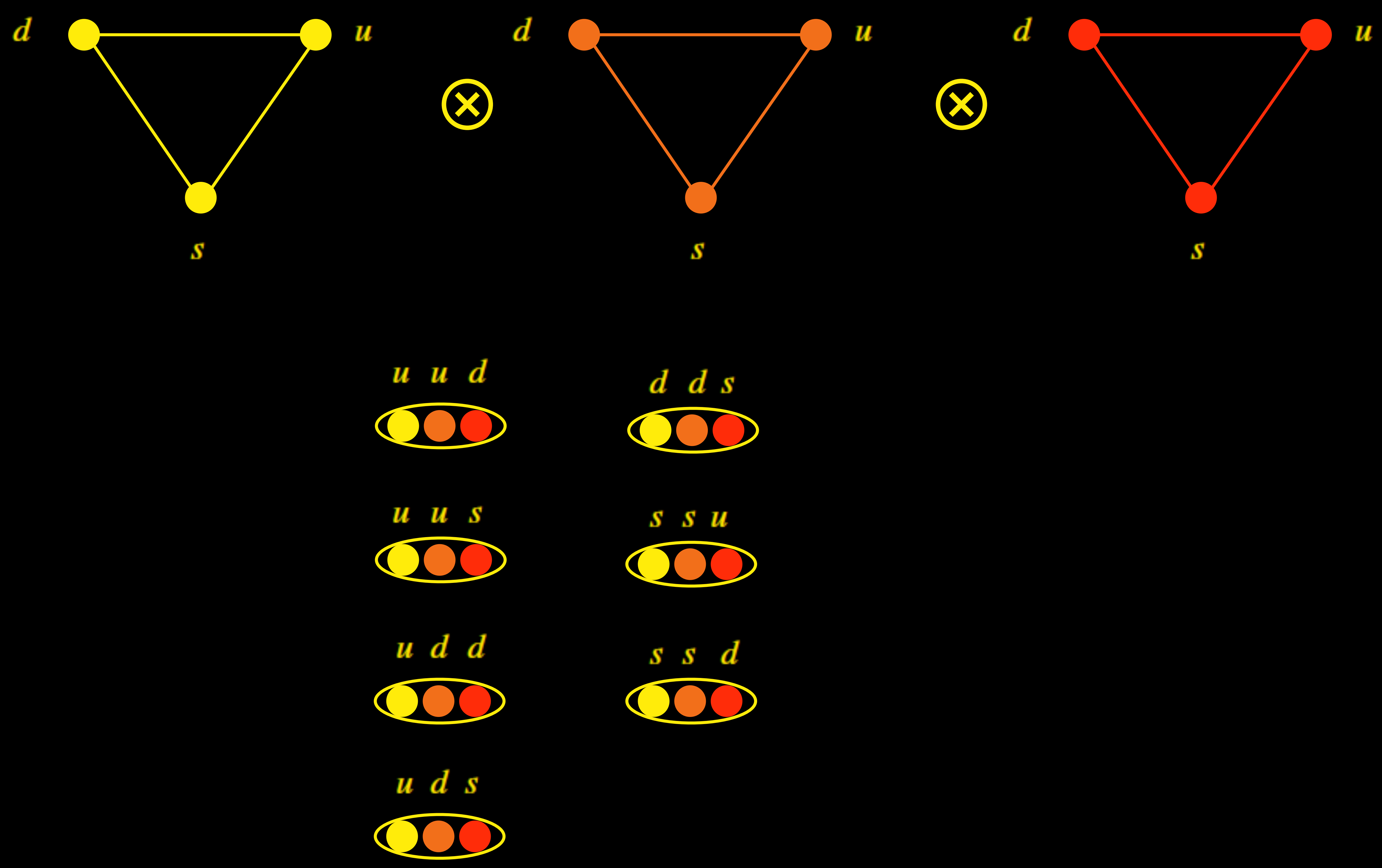
- Baryons are also part of the hadron family
- Baryons are particles composed of a combination of three quarks
- Inversely, particles consisting of three antiquarks are called anti baryons
- Since they consist of an odd combination of subatomic particles with spin 1/2, baryons are fermions

Example Baryons (qq) and AntiBaryons $(\bar{q}\,\bar{q}\,\bar{q})$

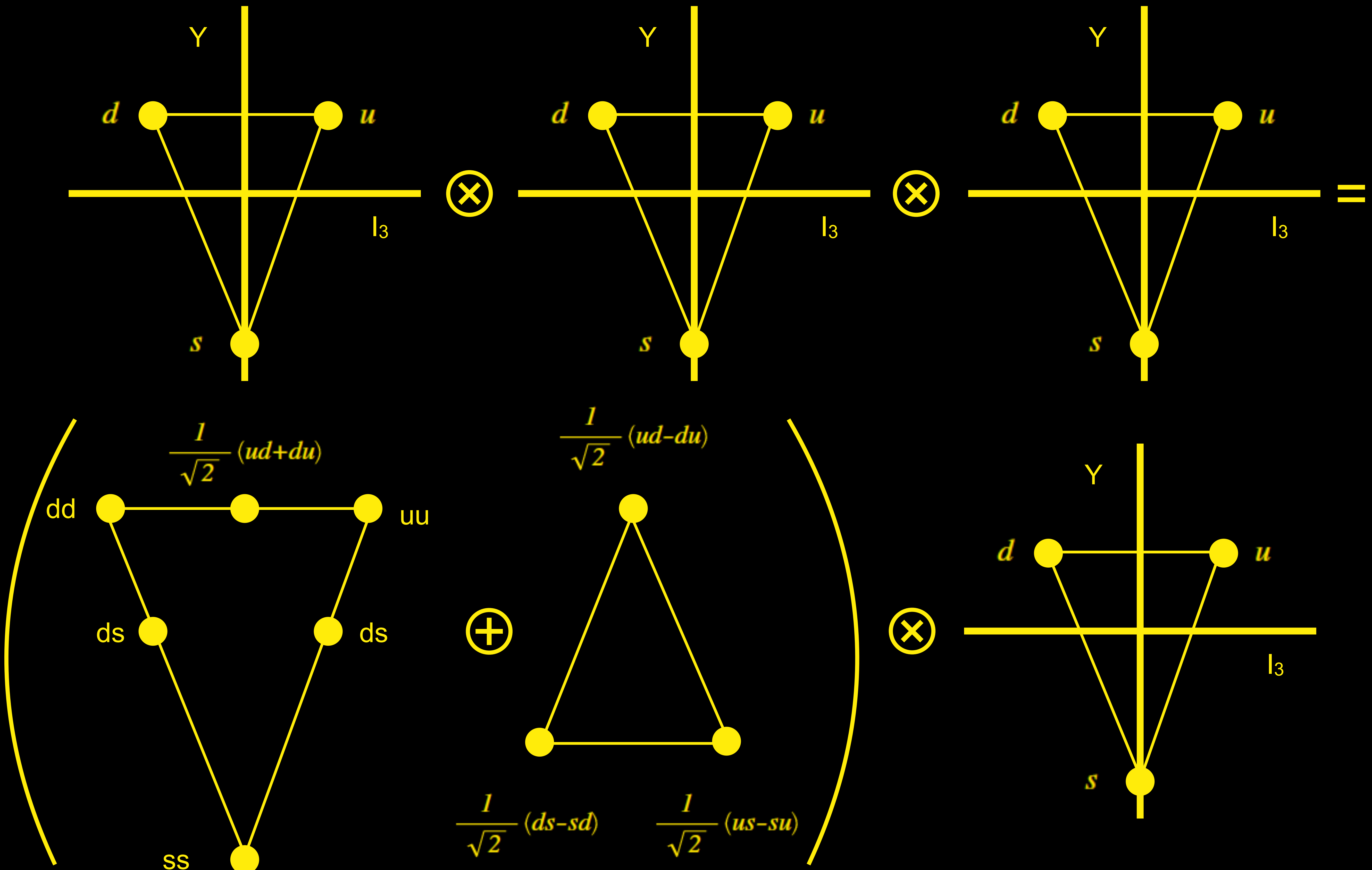
Symbol	Name	Quark Content	Chg	Mass GeV/c^2	Spin
p	proton	*uud*	$+e$	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\,\bar{u}\,\bar{d}$	$-e$	0.938	1/2
n	neutron	*udd*	0	0.940	1/2
Λ	lambda	*uds*	0	1.116	1/2
Δ^{++}	delta++	*u u u*	$+2e$	1.232	3/2
Ω^-	omega-	*s s s*	$-e$	1.672	3/2

Panos.Christakoglou@nikhef.nl

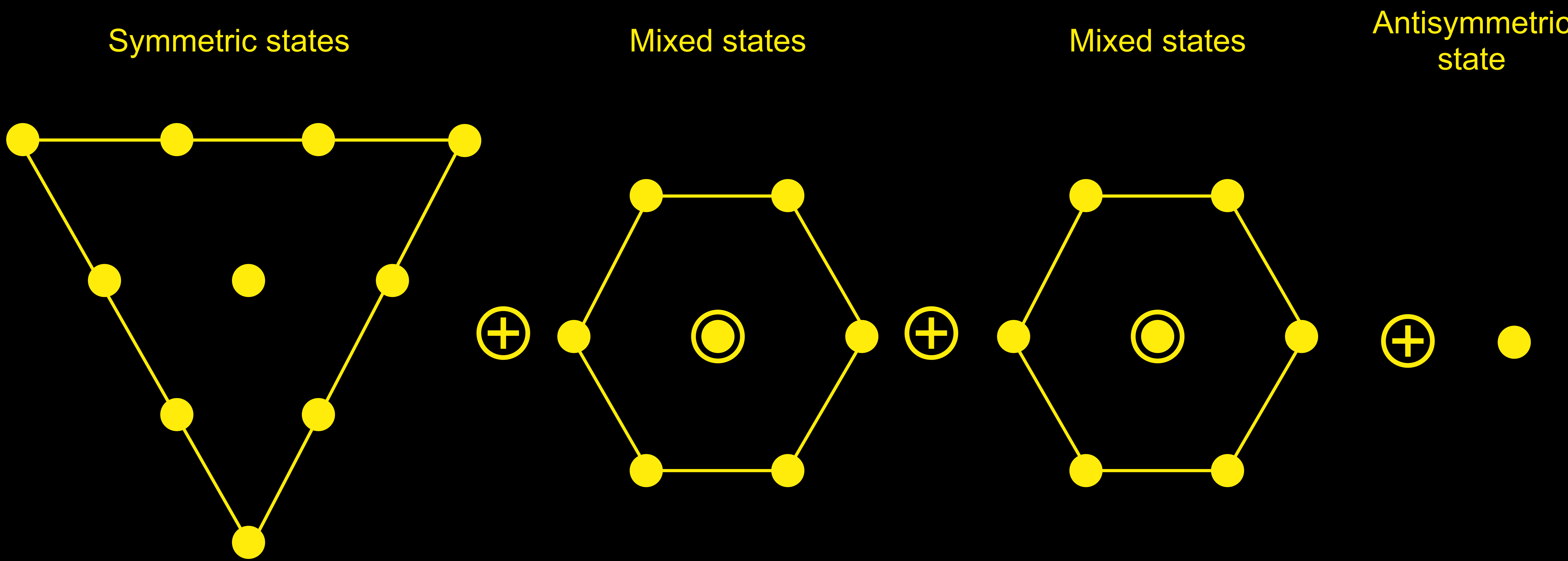
Baryons (cont.)



Baryons (cont.)



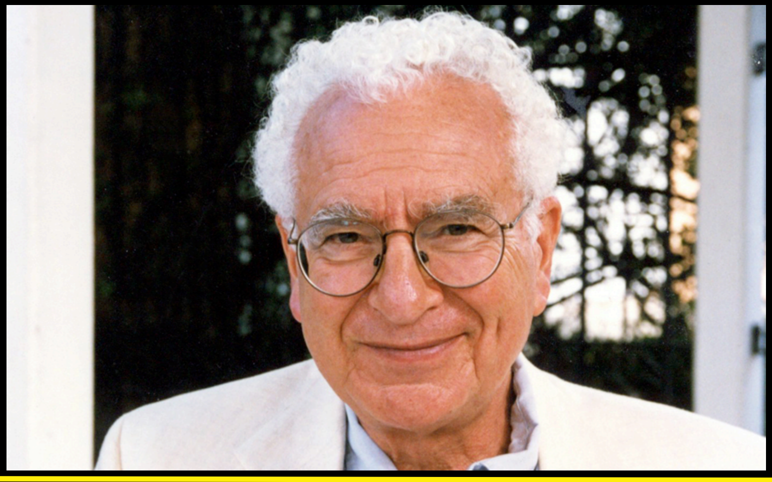
Baryons (cont.)



Strange baryons: baryon octet

Particle	Mass (MeV)	Strangeness
p	938.3	0
n	939.6	0
Λ	1115.6	-1
Σ^+	1189.4	-1
Σ^0	1192.6	-1
Σ^-	1197.4	-1
Ξ^0	1314.9	-2
Ξ^-	1321.3	-2

- ✓ Murray Gell-Mann "The eight-fold way" in 1961



Nobel prize in physics 1969

The Nobel Prize in Physics 1969
Murray Gell-Mann

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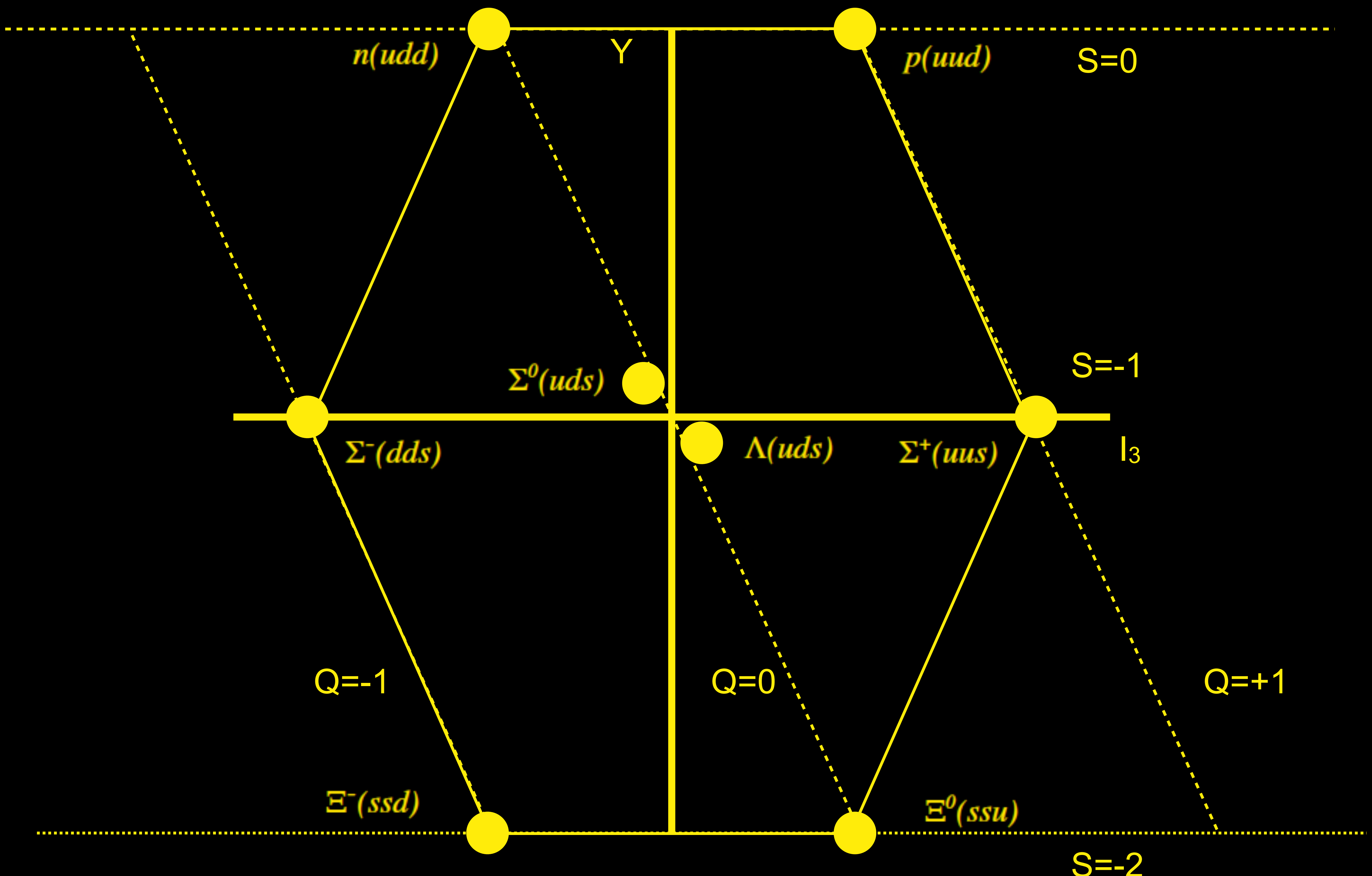
The Nobel Prize in Physics 1969

Murray Gell-Mann
Prize share: 1/1

The Nobel Prize in Physics 1969 was awarded to Murray Gell-Mann *"for his contributions and discoveries concerning the classification of elementary particles and their interactions".*

Nikhef

Baryons (cont.)



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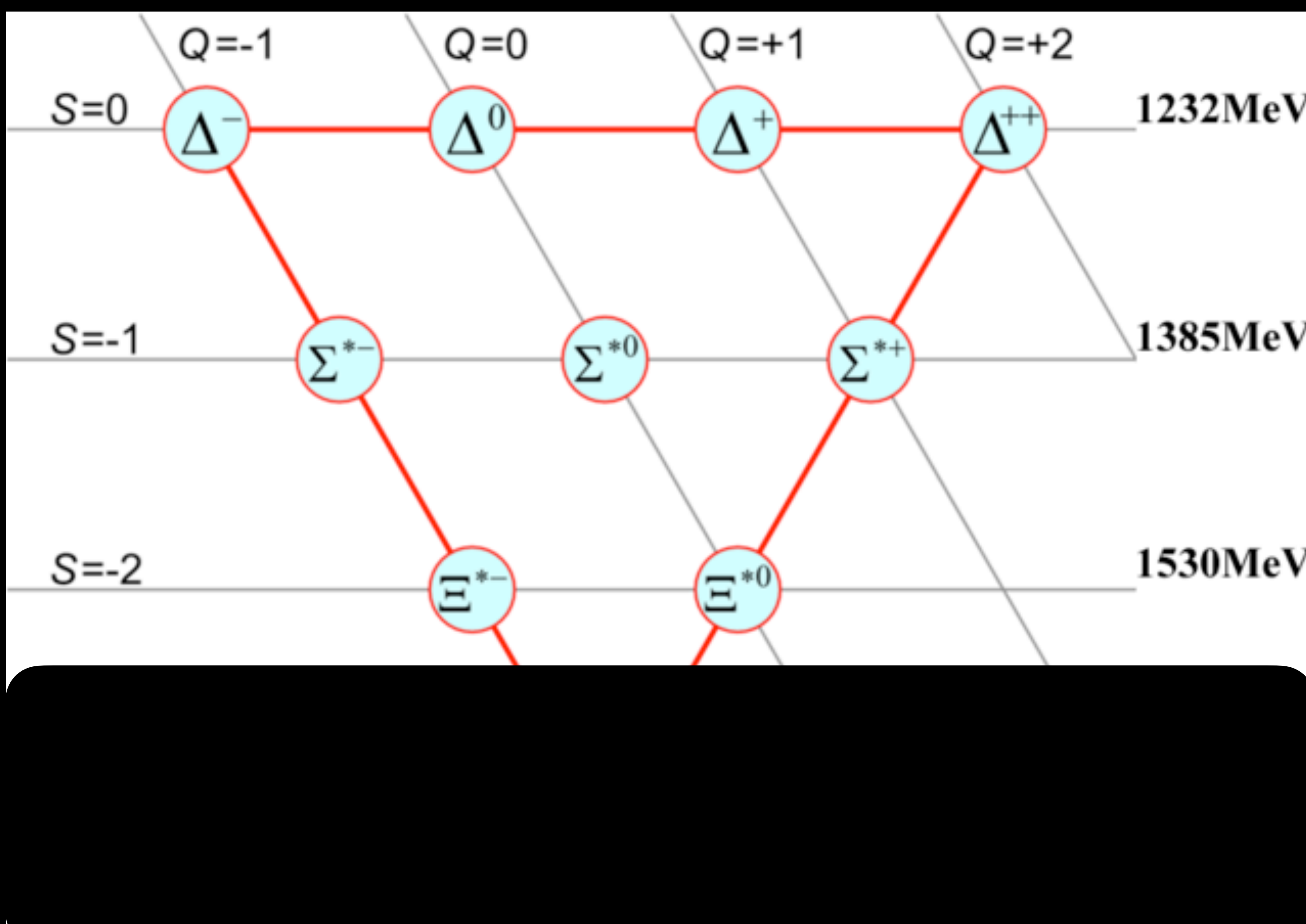
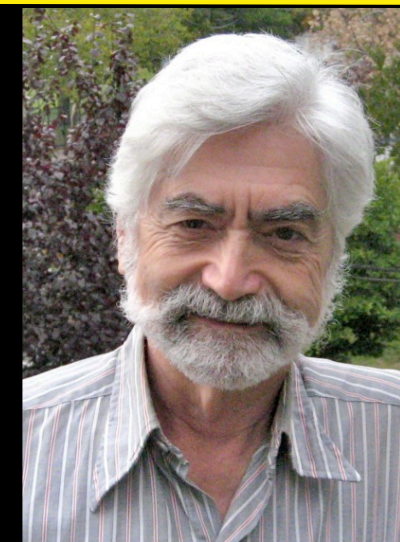
The baryon decuplet: discovery of Ω-baryon

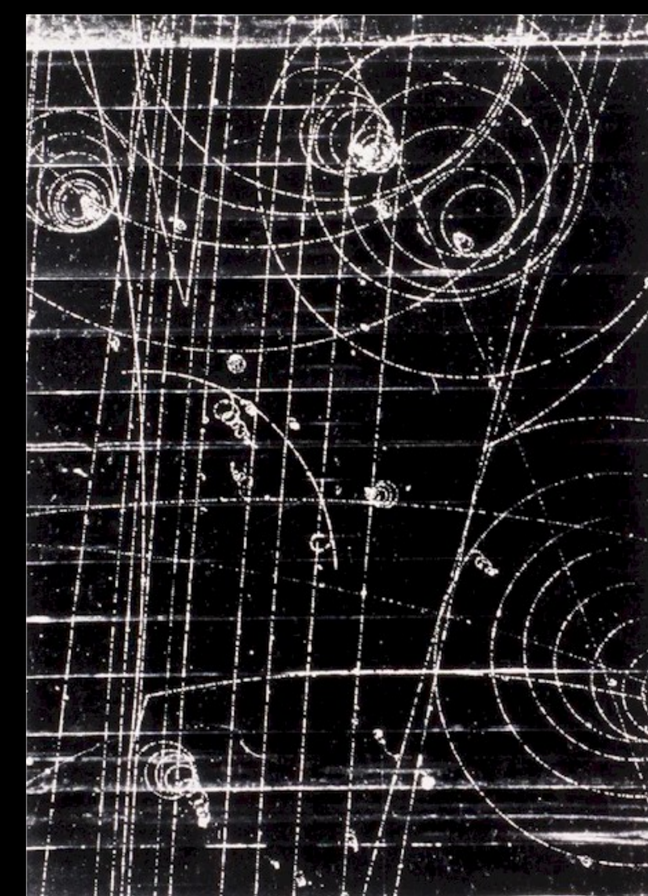
Not all multiplets were complete…





George Zweig

Murray Gell-Mann



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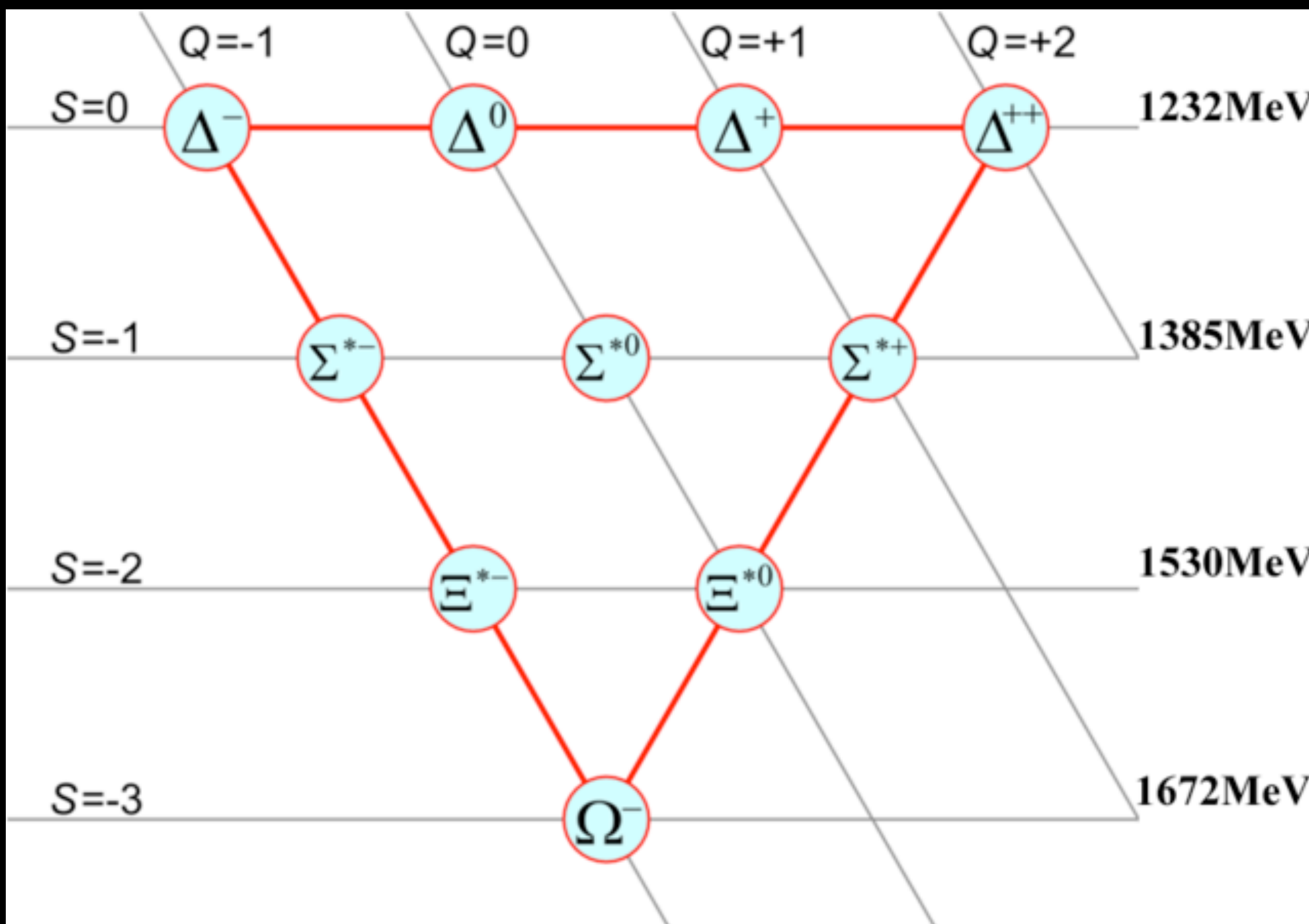

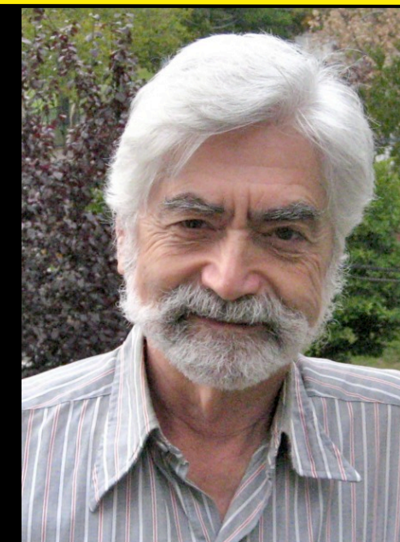

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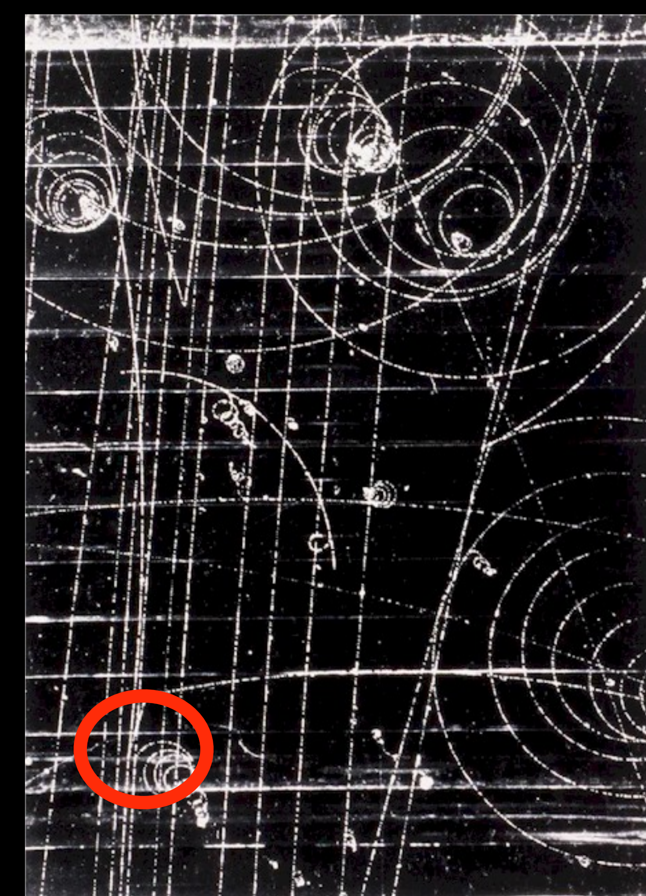
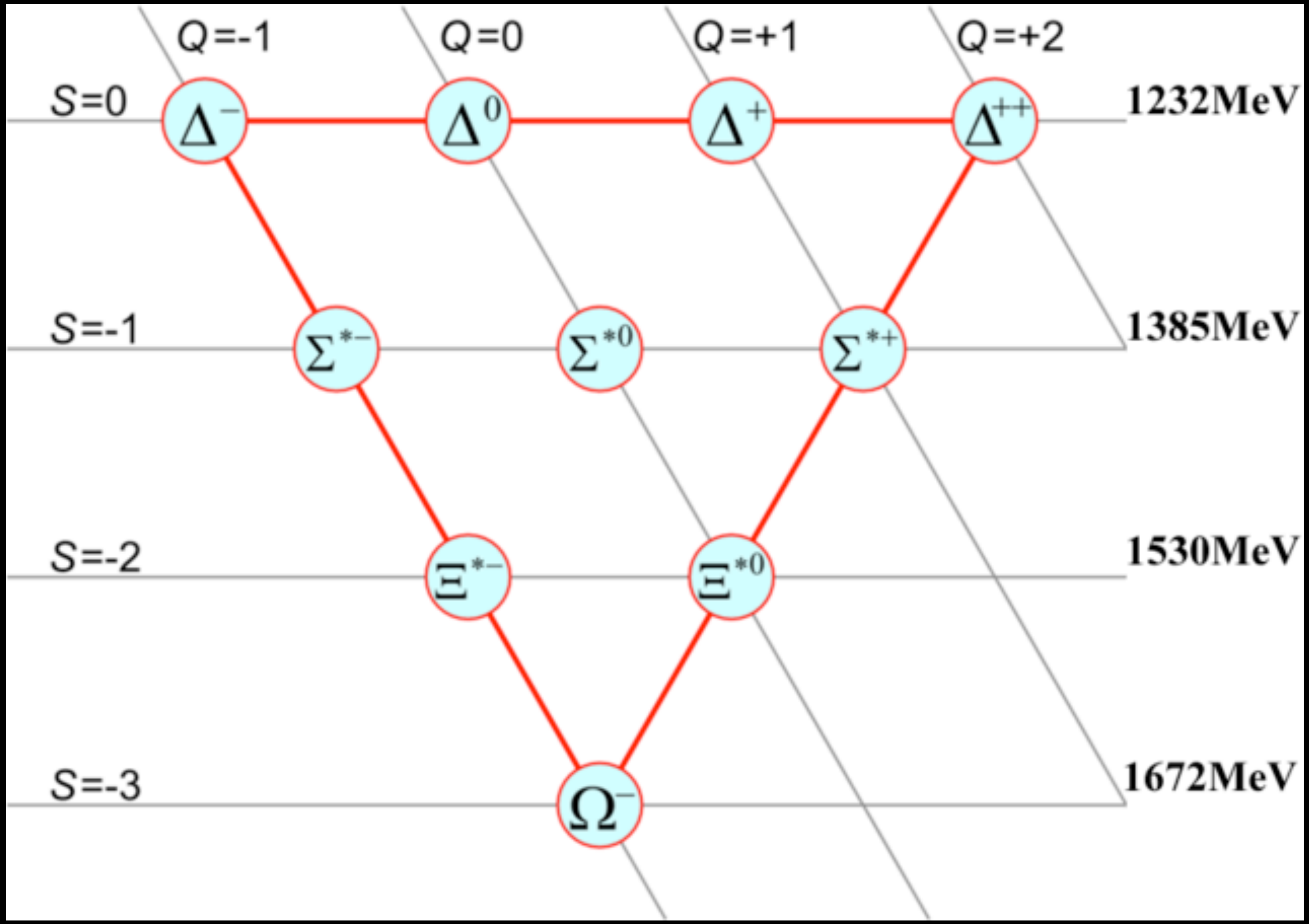
Murray Gell-Mann



The baryon decuplet: discovery of Ω-baryon

Not all multiplets were complete…



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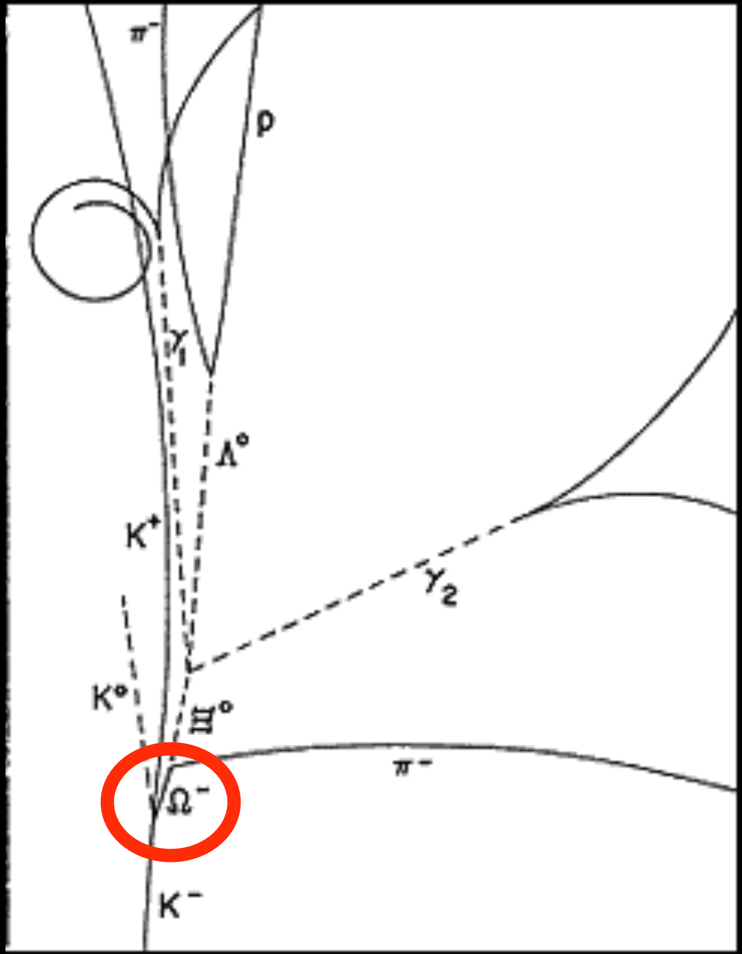
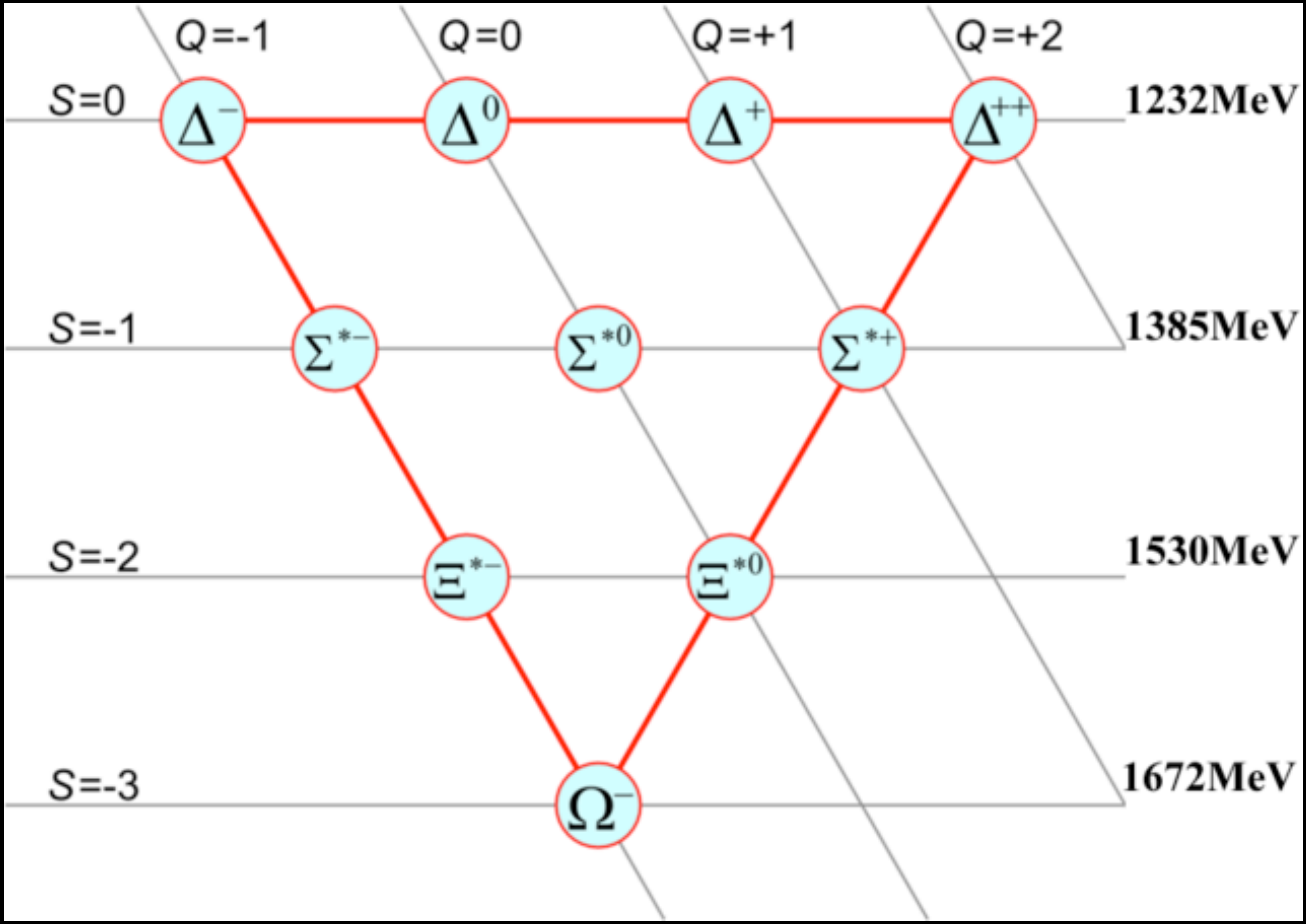
Murray Gell-Mann



Baryons (cont.)



(some of the) Baryons in the quark model

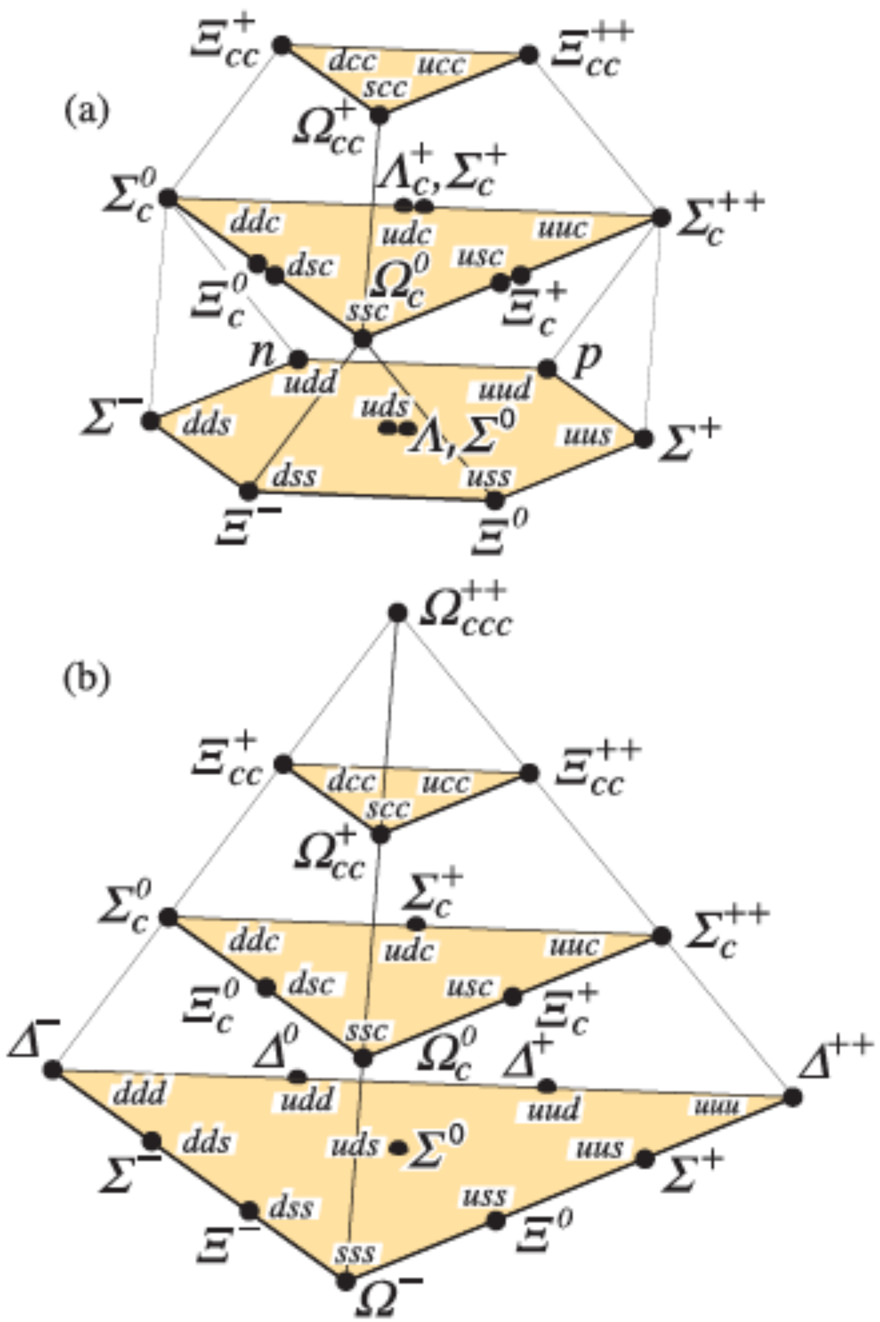
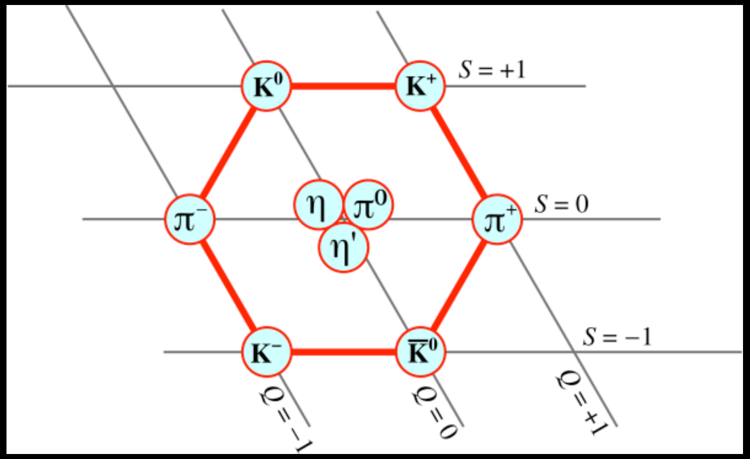


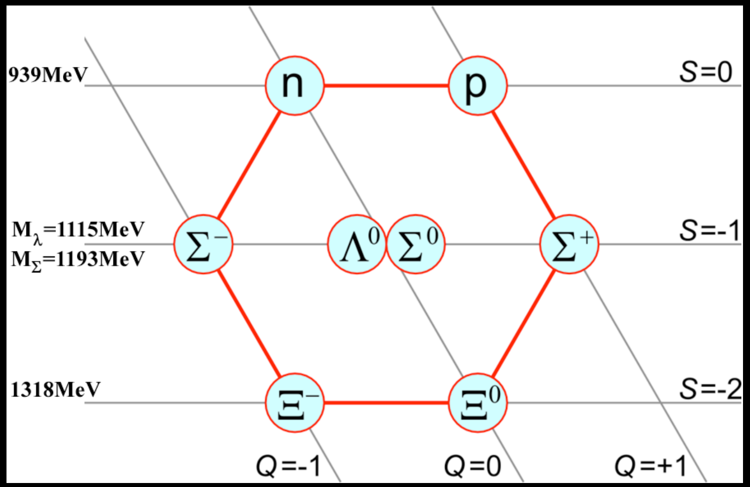
Figure 15.4: SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet. (b) The 20-plet with an SU(3) decuplet.

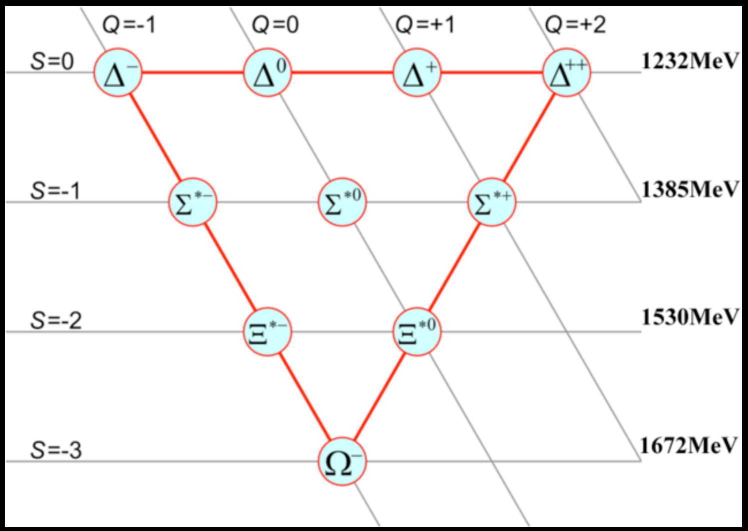
Quark model

- Gell-Mann and Zweig (1964)
  - All multiplets can be explained if you assume that hadrons are composite particles built from more elementary constituents: the quarks and antiquarks
    - Baryons are made of three quarks (antibaryons are made of three antiquarks)
    - Mesons are made of a quark and an antiquark combination
- First quark model consisted of the three lightest quarks (and antiquarks)

up down strange







Problem of the quark model

How can a baryon like the Δ^{++} (uuu) or the Ω^- (sss) exist given the Pauli principle?

$$\Psi = \Psi(space) \cdot \Psi(flavour) \cdot \Psi(spin)$$

Δ^{++} (uuu): u↑ u↑ u↑

Intrinsic spin: $\left|\frac{3}{2}, +\frac{3}{2}\right\rangle = \uparrow\uparrow\uparrow$ symmetric

Quarks: $|uuu\rangle$ symmetric

Ω^- (sss): s↑ s↑ s↑

Intrinsic spin: $\left|\frac{3}{2}, +\frac{3}{2}\right\rangle = \uparrow\uparrow\uparrow$ symmetric

Quarks: $|sss\rangle$ symmetric

Half-integer spin particle ⇒ fermion that obeys the Fermi-Dirac statistics: anti-symmetric wave-functions

Solution: Introduce a new quantum number ⇒ **COLOUR**

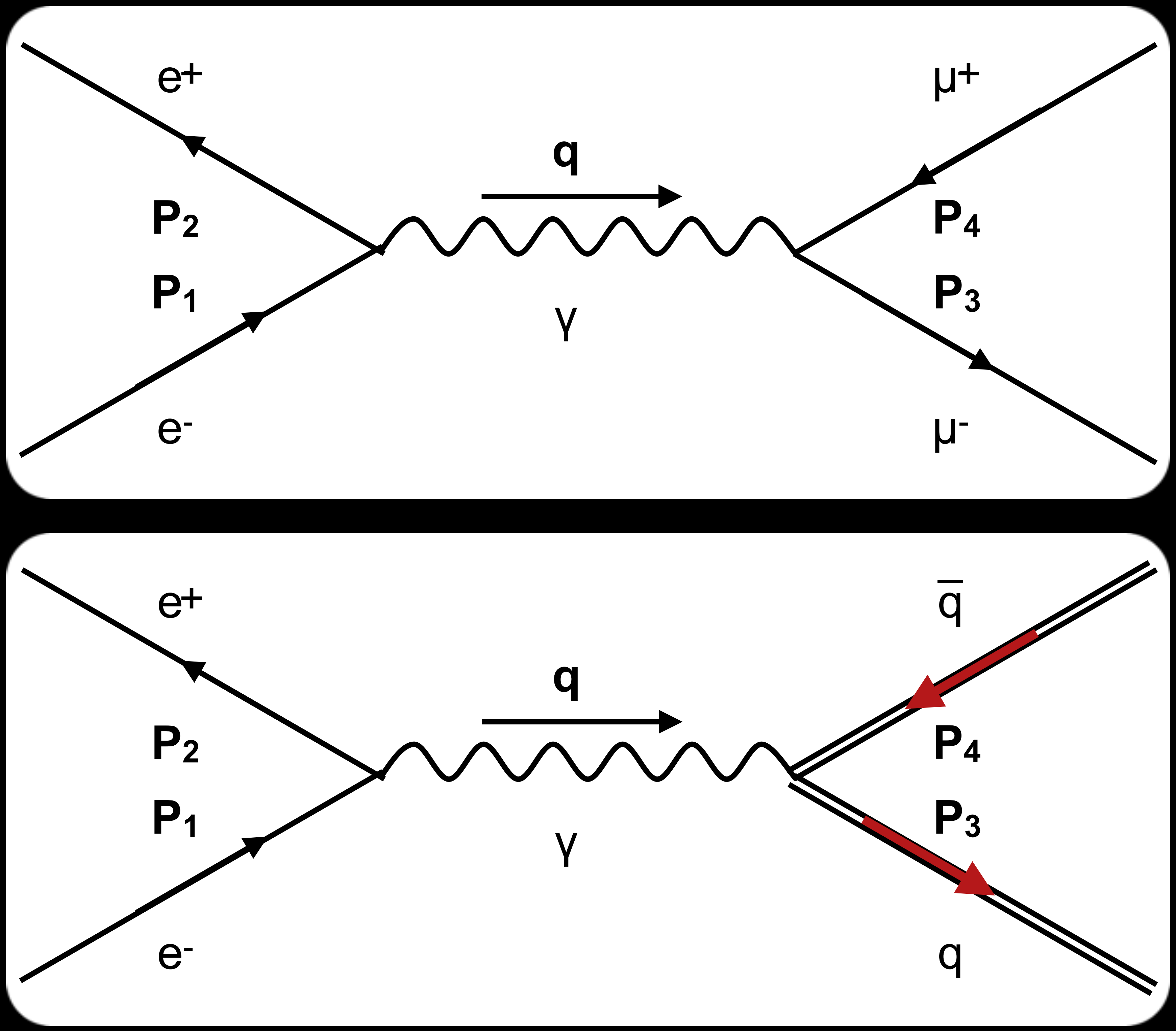
- ✓ Comes with three flavours: RED, GREEN, BLUE
- ✓ Applicable for quarks not leptons!

Δ^{++} (uuu): u↑ (red) u↑ (green) u↑ (blue)

Ω^- (sss): s↑ (red) s↑ (green) s↑ (blue)

EVIDENCE OF COLOUR

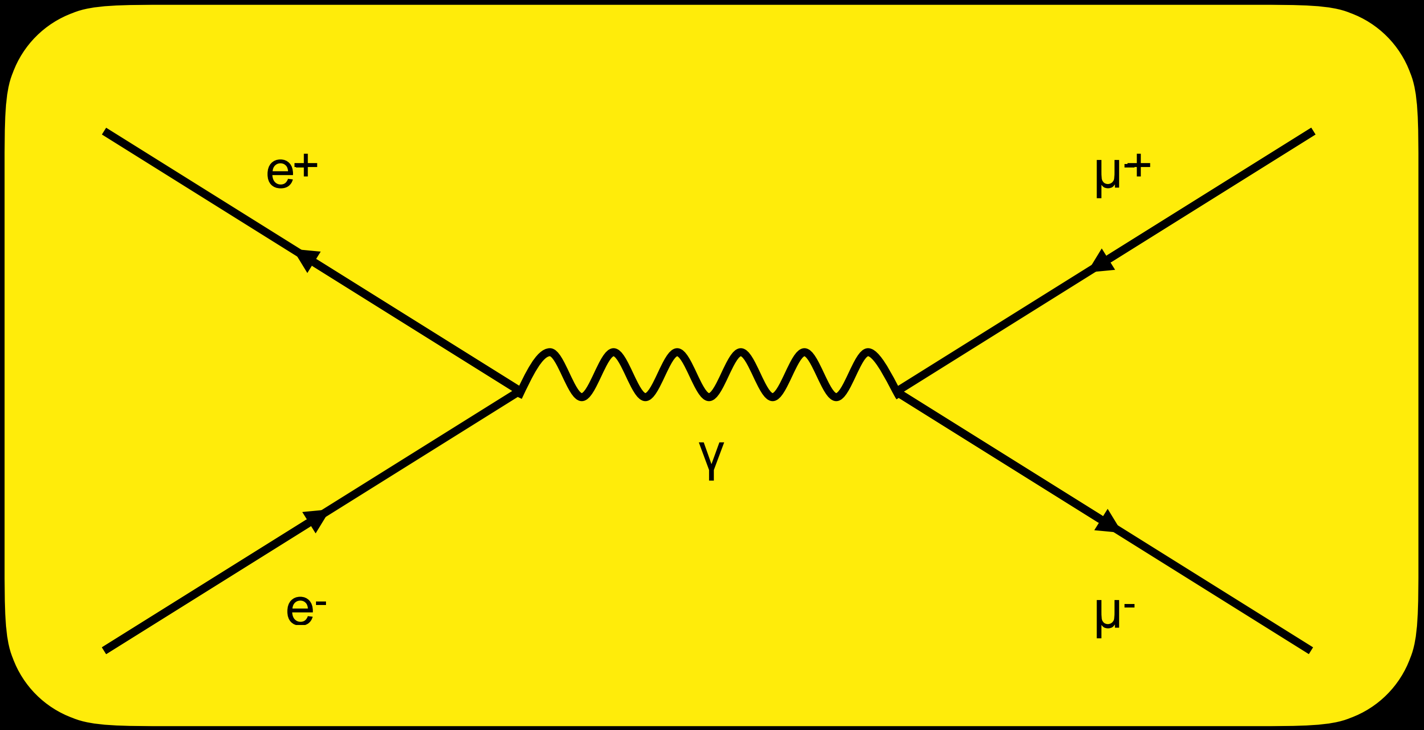
Evidence for colour



✓ Existence of colour via QED processes

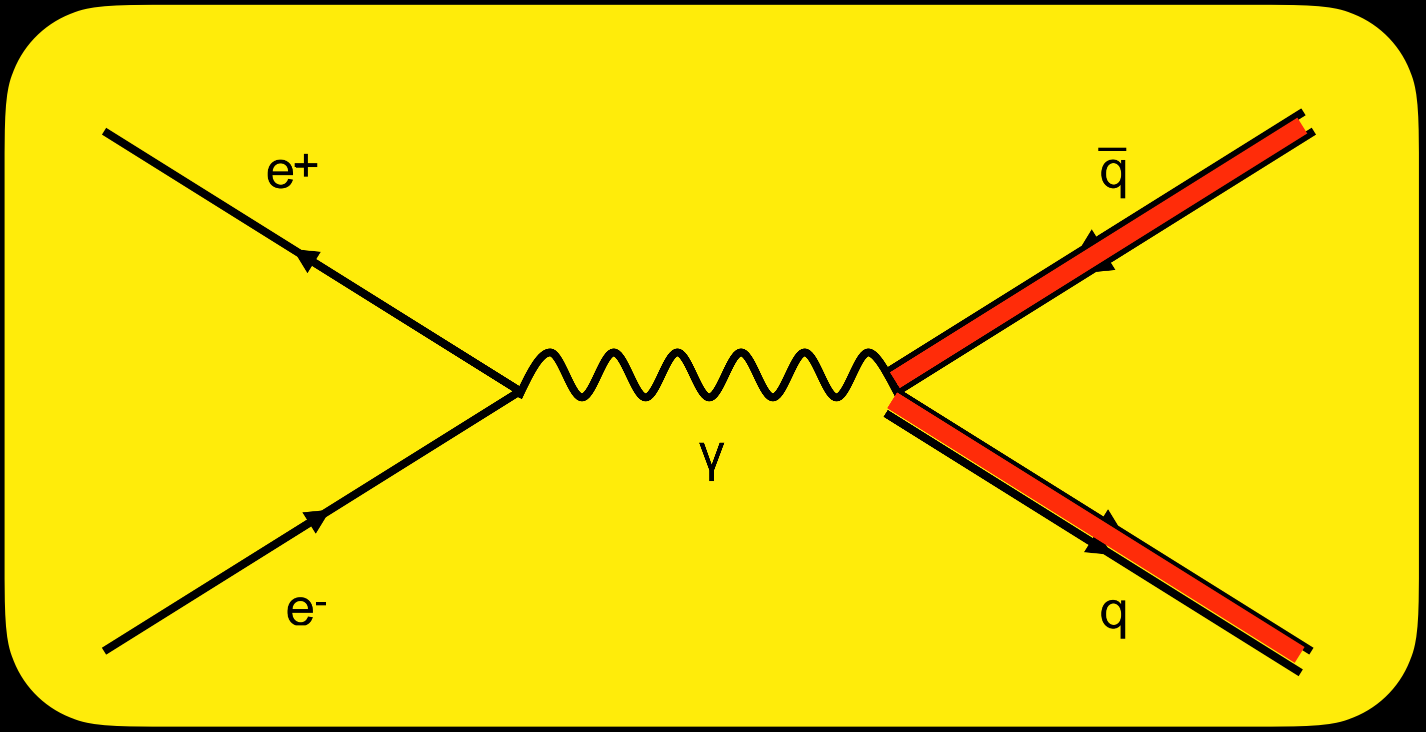
Evidence for colour

- Existence of colour via QED processes
  - The first one (i.e. muon production via electron-positron scattering) is well controlled experimental and is used as a reference



Evidence for colour (cont.)

- How can we probe colour via a QED process?
  - The second process (i.e. quark production via electron-positron scattering) can not actually be observed in nature

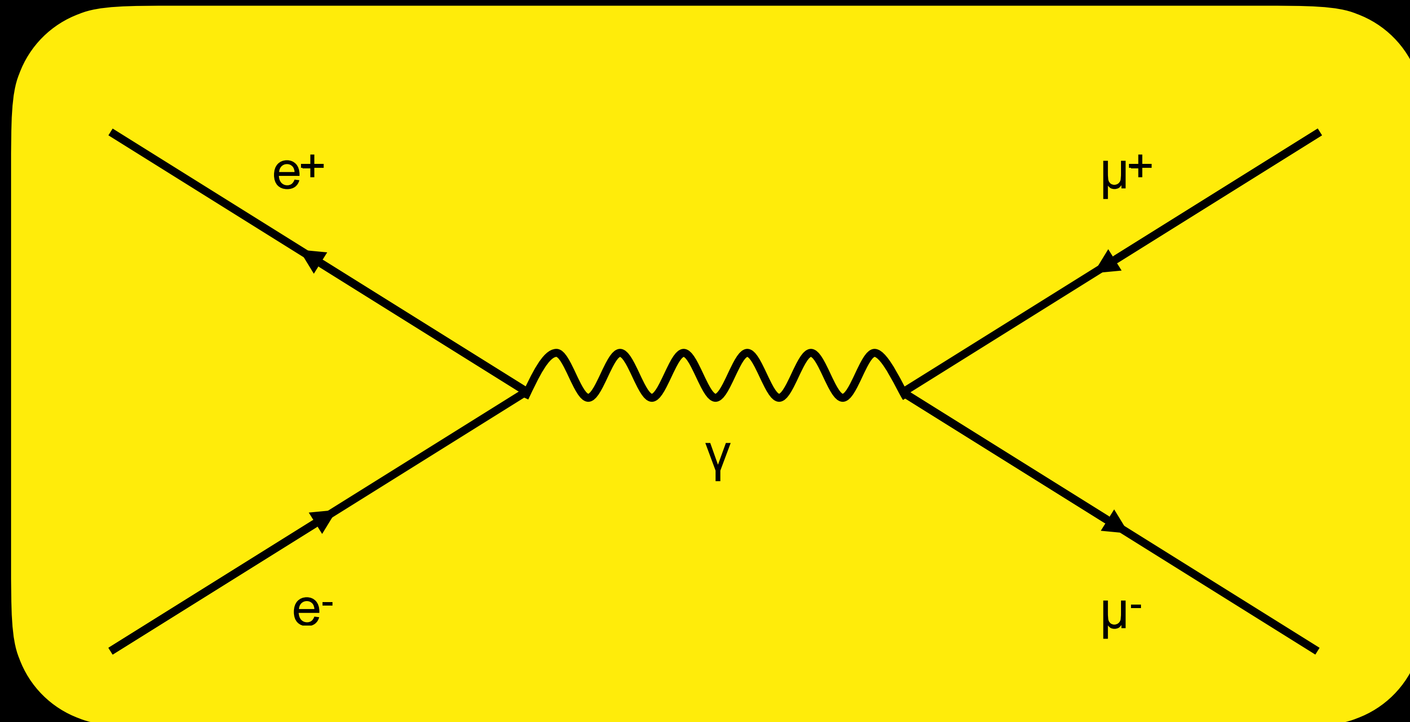


Evidence for colour

- Existence of colour via QED (i.e. E/M) processes
  - The first one (i.e. muon production via electron-positron scattering) is well controlled experimental and is used as a reference
- How can we probe colour via a QED process?
  - The second process (i.e. quark production via electron-positron scattering) can not actually be observed in nature
    - These quarks do not fly free for long (i.e. they can fly as “free” within the size of a hadron)
    - They fragment producing additional q-qbar pairs that when combined form hadrons
      - This is a QCD-type (i.e. strong interactions) process
    - The final state particles are detected as a collimated spray of hadrons ➡JETS
    - Due to energy-momentum conservation, these jets emerge in a back-to-back topology
- Any difference between the cross-sections of these two processes from a naive scaling with the square of the charge will signal the existence of additional factors

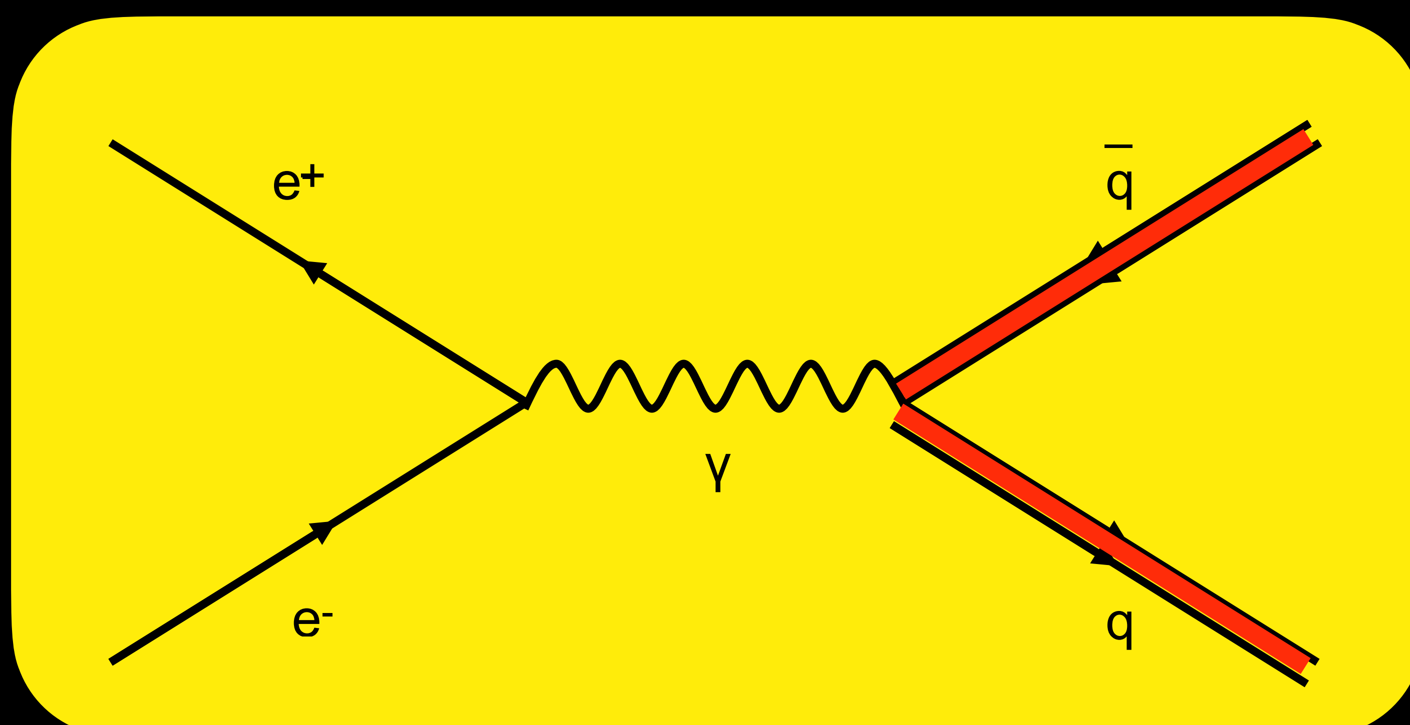
Evidence for colour (cont.)

QED process



Final state
particles that can be seen in nature

QED process

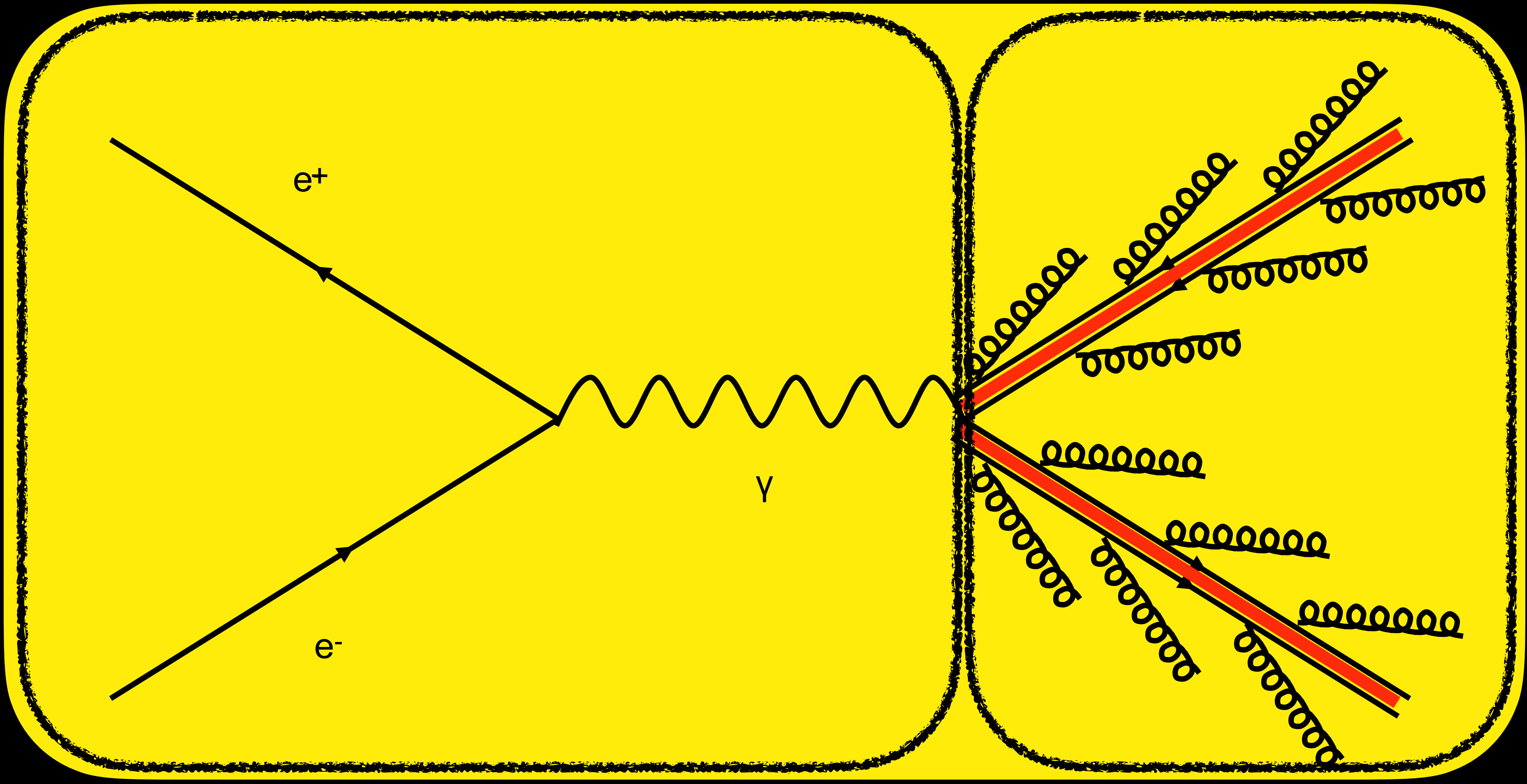


Final state
particles that do not fly free in nature

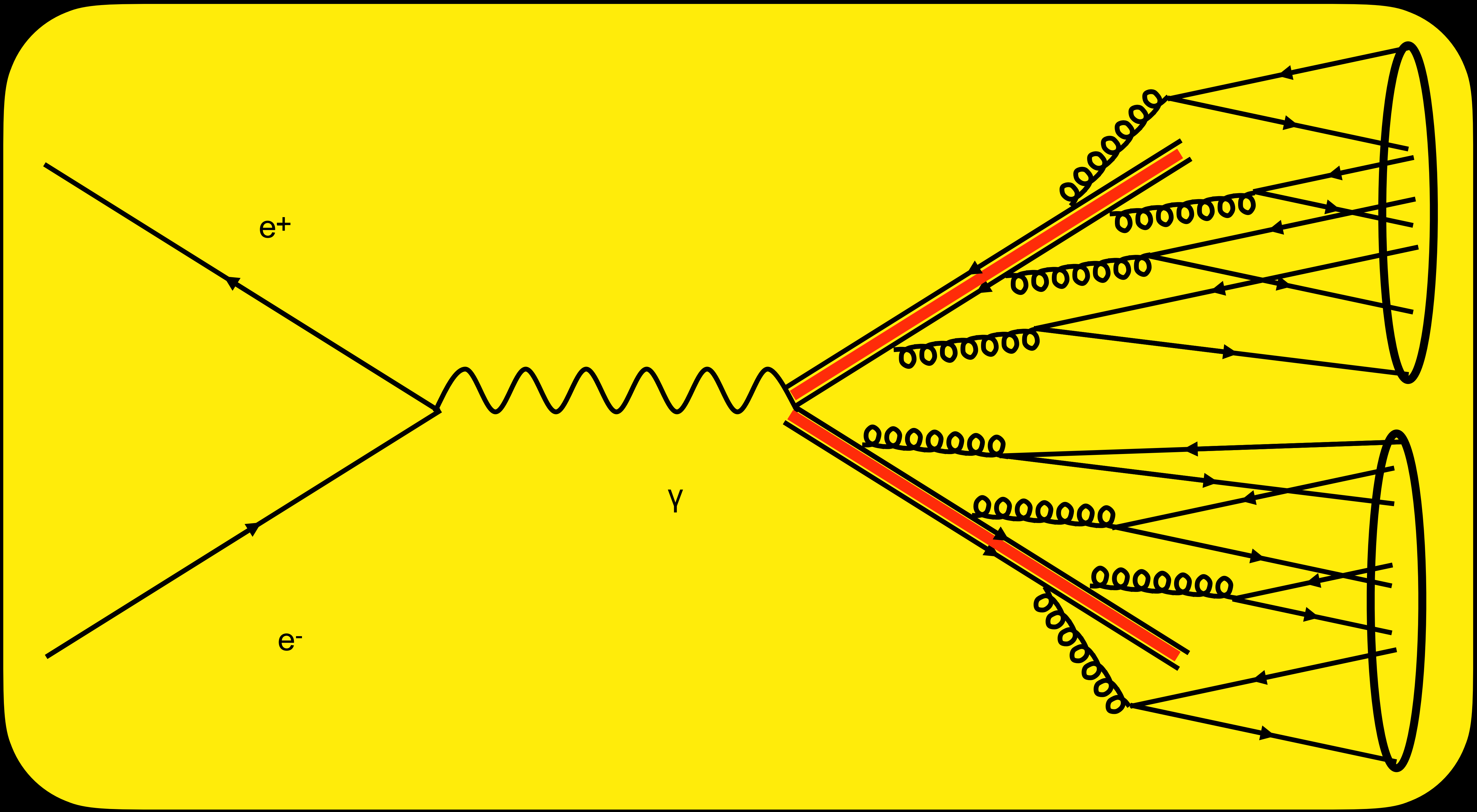
Evidence for colour (cont.)

QED process

QCD process

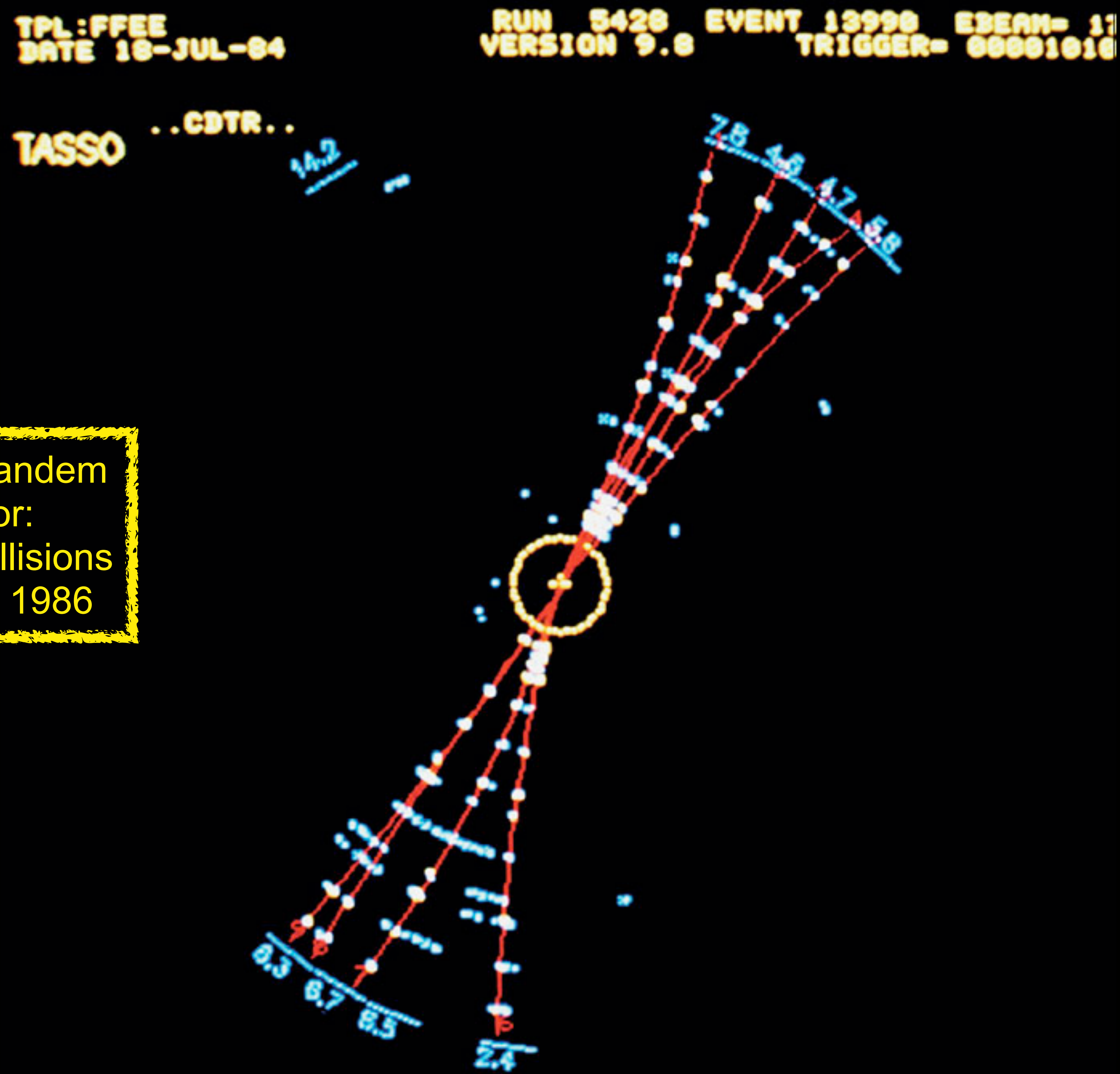


Evidence for colour (cont.)



Two-jet events

TASSO experiment @ PETRA @ DESY



Positron-Electron Tandem Ring Accelerator: electron-positron collisions between 1978 and 1986

e^-e^+ collisions @ $\sqrt{s}$ = 13-31 GeV

Two-jet events

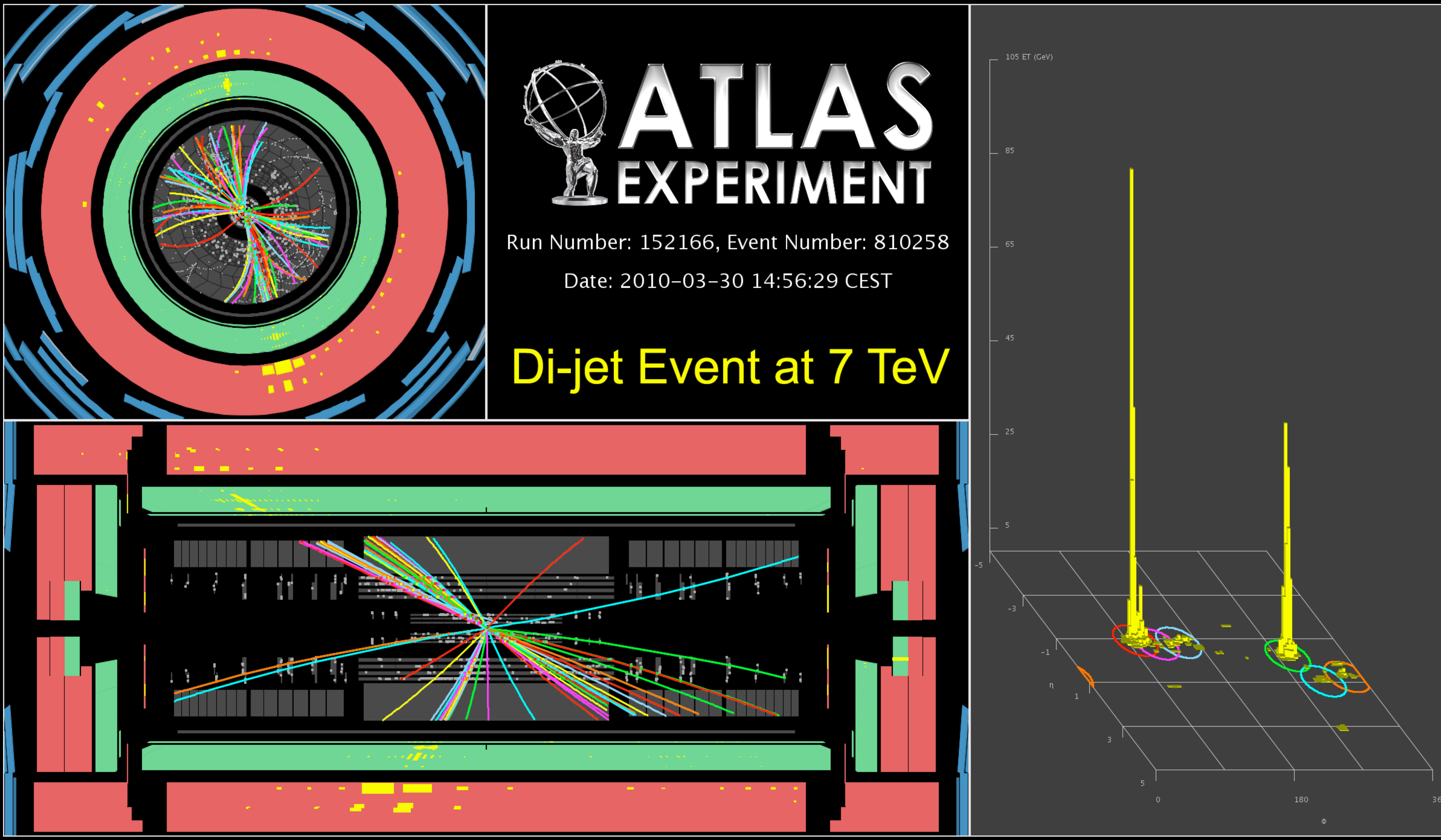
Detector with Electron, Photon and Hadron Identification

DELPHI experiment @ LEP @ CERN

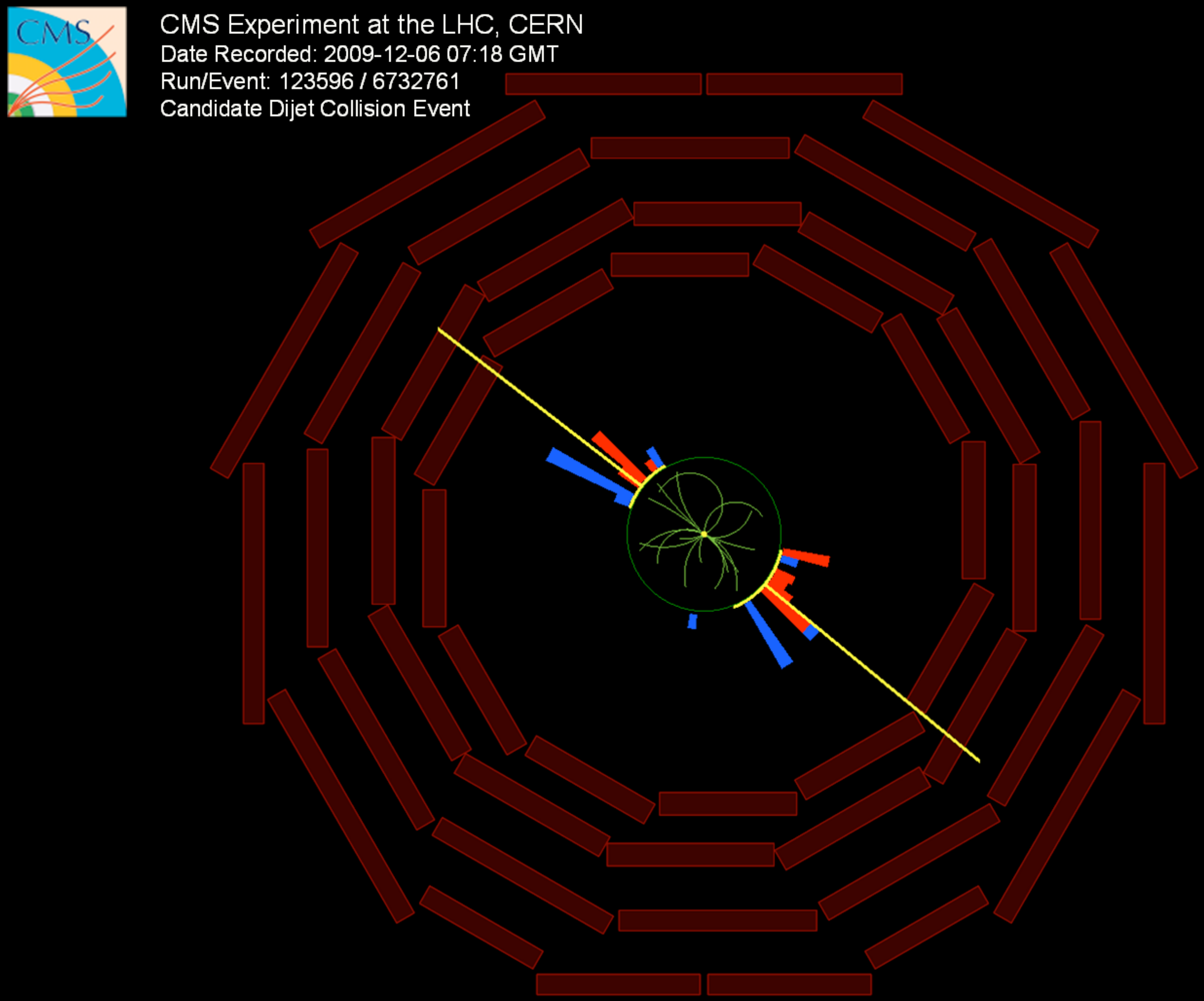
Large Electron-Positron collider @ CERN (predecessor of LHC): electron-positron collisions between 1989 and 2000

e^-e^+ collisions @ $\sqrt{s}$ = 90-209 GeV

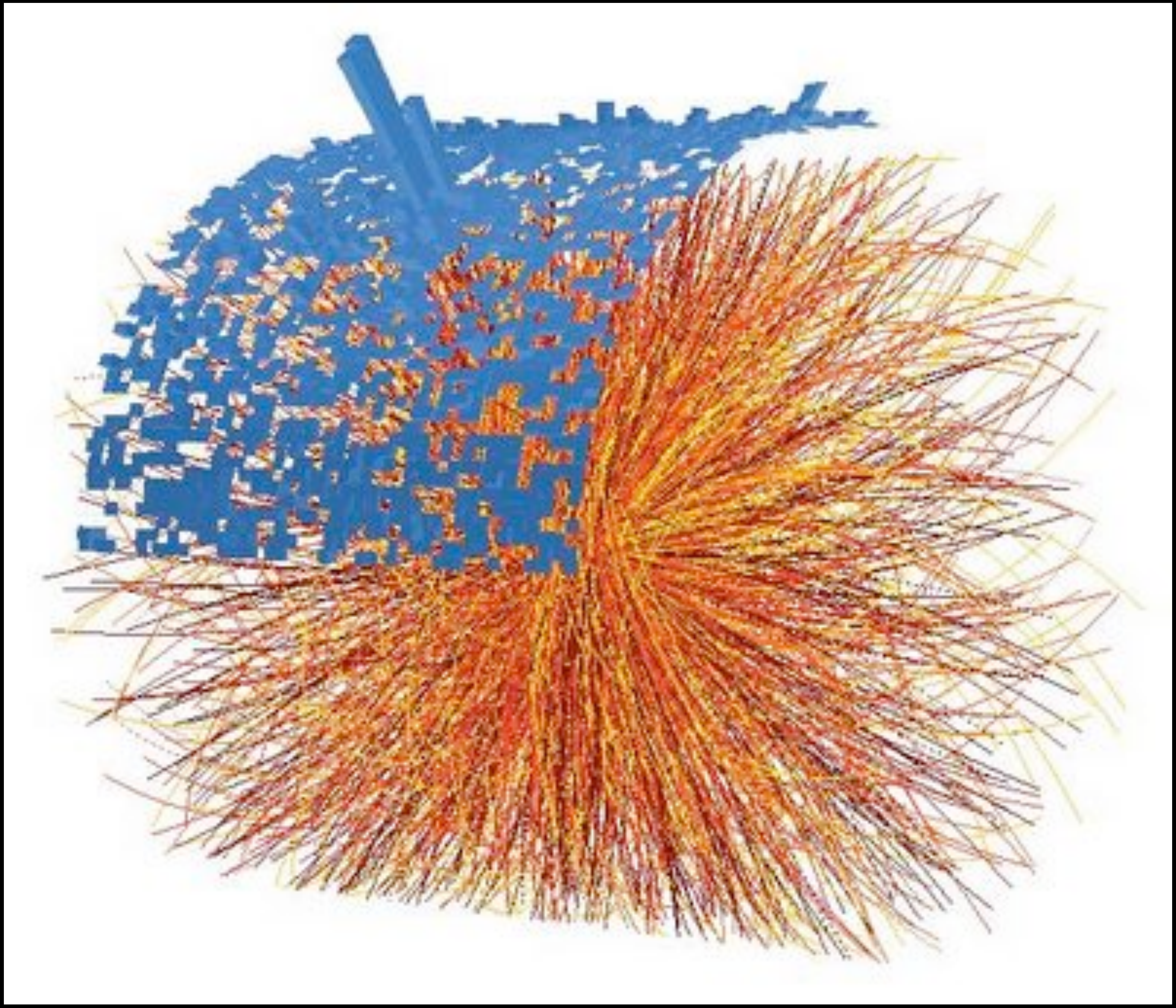
Two-jet events: ATLAS



Two-jet events: CMS

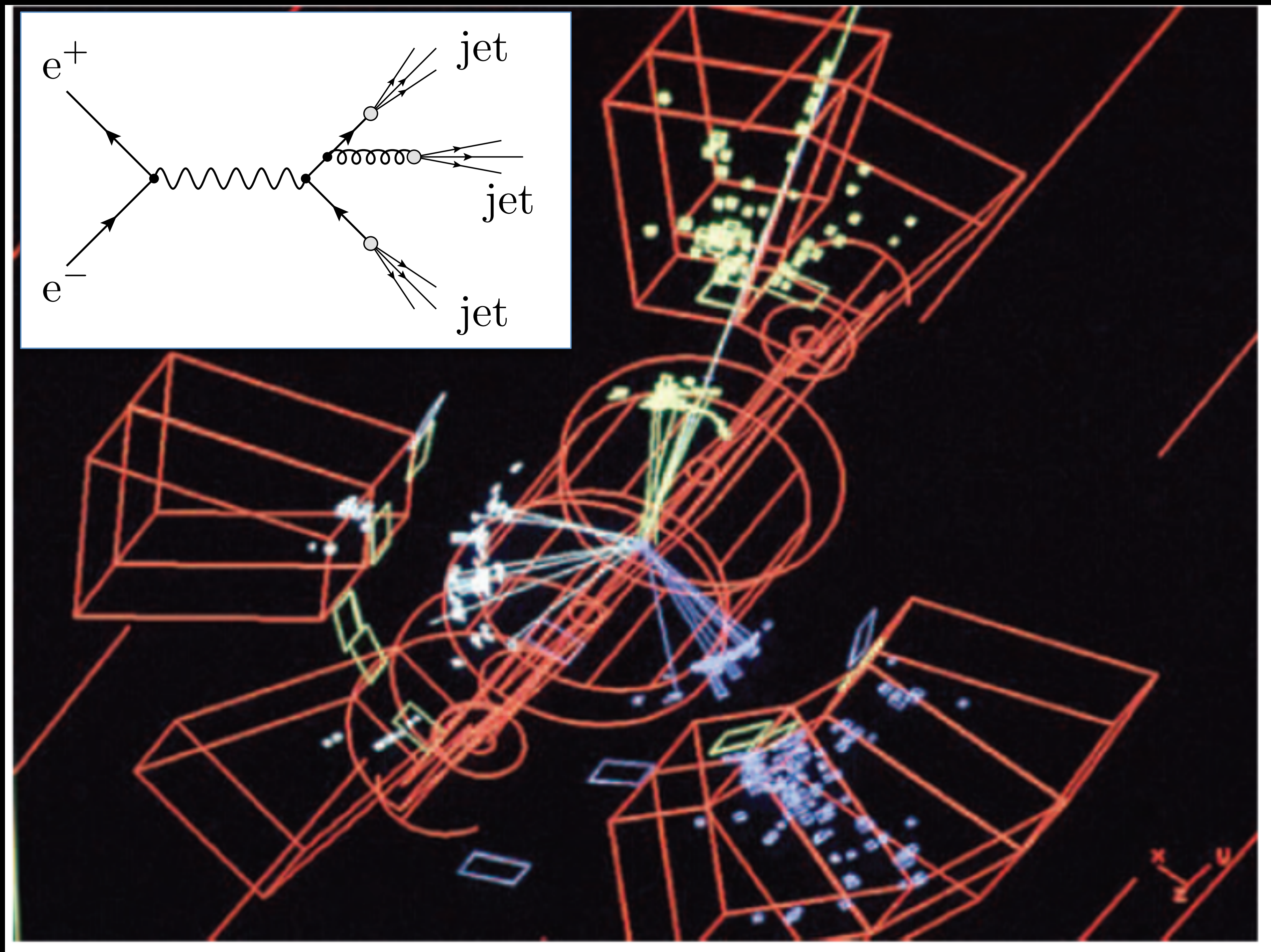


Jet events in heavy-ion collisions (ALICE)

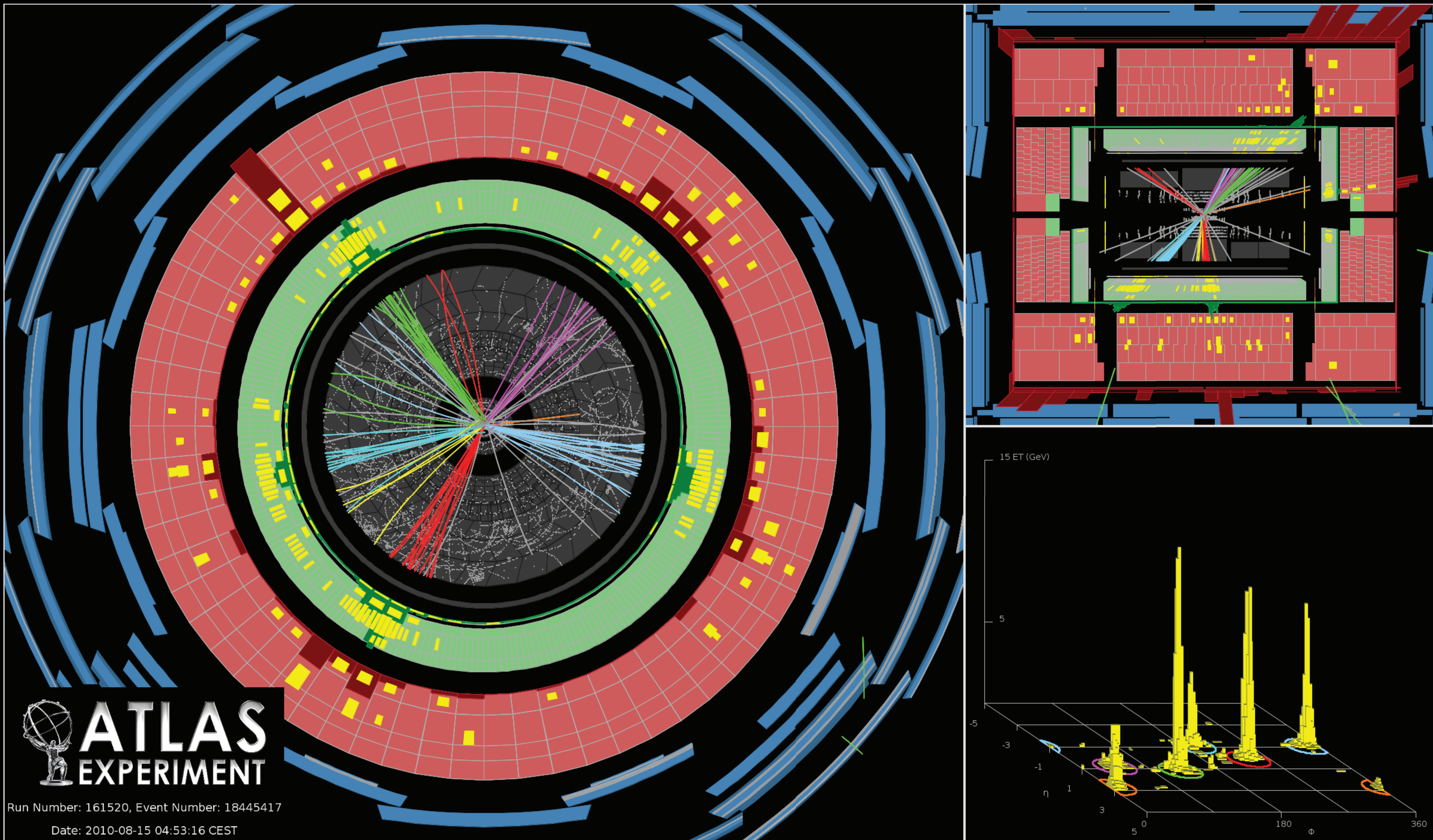


Existence of gluons: three-jet events

TASSO experiment @ PETRA @ DESY

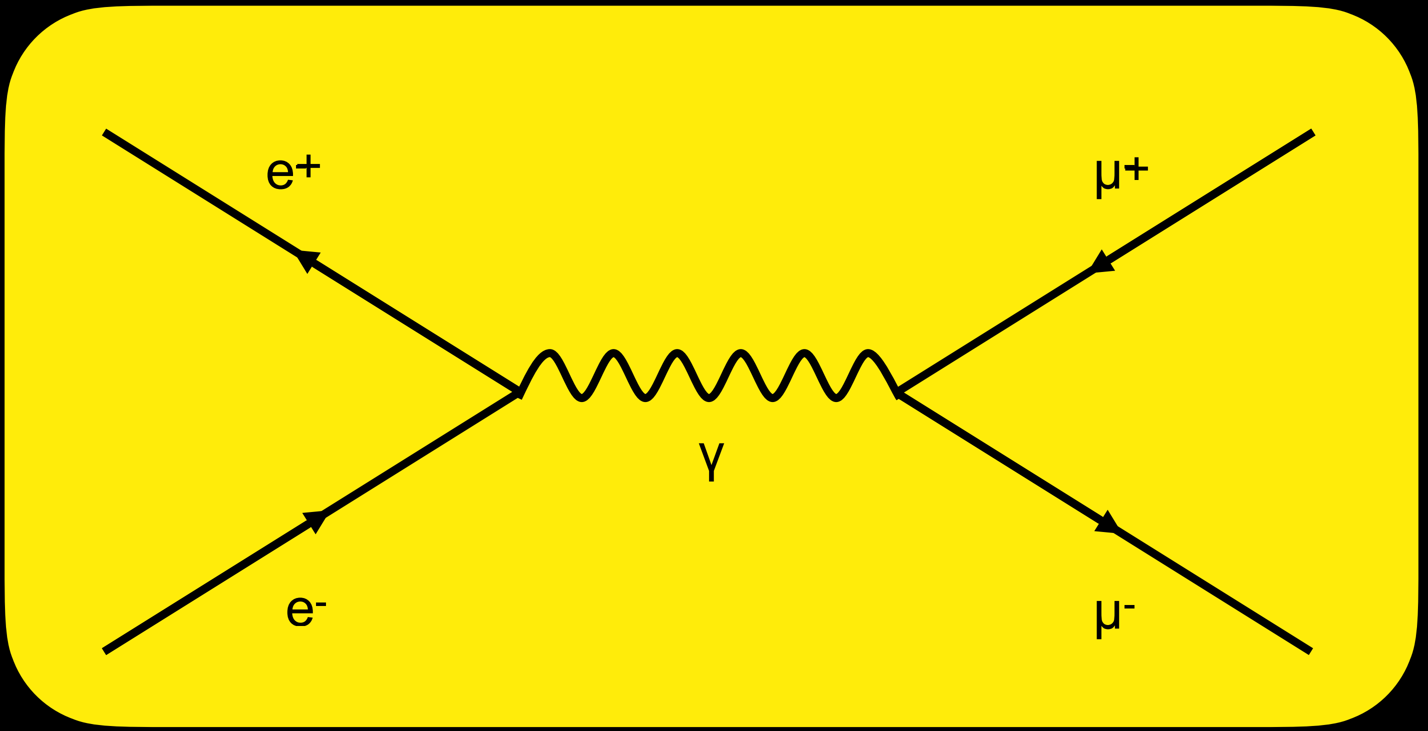


Existence of gluons: five-jet events



Evidence for colour (cont.)

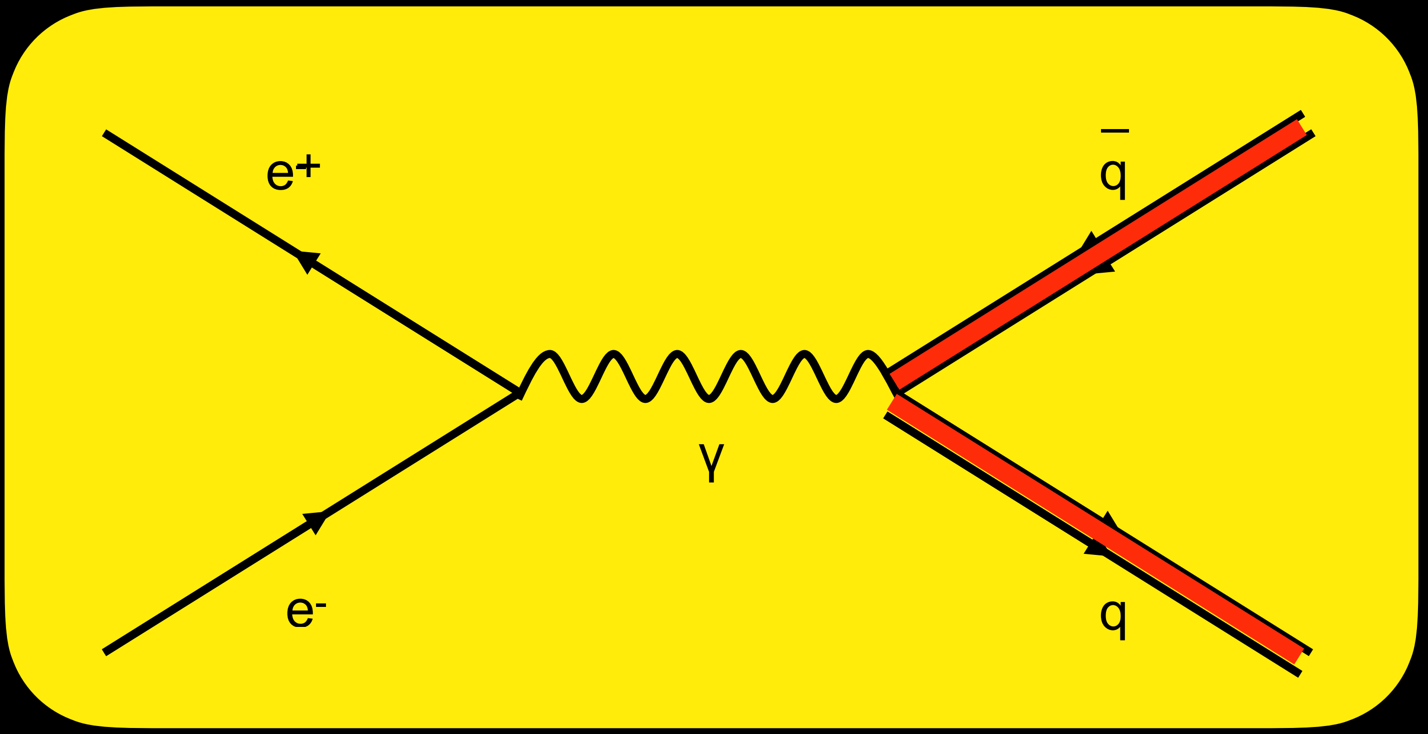
QED process



Final state
particles that can be seen in nature

$$\sigma \sim \left(\frac{a}{E}\right)^2$$

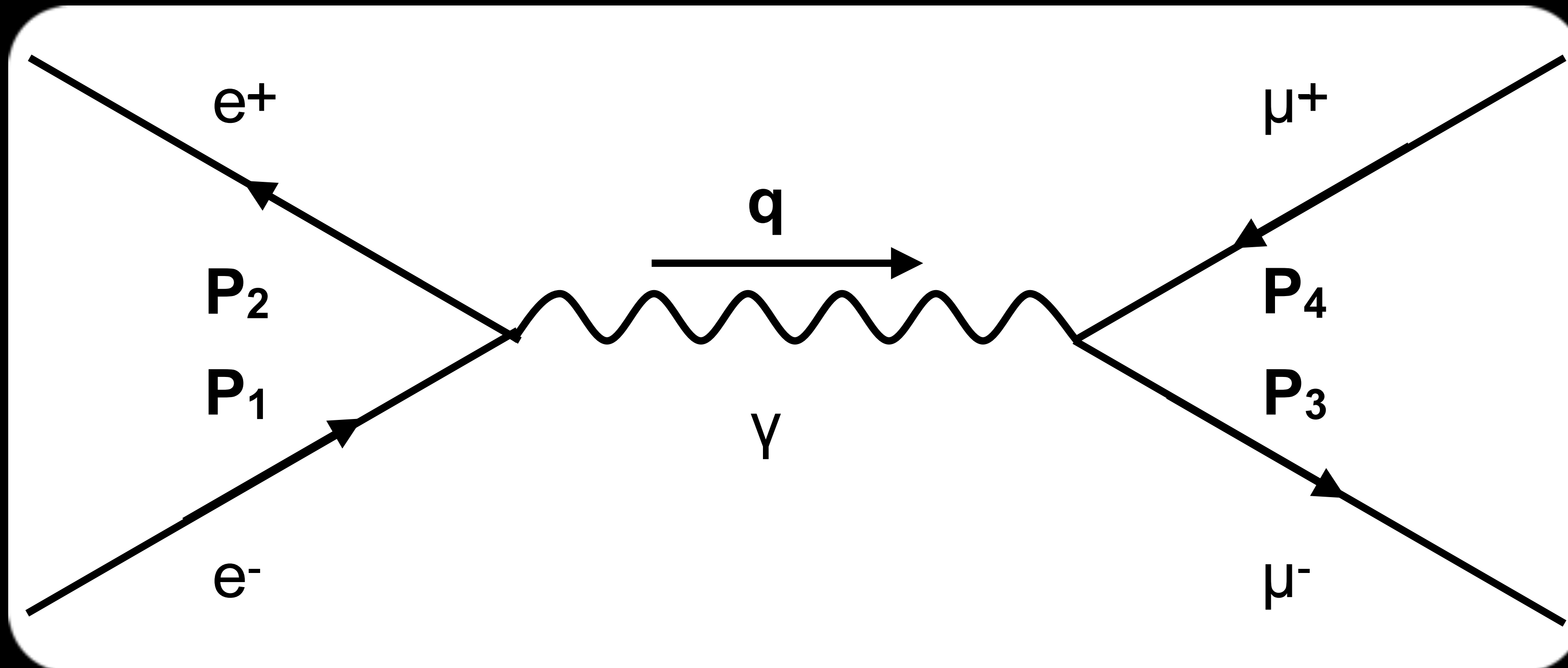
QED process

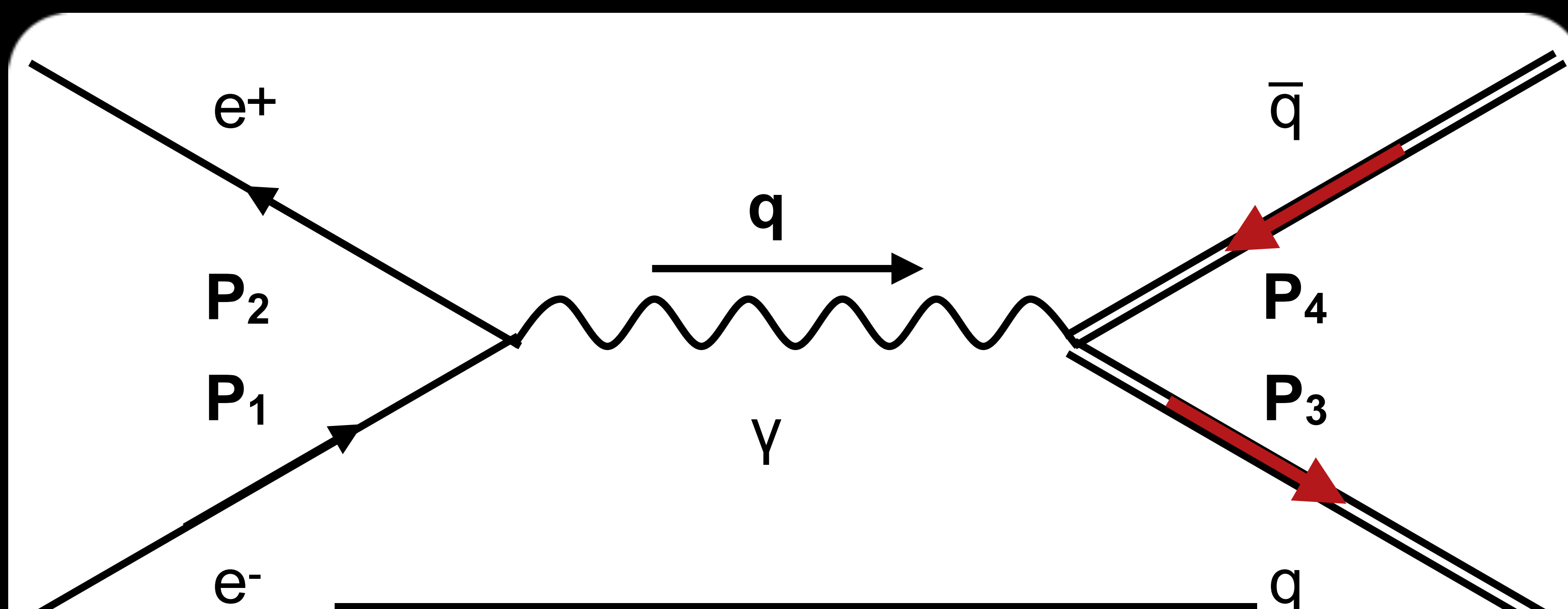


Final state
particles that do not fly free in nature

$$\sigma \sim \left(\frac{Qa}{E}\right)^2$$

Evidence for colour





$$R = \frac{\sigma(e^- e^+ \rightarrow q\,\overline{q} \rightarrow hadrons)}{\sigma(e^- e^+ \rightarrow \mu^- \mu^+)} \sim \sum_i Q_i^2$$

Evidence for colour (cont.)

- Calculate the ratio of the cross-sections of the two processes

$$R=\frac{\sigma(e^-e^+\to q\overline{q}\to hadrons)}{\sigma(e^-e^+\to\mu^-\mu^+)}\sim\sum_{i=1}^{n}Q_i^2$$

- For three quark flavours (u,d,s) the ratio should give:

$$R=\left[\left(\frac{2}{3}\right)^2+\left(\frac{-1}{3}\right)^2+\left(\frac{-1}{3}\right)^2\right]=\frac{2}{3}$$

- For four quark flavours (u,d,s,c) the ratio should give:

$$R=\left[\left(\frac{2}{3}\right)^2+\left(\frac{-1}{3}\right)^2+\left(\frac{-1}{3}\right)^2+\left(\frac{2}{3}\right)^2\right]=\frac{10}{9}$$

- For five quark flavours (u,d,s,c,b) the ratio should give:

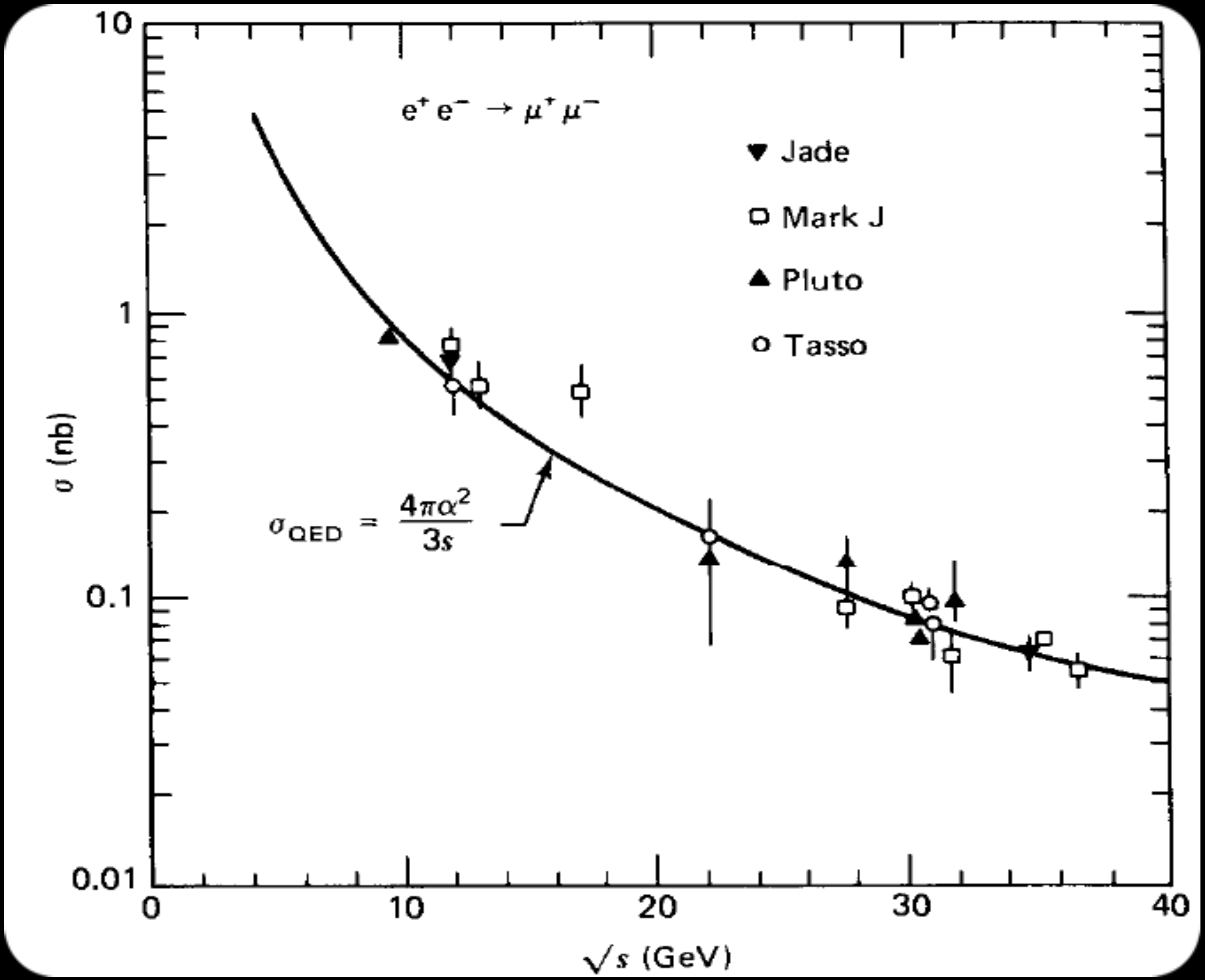
$$R=\left[\left(\frac{2}{3}\right)^2+\left(\frac{-1}{3}\right)^2+\left(\frac{-1}{3}\right)^2+\left(\frac{2}{3}\right)^2+\left(\frac{-1}{3}\right)^2\right]=\frac{11}{9}$$

- For all six quark flavours (u,d,s,c,b,t) the ratio should give:

$$R=\left[\left(\frac{2}{3}\right)^2+\left(\frac{-1}{3}\right)^2+\left(\frac{-1}{3}\right)^2+\left(\frac{2}{3}\right)^2+\left(\frac{-1}{3}\right)^2+\left(\frac{2}{3}\right)^2\right]=\frac{15}{9}$$

Cross-section $e^-e^+ \to \mu^-\mu^+$

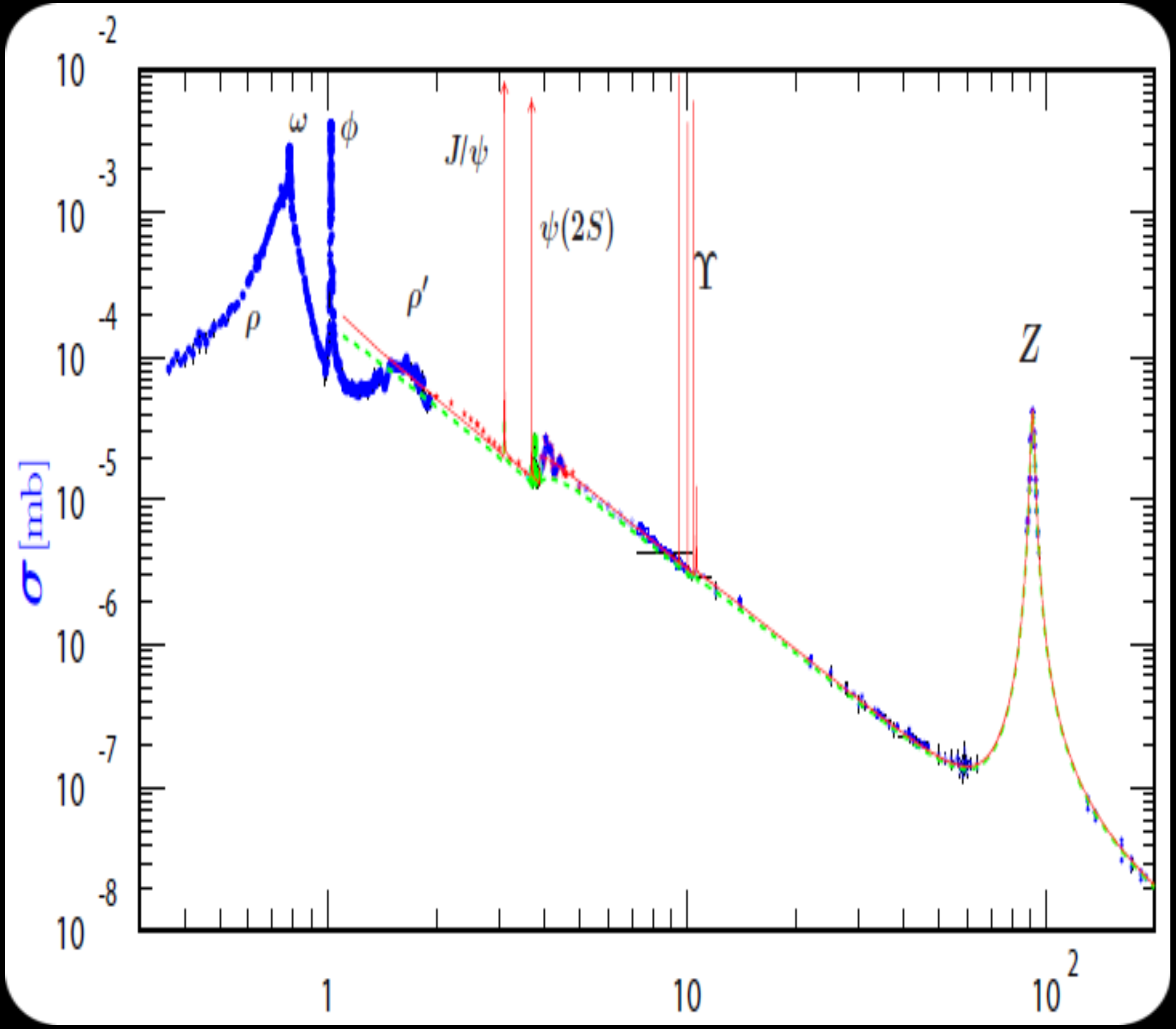
$$\sigma(e^-e^+ \to \mu^-\mu^+) \sim \left(\frac{a}{E}\right)^2$$



✓ At around $\sqrt{s_{NN}}$ = 10GeV → $\sigma(e^-e^+ \to \mu^-\mu^+)$ ~ 0.9nb

Cross-section $e^-e^+ \rightarrow$ qqbar $\rightarrow$ hadrons

$$\sigma(e^-e^+ \rightarrow q\overline{q} \rightarrow hadrons) \sim \left(\frac{Qa}{E}\right)^2$$



✓ At around $\sqrt{s_{NN}}$ = 10GeV $\rightarrow$ $\sigma(e^-e^+ \rightarrow$ qqbar $\rightarrow$ hadrons) ~ 3.0nb

Evidence for colour (cont.)

- At ~10GeV (beyond the threshold for the b-quark creation) the ratio should be

$$R=\left[\left(\frac{2}{3}\right)^2+\left(\frac{-1}{3}\right)^2+\left(\frac{-1}{3}\right)^2+\left(\frac{2}{3}\right)^2+\left(\frac{-1}{3}\right)^2\right]=\frac{11}{9}$$

- But experimentally it turns out to be
  - $\sigma(e^-e^+\rightarrow\mu^-\mu^+)$ ~ 0.9nb
  - $\sigma(e^-e^+\rightarrow$qqbar$\rightarrow$hadrons) ~ 3.0nb
  - R~3

- The problem with the calculations assuming no additional quantum number persists for all energy ranges
- Solution: $R=f\sum_{i=1}^{n}Q_i^2$
  - where f is the number of colours
  - turns out to be 3 experimentally!!!

Evidence for colour (cont.)

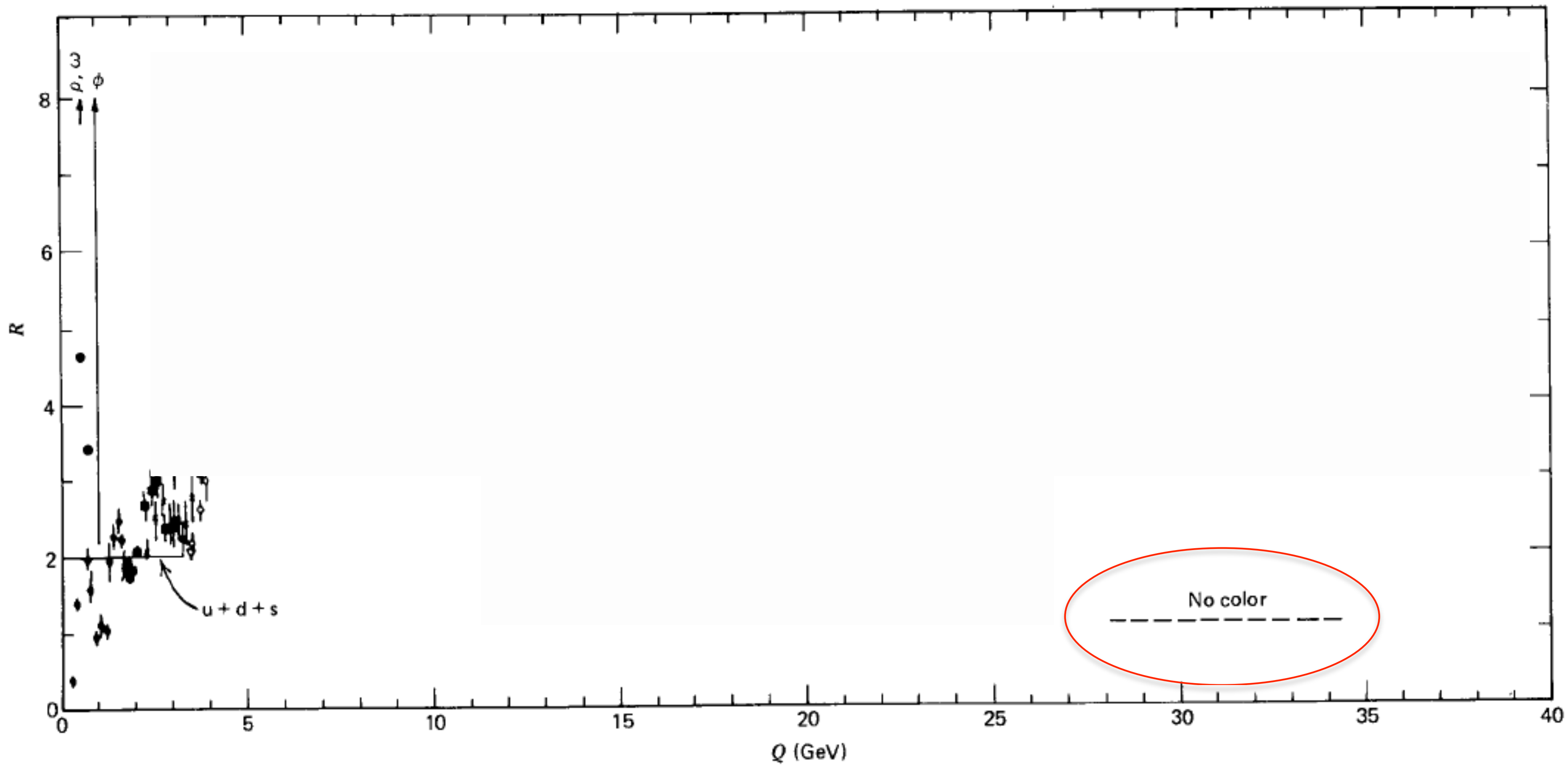


Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)

Evidence for colour (cont.)

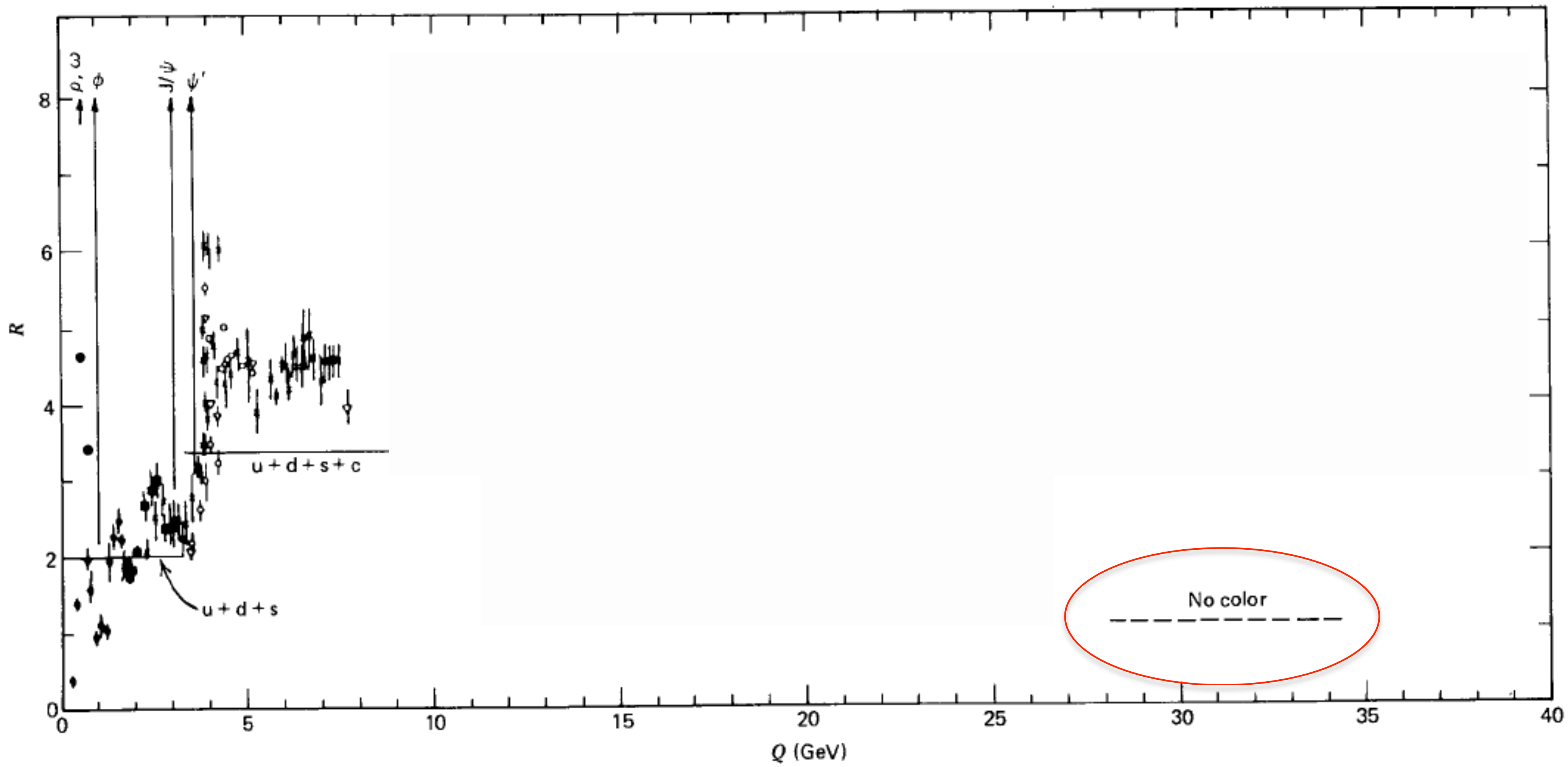


Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)

Evidence for colour (cont.)

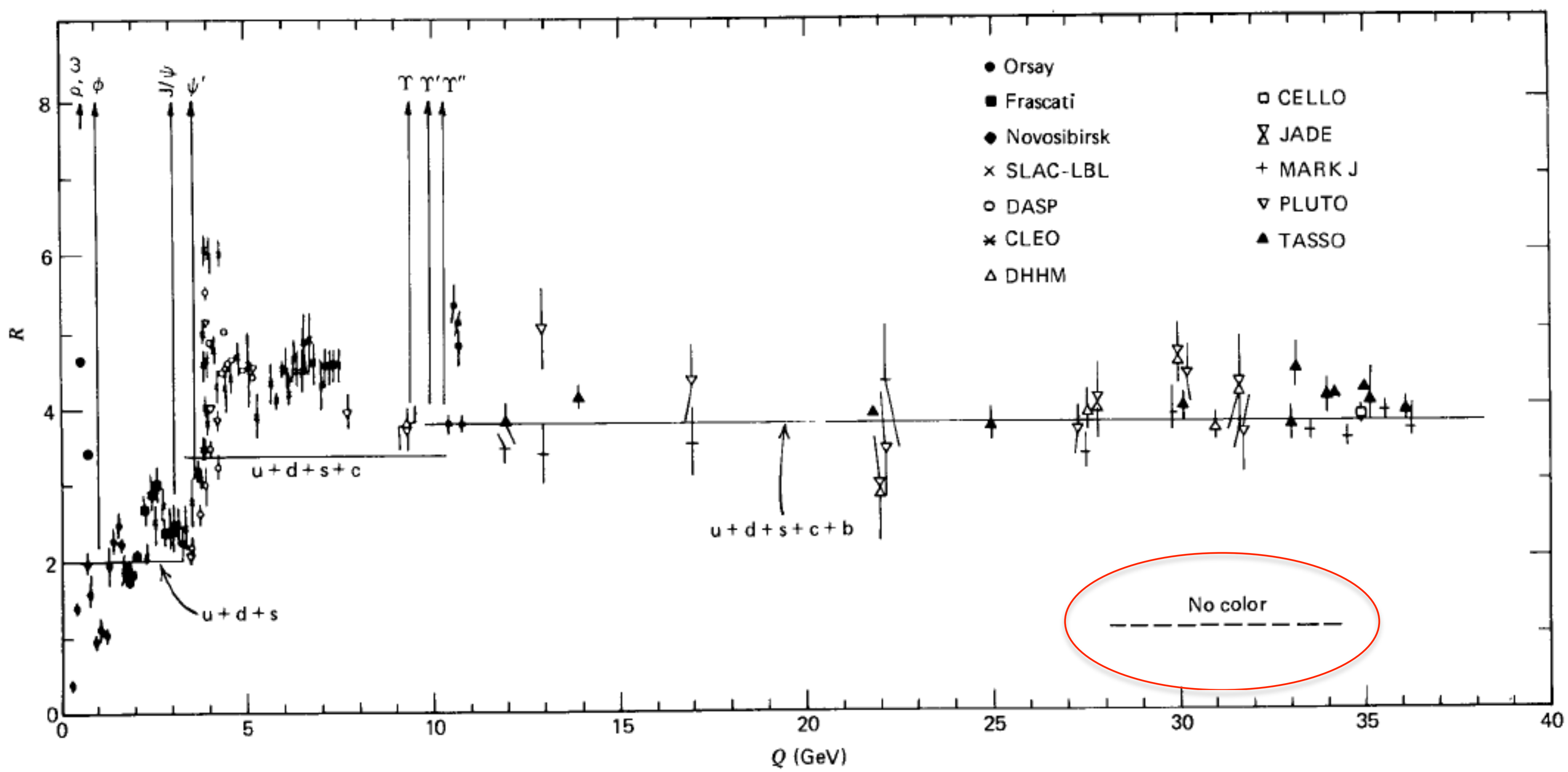
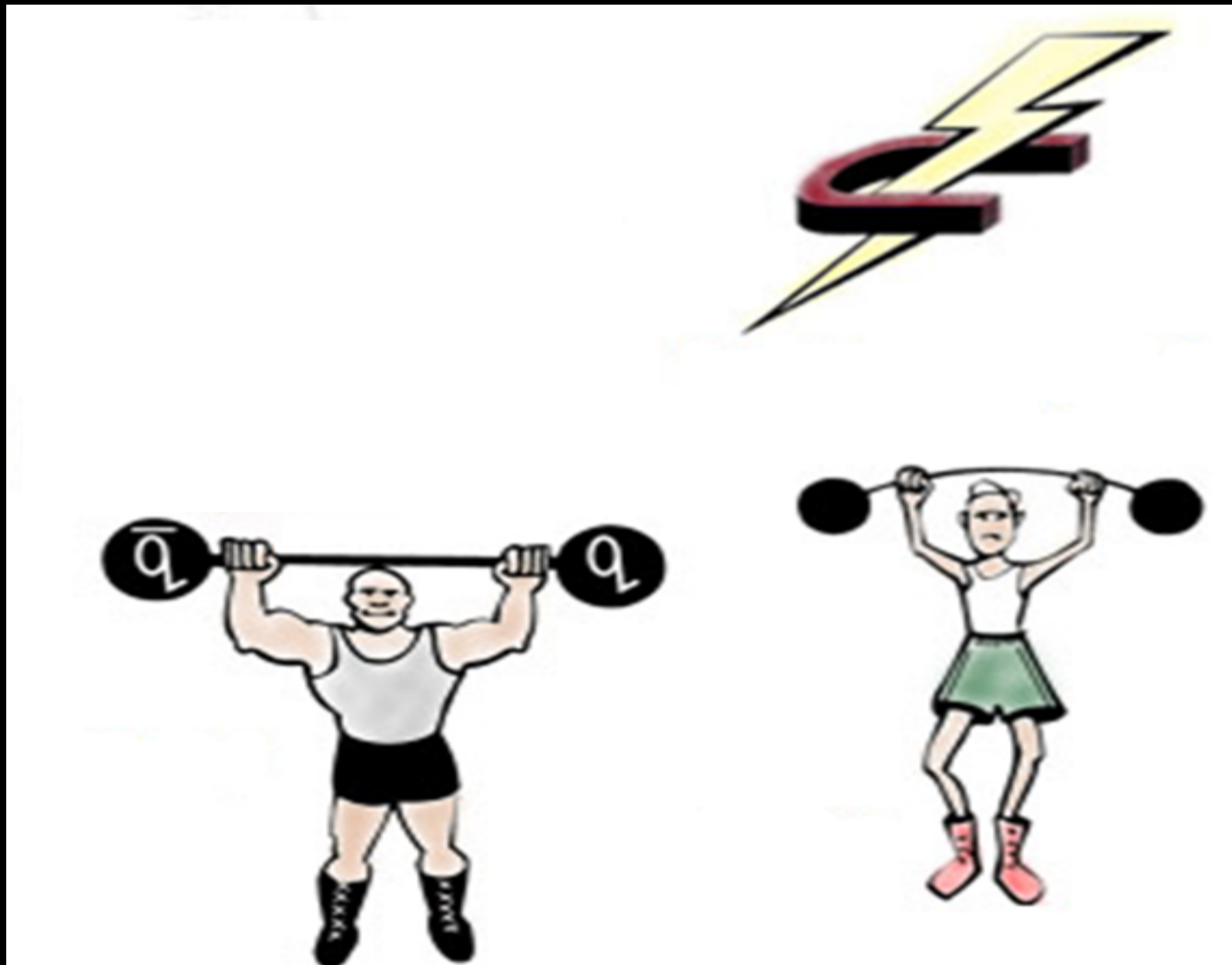


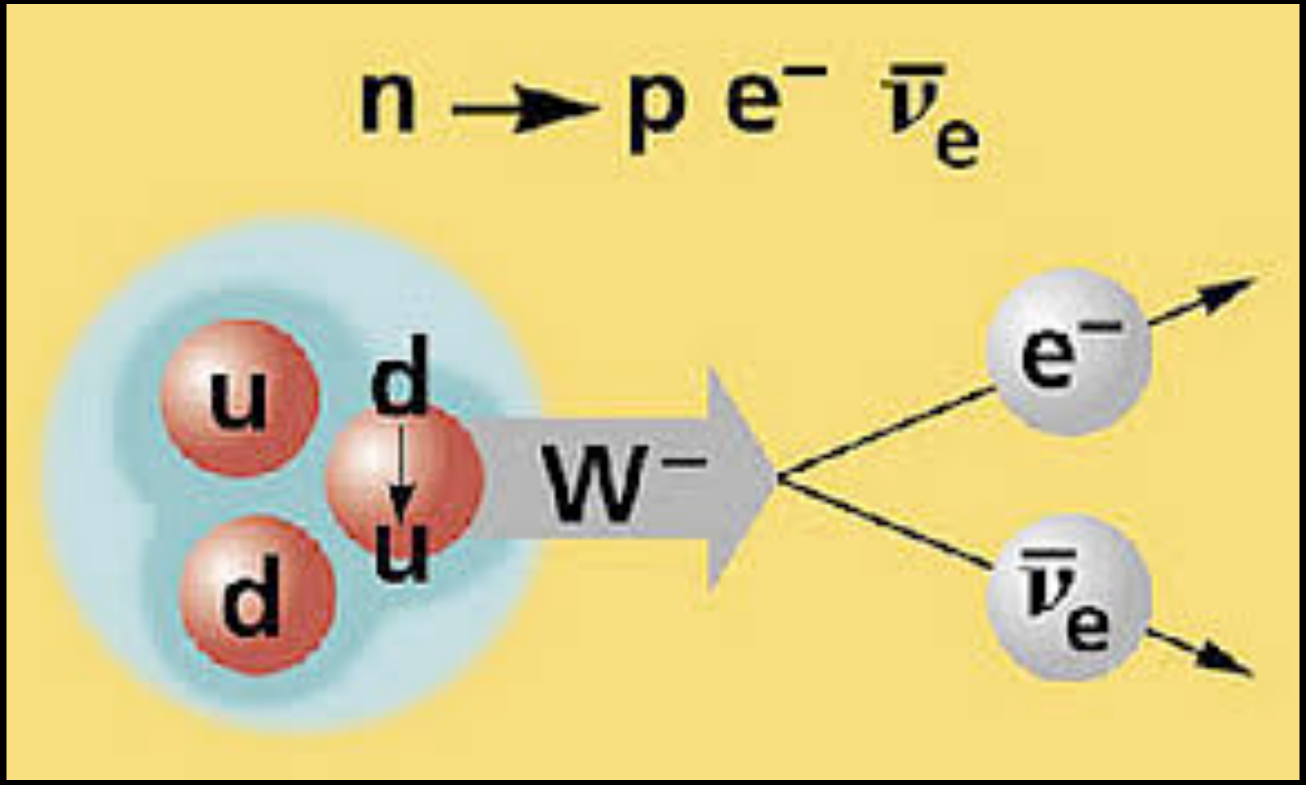
Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)

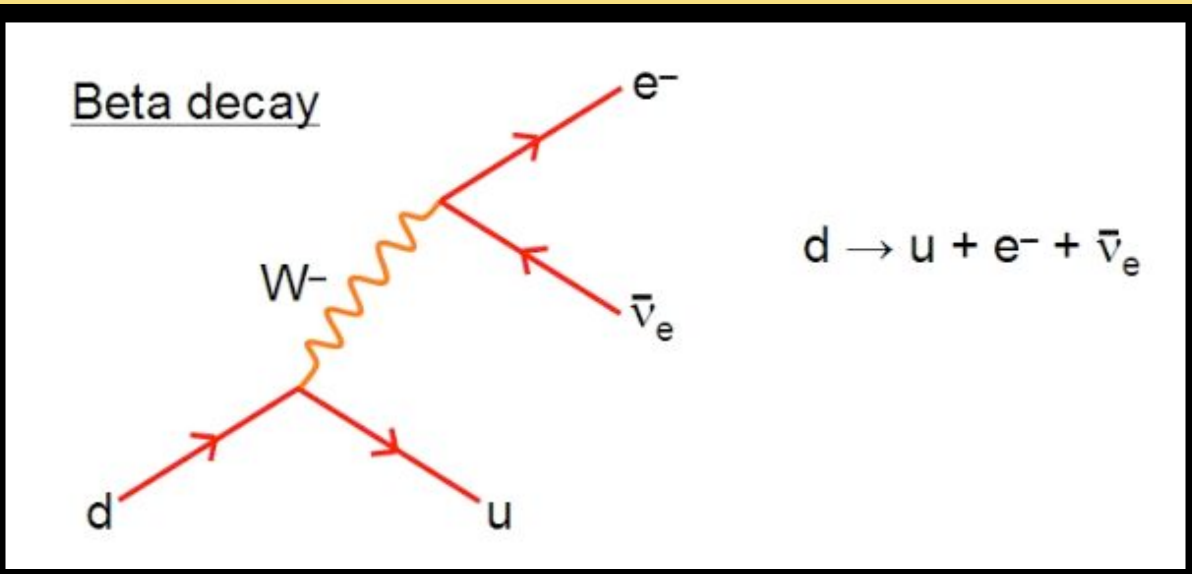
INTERACTIONS

Particle interactions



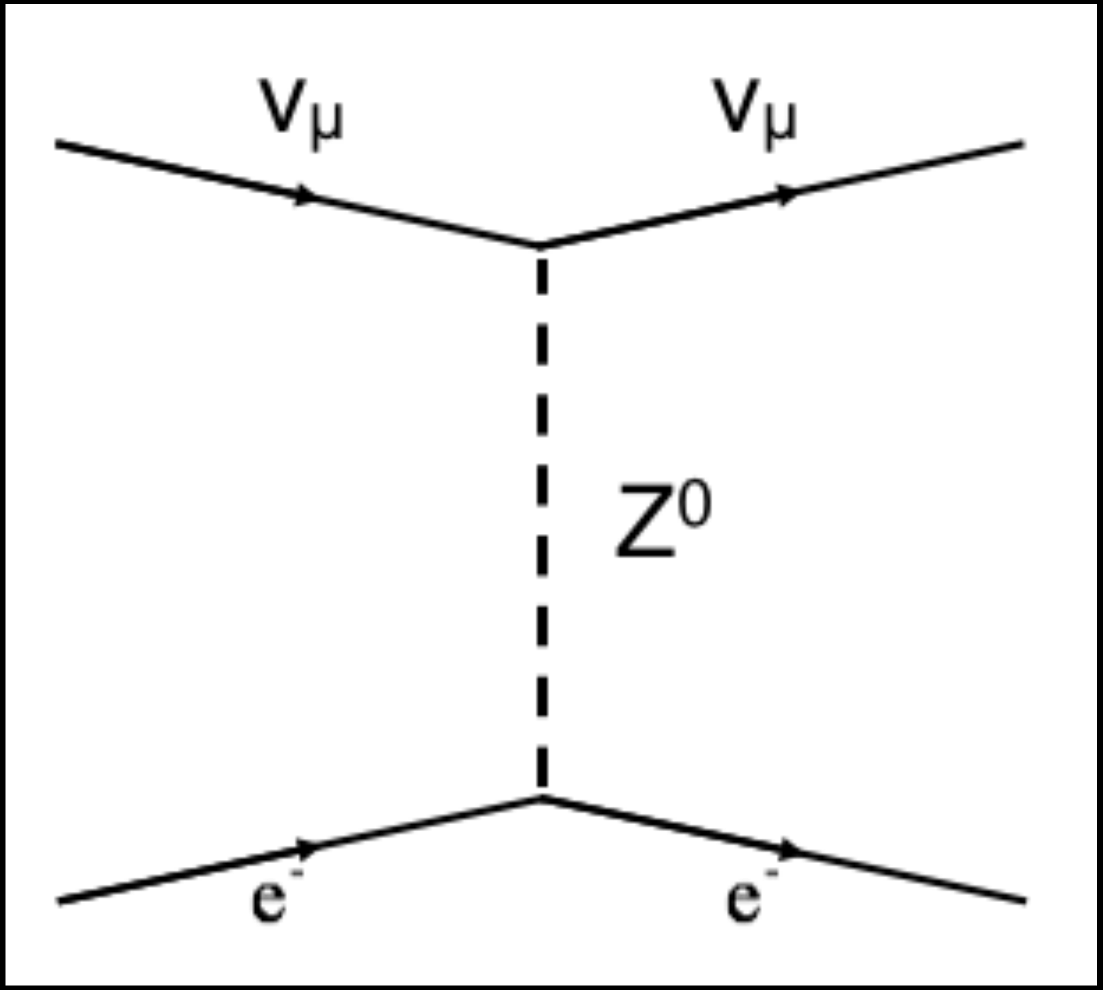
Particles and interactions: weak interactions

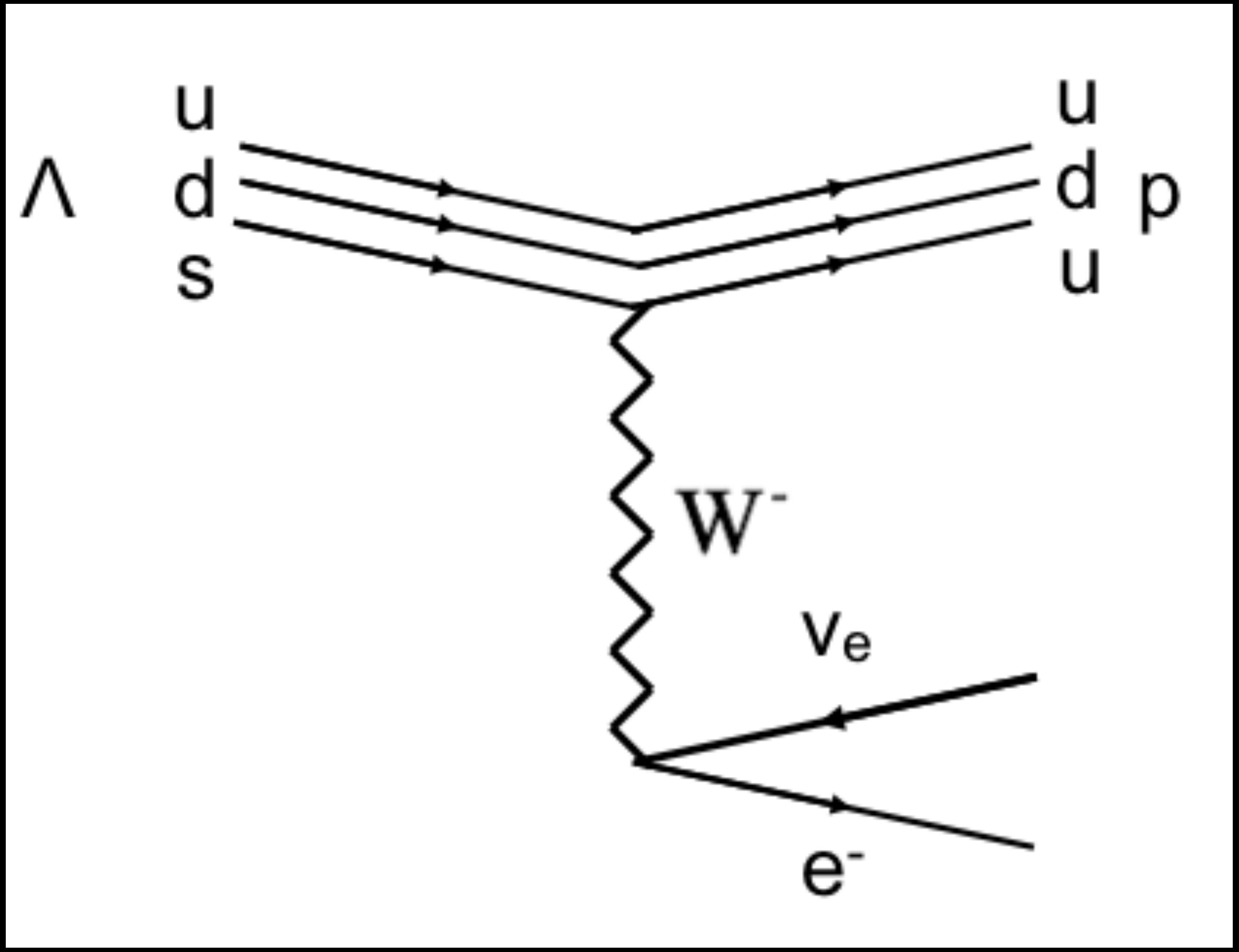




✓ Responsible for β-decay

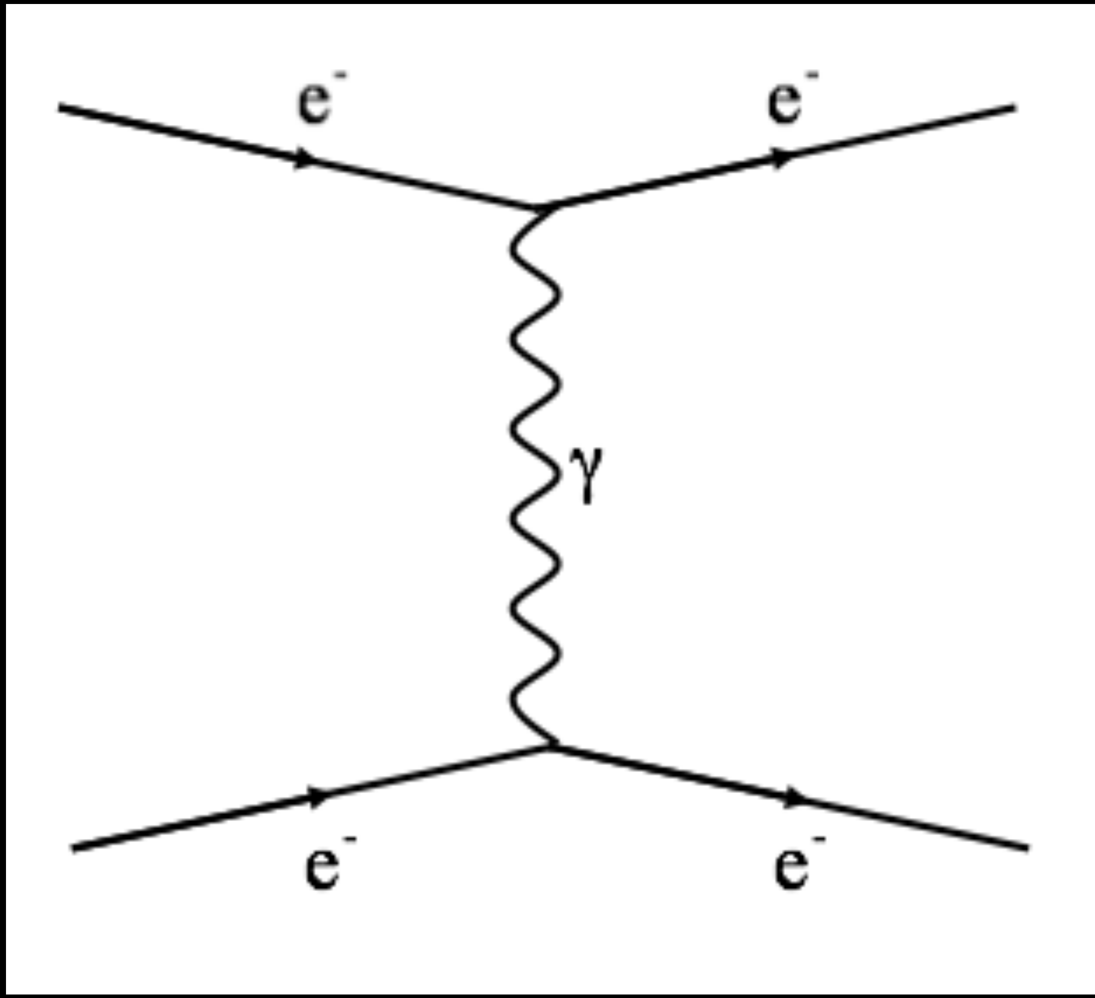
Particles and interactions: weak interactions





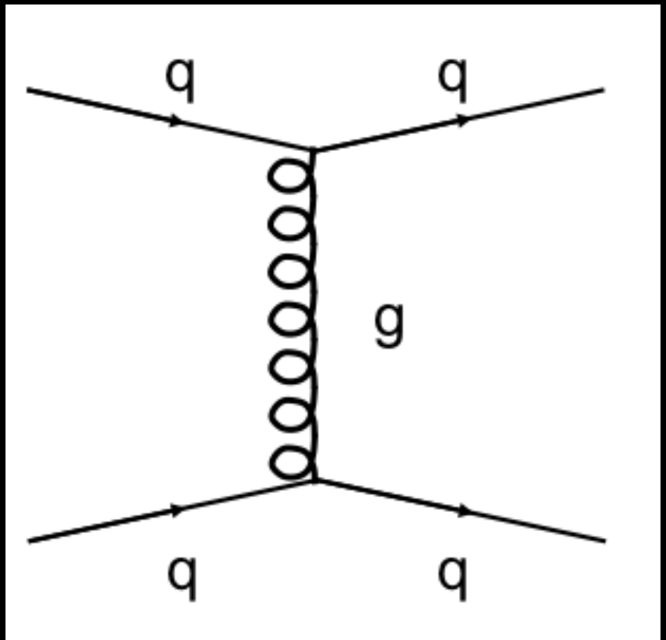
- ✓ Mediated by the W and Z bosons which are massive
- ✓ Acts on leptons but also quarks (and hadrons)
- ✓ Changes the flavour of quarks
  - Long lived decaying particles ~10^{-10}sec

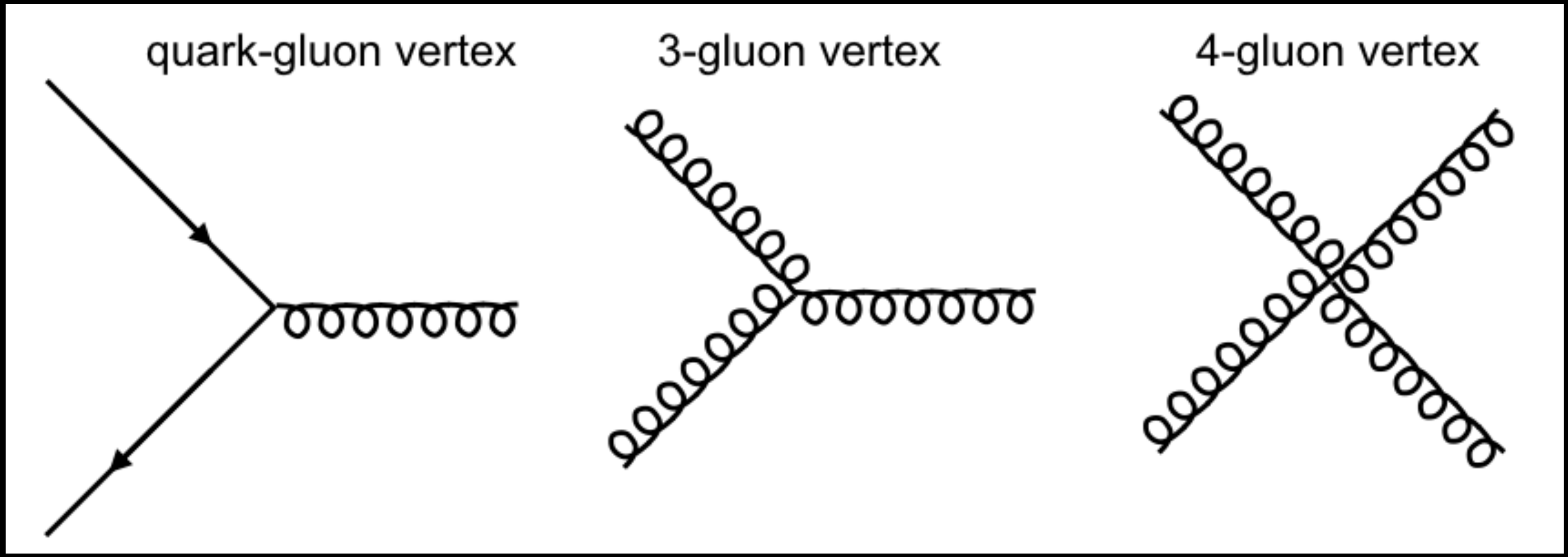
Particles and interactions: electromagnetic interactions



- Mediated by the photon (γ)
- Stronger than the weak interaction
- Acts on leptons and quarks (and hadrons)

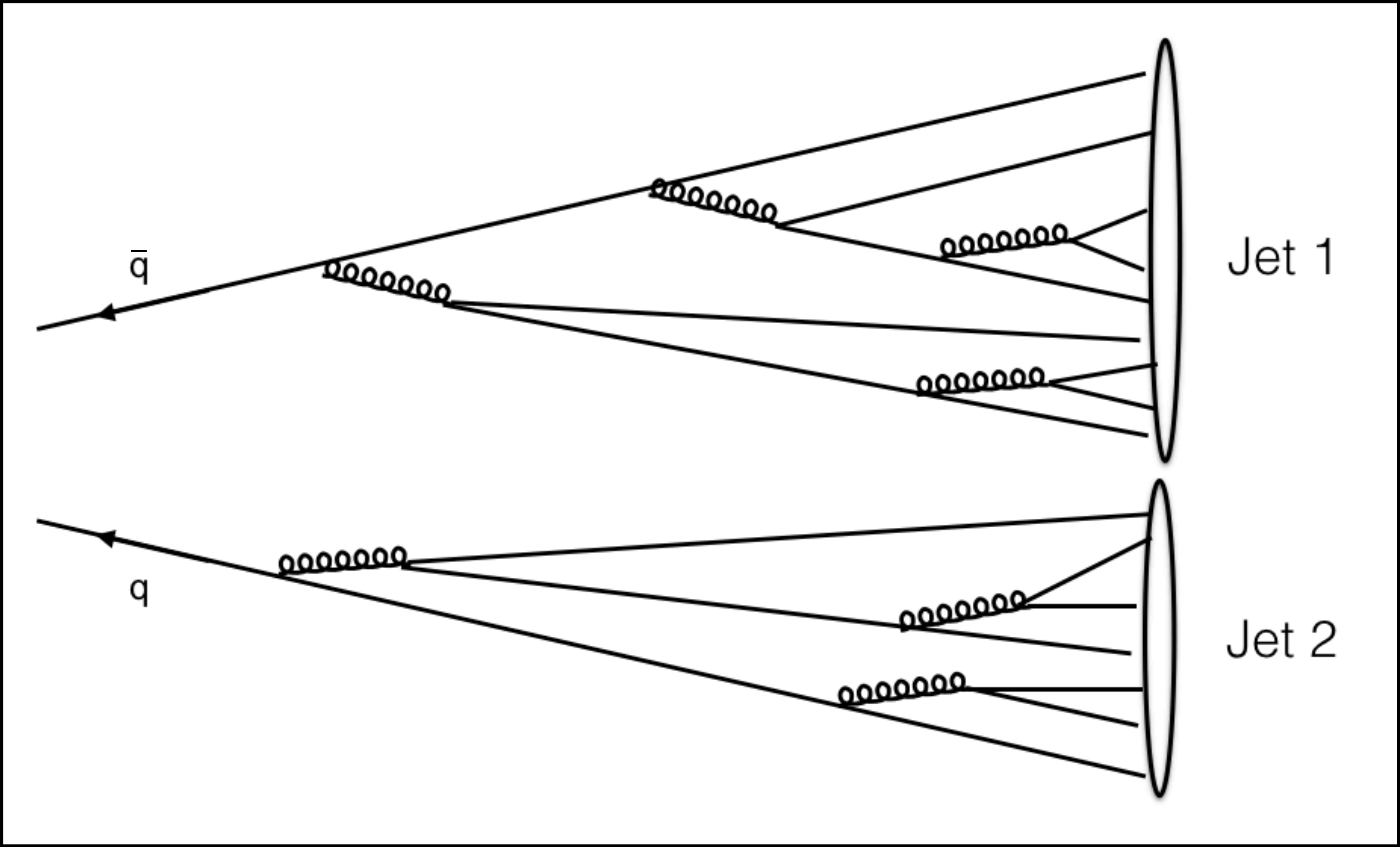
Particles and interactions: strong interactions





- ✓ Mediated by the gluon (g)
- ✓ Strongest interaction in the standard model
- ✓ Acts on gluons and quarks (and hadrons)
- ✓ Responsible for binding composite particles made of quarks and gluons (e.g. protons)

Particles and interactions: strong interactions (jets)



Particles and interactions

Table 5.2: INTERACTIONS AND SUBATOMIC PARTICLES. Entries not in parentheses are for particles that exist free in nature. The particles in parentheses are permanently confined.

Particle	Type	Weak	Electromagnetic	Hadronic
Photon	Gauge boson	No	Yes	No
$W^{\pm}, Z^0$	Gauge bosons	Yes	Yes	No
(Gluon)	Gauge boson	No	No	Yes
Leptons				
Neutrino	Fermion	Yes	No	No
Electron	Fermion	Yes	Yes	No
Muon	Fermion	Yes	Yes	No
Tau	Fermion	Yes	Yes	No
Hadrons				
Mesons	Bosons	Yes	Yes	Yes
Baryons	Fermions	Yes	Yes	Yes
(Quarks)	Fermions	Yes	Yes	Yes

Particle interactions

- Weak interactions, mediated by the massive $W^{\pm}$ and Z^0 bosons
  - The weak force acts on leptons but also quarks (and thus hadrons) and can change the flavour of quarks
  - The decay of particles through the weak force takes anything between 10^{-13} sec and several minutes

- Electromagnetic interactions, mediated by the massless photon (γ)
  - The electromagnetic force acts on leptons and quarks (and thus hadrons)
  - A typical decay lifetime is about 10^{-16} sec

- Strong interactions, mediated by the eight gluons (g)
  - It is the strongest interaction in the standard model
  - The strong force acts on gluons and quarks (and thus hadrons) and is responsible for binding composite particles made of quarks and gluons (e.g. protons)
  - A typical decay lifetime is about 10^{-23} sec

Deciding on the type of interaction

- Deciding which interaction is responsible about a given decay of the form $A \rightarrow B + C$ among the three available is not straightforward unless we know the lifetime of the decay.

- "standard candles" to help us decide which force is involved:

  - If an interaction involves neutrinos, then it's the weak force that is responsible

  - If an interaction involves photons, then the responsible force is the electromagnetic

  - If there is any (quark)flavour changing process, then it's the weak force that is responsible

Panos.Christakoglou@nikhef.nl

Conservation laws

- **Kinematic constrains:** Conservation of energy, momentum and angular momentum
  - As an example a particle cannot decay spontaneously into particles heavier than itself
- **Conservation of electric charge:** All three interactions conserve electric charge
- **Conservation of colour:** Both the weak and the electromagnetic forces do not feel the colour. It's only the strong interactions that can affect it and in these interactions colour is always conserved.
- **Conservation of baryon number:** In any interaction the baryon number (i.e. +1 for baryons and -1 for antibaryons) is conserved
- **Conservation of lepton number:** Leptons do not feel the strong force so the lepton number is conserved by construction. In both the weak and the electromagnetic interactions, the individual lepton numbers i.e. electron, muon and tau lepton numbers are conserved.
- **Conservation of quark flavour:** E/M and strong interactions do not change quark flavour but weak interactions can

Particle decays

- Consider a number of independent particles, each having probability λ to decay
- The number of decayed particle within dt is given by

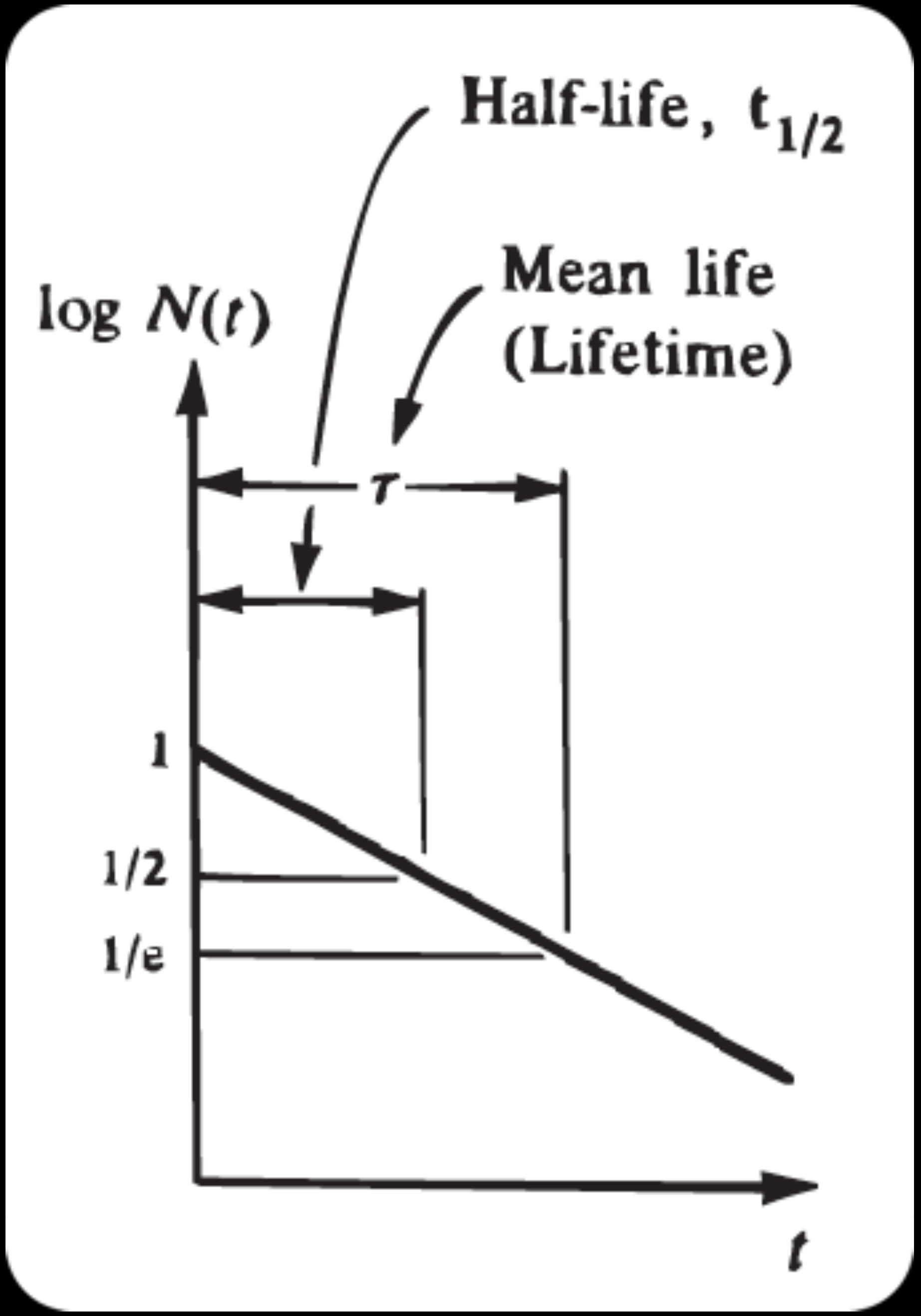
$$dN = -\lambda N(t) dt$$

$$\int_{N_0}^{N(t)} N dN = \int_0^t -\lambda dt$$

$$N(t) = N_0 e^{-\lambda t}$$

- Decay half life ($t_{1/2}$): the time it takes for half of the sample of particles to decay
- Mean lifetime (τ): The average time a particle exists before decaying

$$\tau = \frac{1}{\lambda} = \frac{t_{1/2}}{\ln 2}$$



Particle decays (cont.)

- The wave function of a particle at rest is given by

$$\psi(t)=\psi(0)e^{-iEt/\hbar}$$

- If the energy is real the probability of finding the particle is not time-dependent

$$|\psi(t)|^2=|\psi(0)|^2$$

- Allow the particle to decay, one has to introduce an imaginary part to the energy, such that

$$E=E_0-i\frac{\Gamma}{2}$$

- The probability of finding the particle becomes then

$$|\psi(t)|^2=|\psi(0)|^2e^{-\Gamma t/\hbar}$$

- which agrees with the decay law for

$$\Gamma=\lambda\hbar$$

- The wave function is then given by

$$\psi(t)=\psi(0)e^{-iE_0t/\hbar}e^{-\Gamma t/2\hbar}$$

Particle decays (cont.)

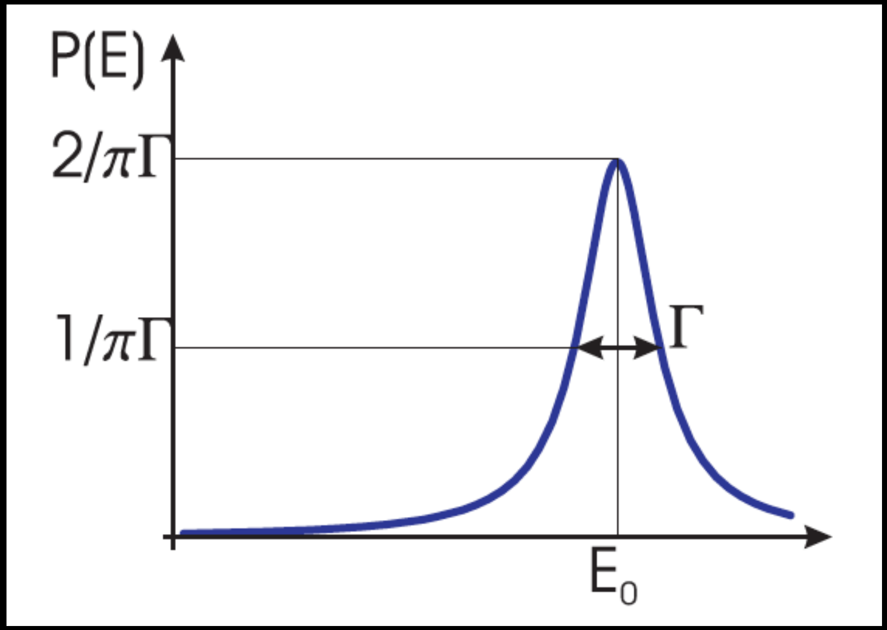
- The probability density of finding a particle with energy E is given by

$$P(E) = (const)\frac{\hbar^2}{2\pi}\frac{|\psi(0)|^2}{(E-E_0)^2+(\Gamma/2)^2}$$

$$\int_{-\infty}^{\infty} P(E)dE = 1 \longrightarrow (const) = \frac{\Gamma}{\hbar^2|\psi(0)|^2}$$

$$P(E) = \frac{\Gamma}{2\pi}\frac{1}{(E-E_0)^2+(\Gamma/2)^2}$$

- The energy of a decaying particle is not sharp but has a width ➡ **natural line width**
- The shape is called Breit-Wigner



- Γ is the full width half maximum (FWHM) $\tau\Gamma = \hbar$

Particle decays (cont.)

Particle	Mass (MeV/c^2)	Main Decays	Decay Energy (MeV)	Lifetime (sec)	Class
μ	106	$e\nu\bar{\nu}$	105	2.2×10^{-6}	W
$\pi^{\pm}$	140	$\mu\nu$	34	2.6×10^{-8}	W
π^0	135	$\gamma\gamma$	135	8.7×10^{-17}	EM
η	549	$\gamma\gamma, \pi\pi\pi$	549	6.3×10^{-19}	EM
ρ	769	$\pi\pi$	489	4.3×10^{-24}	H
n	940	$pe^-\bar{\nu}$	0.8	0.90×10^3	W
Λ	1116	$p\pi^-, n\pi^0$	39	2.6×10^{-10}	W
Δ	1232	$N\pi$	159	6×10^{-24}	H
$D^{\pm}$	1869	$\overline{K^0} + \cdots$		9.2×10^{-13}	W
D^0	1865	$K^{\pm} + \cdots$		4.3×10^{-13}	W
^{8}Be*	3726	2α	3	6×10^{-22}	H

- ✓ Strong interactions: ~10^{-23} s
- ✓ E/M interactions: ~10^{-18} s
- ✓ Weak interactions: ~10^{-10} s

Backup

Nuclei

- Complicated structures
- In the 30's it was well established that the electric charge Q and the mass M are characterised by two integers, Z and A:

$$Q = Ze \qquad M \approx A m_p$$

- The nuclear charge Z was determined by
  - the α-particle scattering experiment of Rutherford
  - X-ray scattering
  - the energy of characteristic X-rays
- The nuclear charge Z is identical to the chemically determined atomic number
- The mass A was determined from mass spectroscopy
  - A given element can have nuclei with different values of A

Nuclei (cont.)

- The ground state of any nuclear species is characterised by two integer numbers: A and Z

- The understanding of this relationship was rather unclear until the discovery of the Neutron by Chadwick in 1932
  - A nucleus (A,Z) is composed of Z protons and N = A - Z neutrons
  - neutrons and protons are about of the same mass therefore the mass of the nucleus is A times the mass of the proton
  - The mass number A is the sum of the number of protons and neutrons and is also called the baryon number

- The charge is completely due to the protons so Z

Nuclei (cont.)

- **Nuclide**: a particular nuclear species with a given number of protons and neutrons,
- **Isotopes**: are nuclides with the same number of protons (same Z)
- **Isotones**: are nuclides with the same number of neutrons (same N)
- **Isobars**: are nuclides with the same total number of nucleons A
- A particular nuclide is characterised as (A,Z) or as

$${}^{A}_{Z}X \qquad {}^{4}_{2}He$$

- Stable nuclide, characterised by N = A - Z and Z only exist in a small band in the N-Z plane:
  - The curve initially starts at 45° for nuclides with equal number of protons and neutrons
  - Then the nuclides become neutron rich
- At the mass number A = 1 nuclear and particle physics meet.
  - It is temping to consider the nucleons (protons and neutrons) as the two building blocks of heavier nuclides.
  - However there are more A = 1 hadrons.

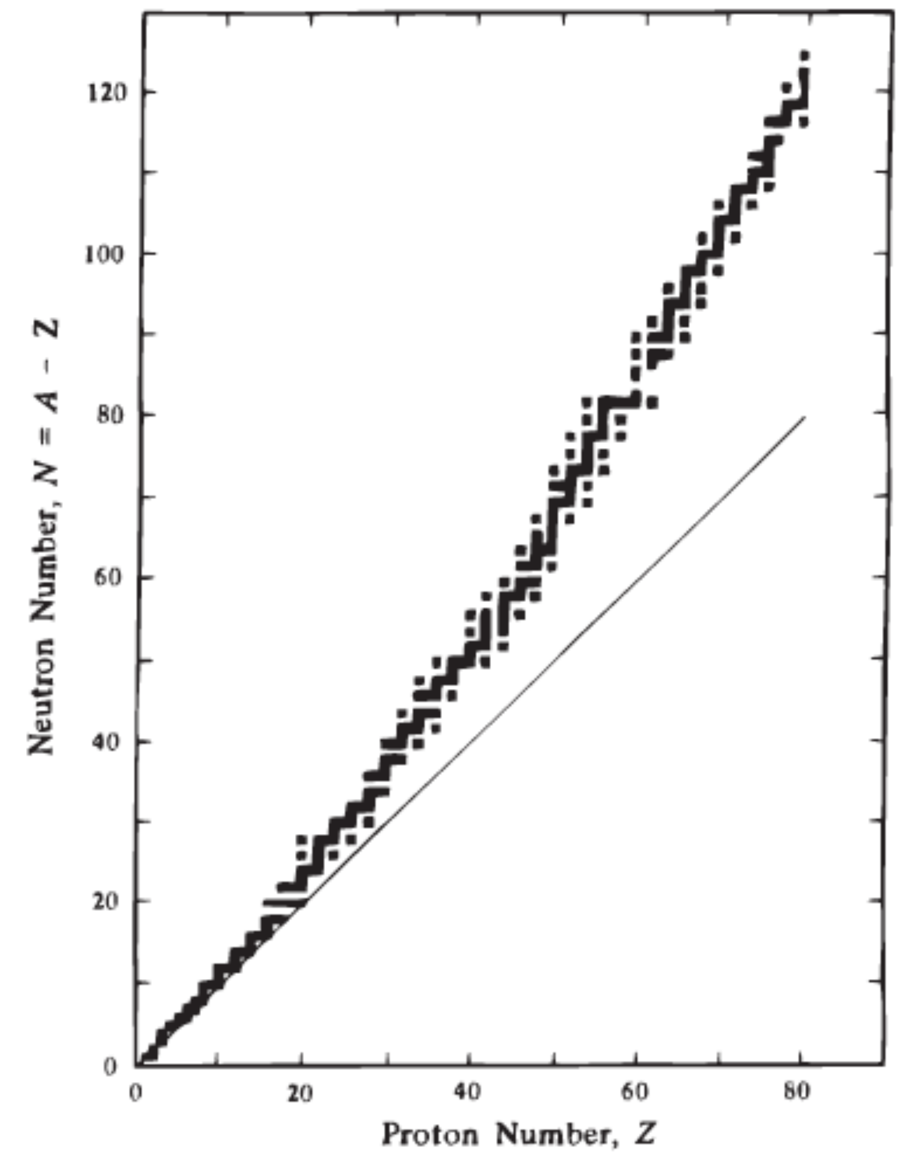
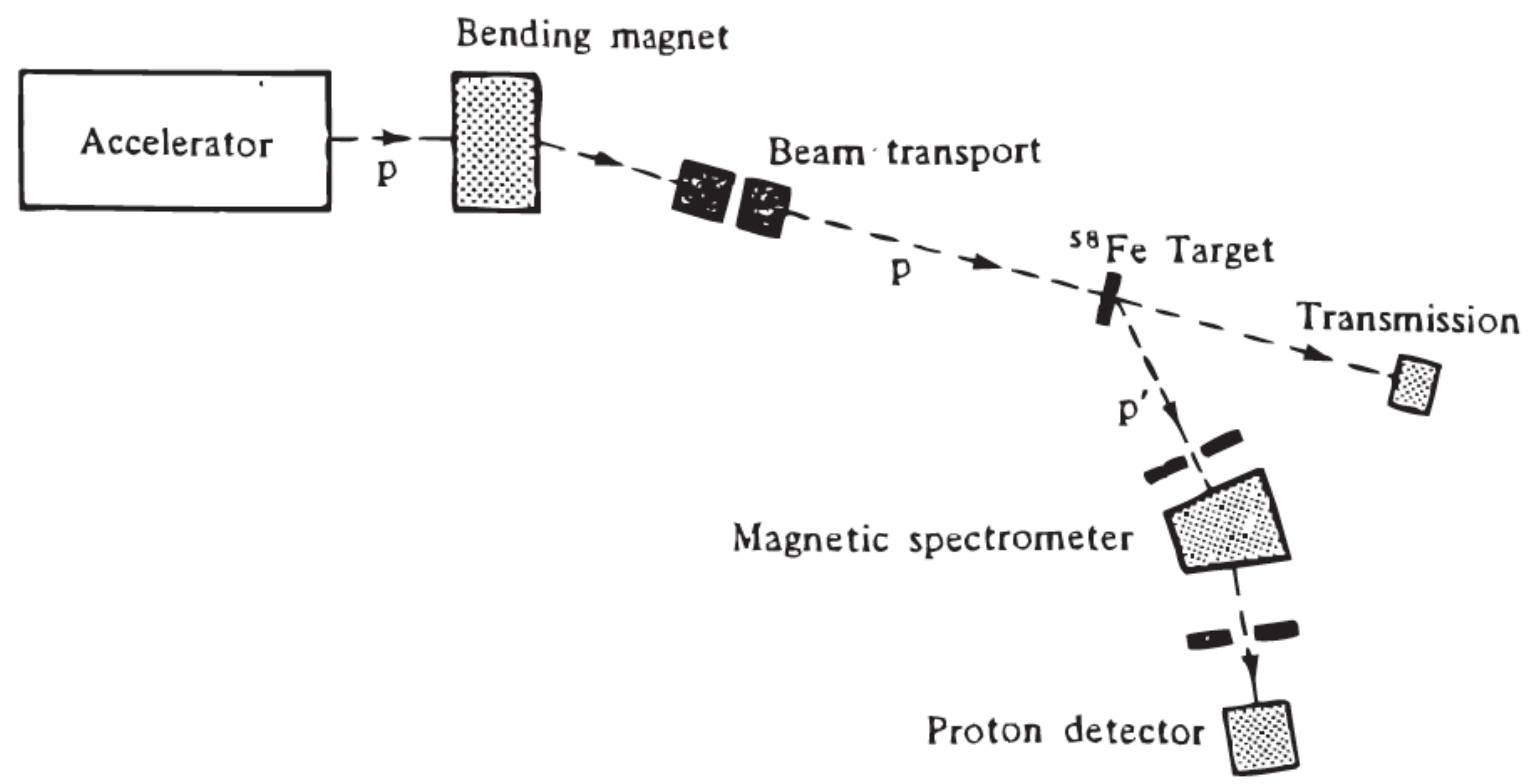


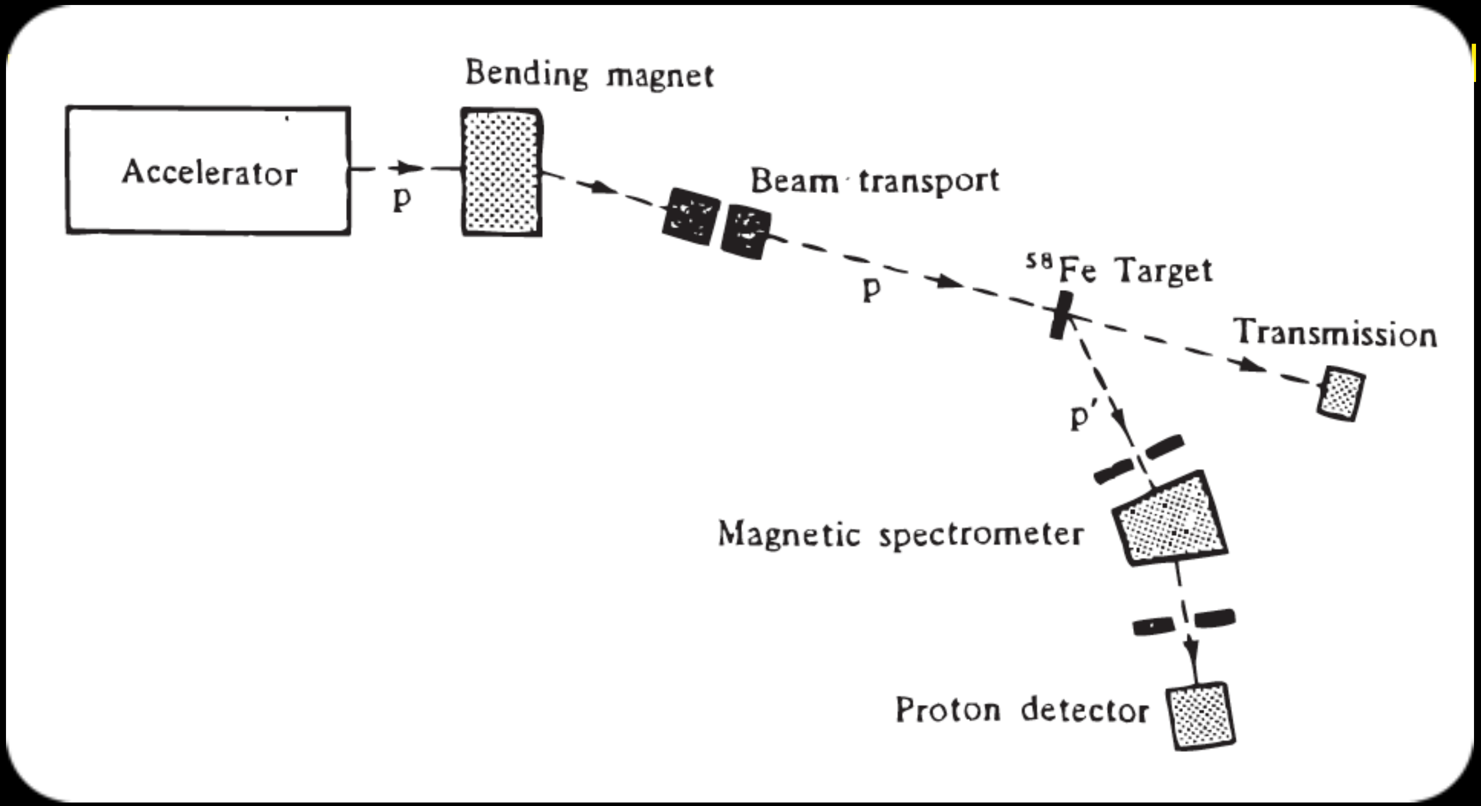
Figure 5.20: Plot of the stable nuclides. Each stable nuclide is indicated as a square in this $N - Z$ plot. The solid line would correspond to nuclides with equal proton and neutron numbers. (After D.L. Livesey, *Atomic and Nuclear Physics*, Blaisdell, Waltham, MA, 1966.)

Excited states of nuclides and baryons

- The study of different nuclear and particle states is performed within the field of nuclear and particle spectroscopy
- As an example, the nuclide ^{58}Fe with a natural abundance of 0.31%
  - Its energy levels can be investigated with the setup below



Excited states of nuclides and baryons (cont.)



- An accelerator produces a proton beam with a well defined energy
- The beam is transported to a scattering centre where it hits a thin target
- The target consist of an iron foil enriched with the nuclide under study
- The transmission through the foil can be studied as a function of the energy of the incoming proton
- The beam scatters off the target and changes its direction and energy (transition indicated as p ➡ p')
- If the kinetic energy of the incoming proton is Ep and the outgoing is Ep', then the nucleus received an energy ΔE = Ep - Ep'

Excited states of nuclides and baryons (cont.)

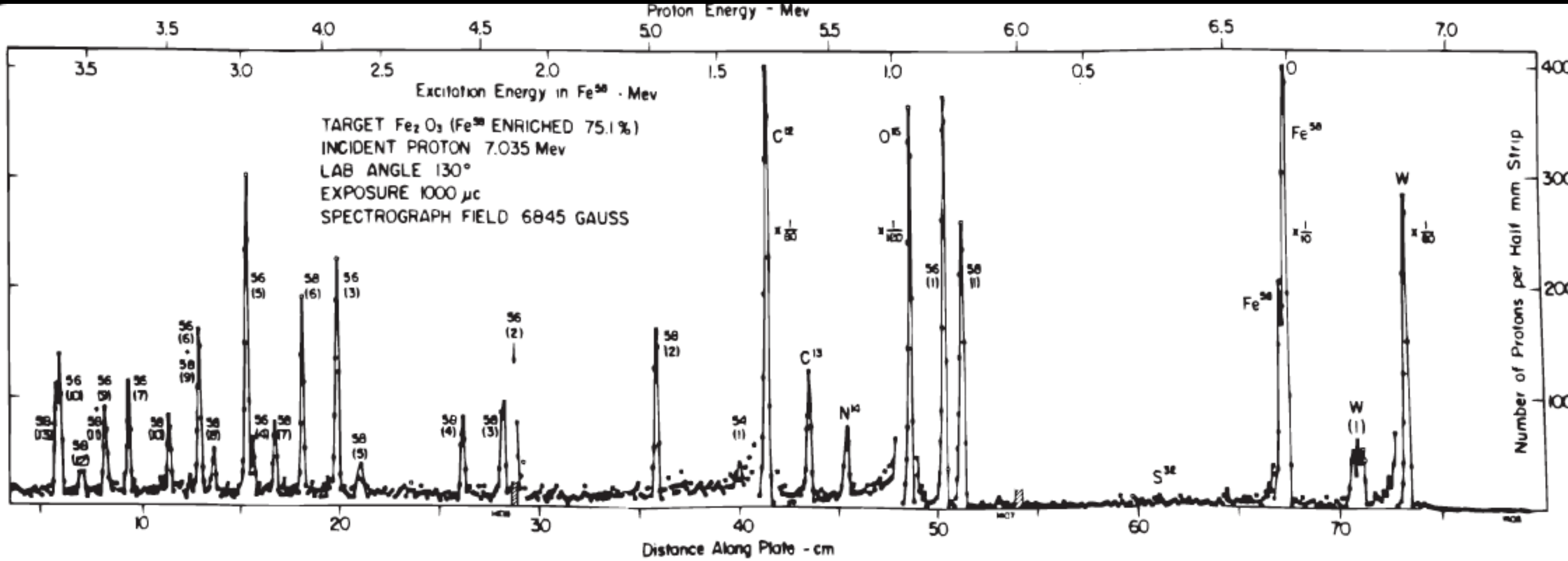


Figure 5.33: Spectrum of protons scattered from enriched ^{58}Fe (75.1%) target. The detector consists of photographic plates so that many lines can be observed simultaneously. [From A. Sperduto and W. W. Buechner, *Phys. Rev.* **134**, B142 (1964).] Since the target still contains some isotopes other than ^{58}Fe, additional lines appear. The iron lines are labeled by the mass number A.

Excited states of nuclides and baryons (cont.)

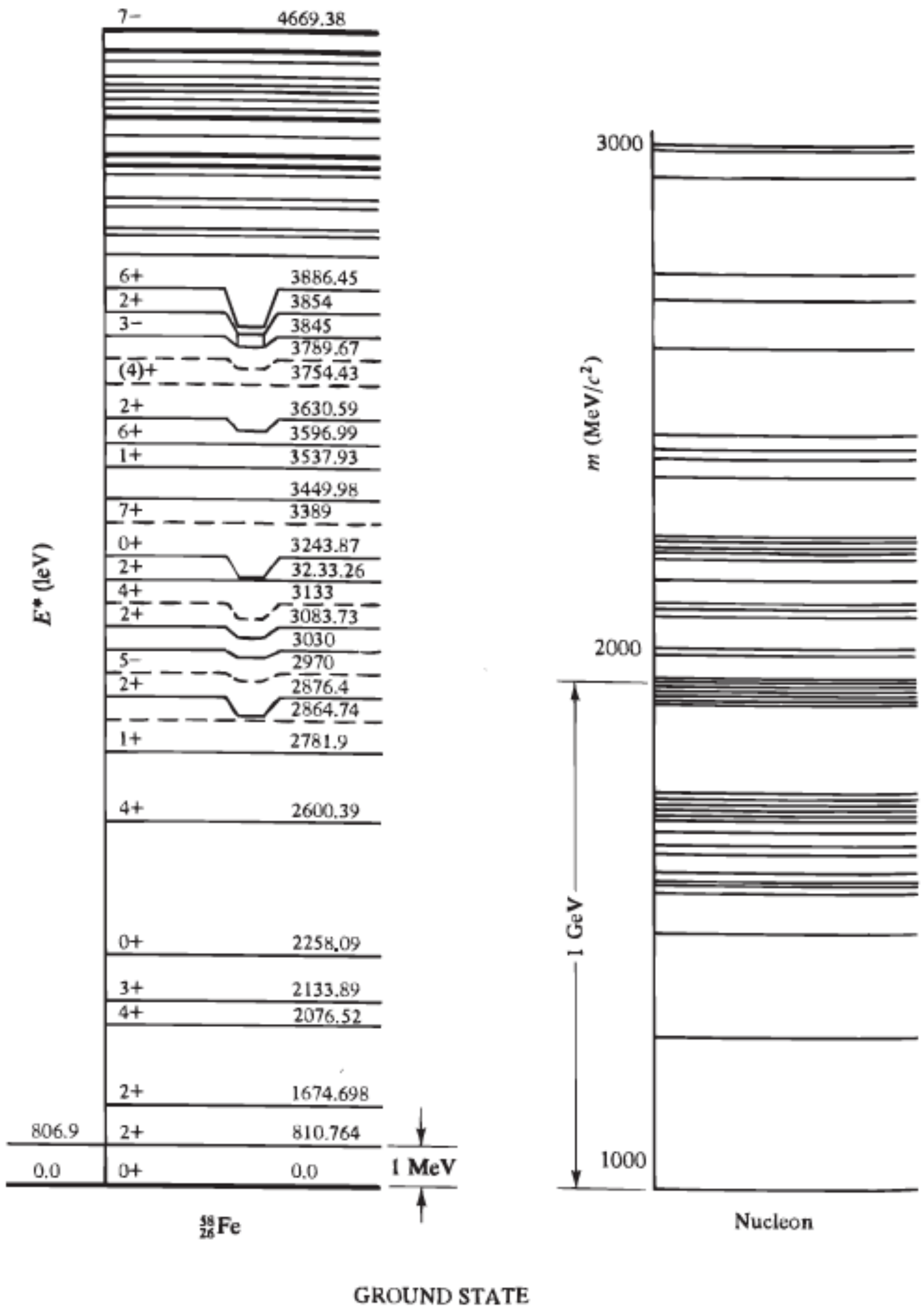


Figure 5.37: Ground state and excited states of the nuclide ^{58}Fe and of the nucleon (neutron and proton). The region above the nuclear ground state in Fig. 5.36 has been enlarged by a factor of about 5000. The spectrum of the nucleon in Fig. 5.36 has been magnified about 40 times. The nuclear states have widths of the order of eV or less and consequently can be observed separately. The excited particle states or resonances, on the other hand, have widths of the order of a few hundred MeV; they overlap and are often very difficult to find. It is likely that many additional levels exist.