

Rozdział 2

Model kwarków

**Systematyka cząstek w modelu
kolorowych kwarków i gluonów**

**Konstrukcja multipletów
mezonowych i barionowych**



A SCHEMATIC MODEL OF BARYONS AND MESONS *

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If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" ¹⁻³⁾, we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone ⁴⁾. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^- , s^- , u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" ⁶⁾ q and the members of the anti-triplet as anti-quarks \bar{q} . Baryons can now be constructed from quarks by using the combinations (qqq) , $(qqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

“Praca z propozycją istnienia kwarków została przyjęta do druku w *Physics Letters* tylko dlatego, że autorem był Gell-Mann. Redaktor pomyślał sobie: ta praca jest zwariowana, ale jeśli ją zaakceptujemy i okaże się nonsensem, to blamaż spadnie na Gell-Manna, a nie na *Physics Letters*. Jeśli jednak ją odrzucimy a okaże się prawdziwa, to będą się z nas wyśmiewać.”



Harry Lipkin (1997)

Podstawowe informacje

Oryginalne symbole kwarków: n , p , λ

Potem zmienione (za sugestią Feynmana) na d (*down*), u (*up*), s (*strange*)

kolejne kwarki: c (*charm*) - 1974

b (*bottom, beauty*) - 1977

t (*top, truth*) - 1995

mezony $q_i \bar{q}_j$ kwarki walencyjne

bariony $q_i q_j q_k$

antybariony $\bar{q}_i \bar{q}_j \bar{q}_k$

(poza kwarkami walencyjnymi są jeszcze kwarki morza)

(*valence quarks, sea quarks*)

dziwność

↓

Wzór Gell-Manna-Nishijimy: $Q = I_3 + B/2 + S/2 = I_3 + Y/2$

↑

liczba barionowa hipertładunek

Wzór uogólniony: $Q = I_3 + B/2 + S/2 + C/2 + b/2 + t/2$

„zapachy” kwarków

Kwarki

	B	e_q	S	C	b	t	J	I_3
d	1/3	- 1/3	0	0	0	0	1/2	-1/2
u	1/3	+2/3	0	0	0	0	1/2	1/2
s	1/3	- 1/3	-1	0	0	0	1/2	0
c	1/3	+2/3	0	1	0	0	1/2	0
b	1/3	- 1/3	0	0	-1	0	1/2	0
t	1/3	+2/3	0	0	0	1	1/2	0

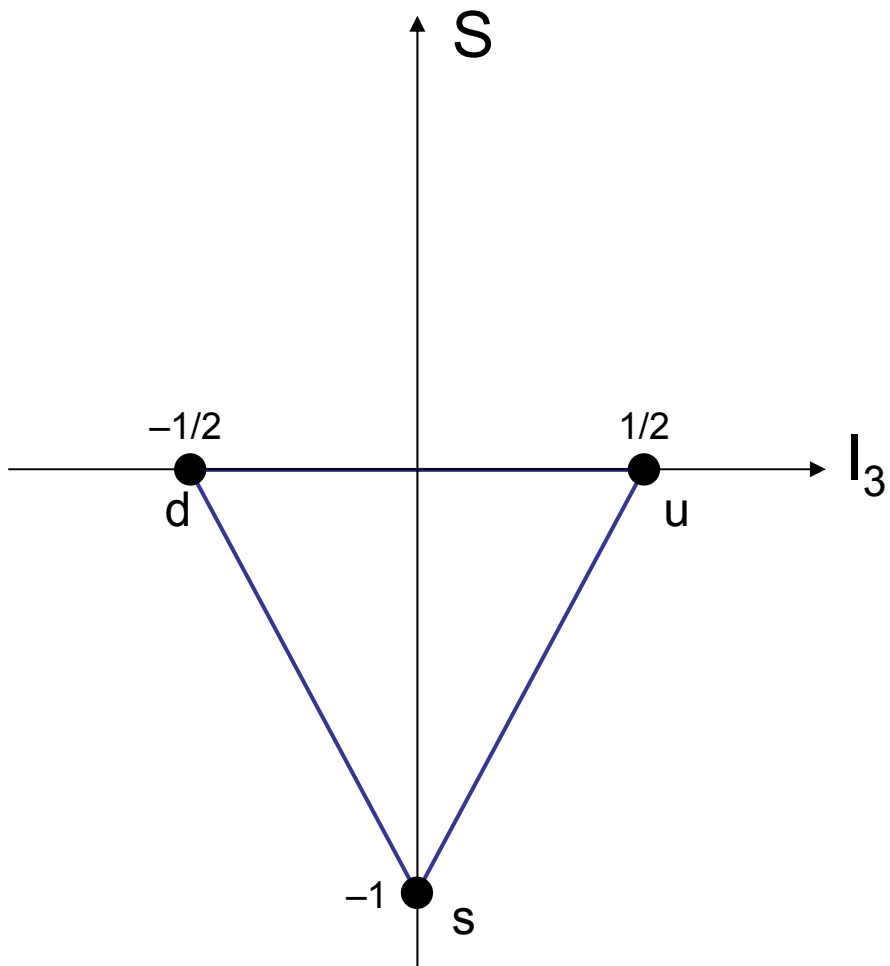
Kwarki i antykwarki są fermionami o spinie 1/2

Antykwarki

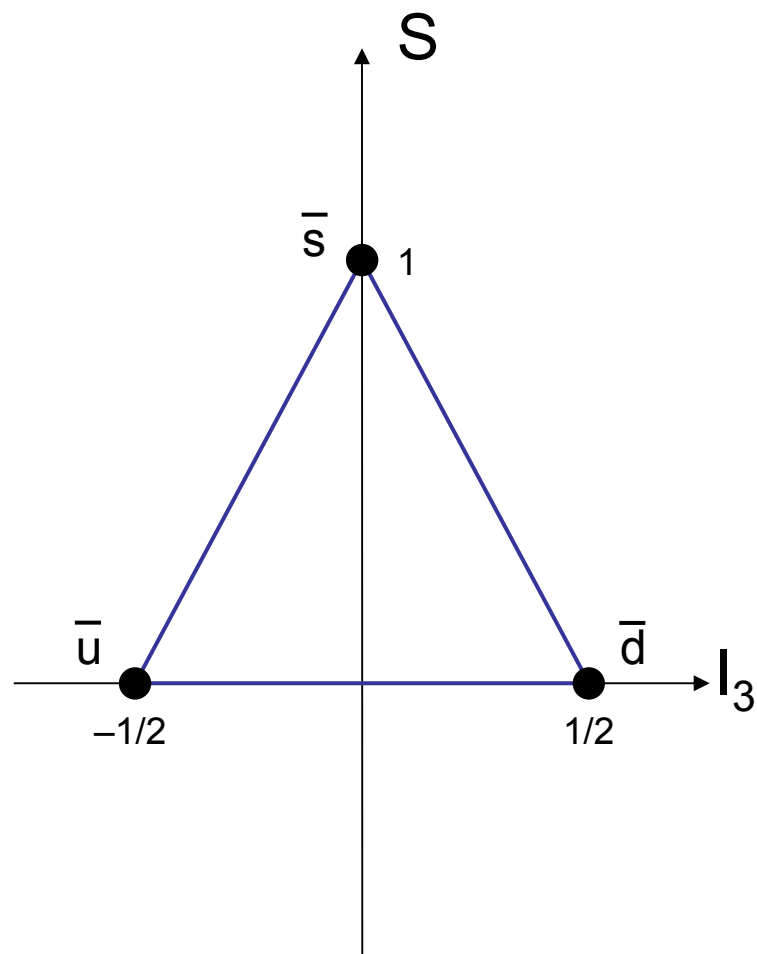
	B	e_q	S	C	b	t	J	I_3
\bar{d}	-1/3	+1/3	0	0	0	0	1/2	1/2
\bar{u}	-1/3	-2/3	0	0	0	0	1/2	-1/2
\bar{s}	-1/3	+1/3	1	0	0	0	1/2	0
\bar{c}	-1/3	-2/3	0	-1	0	0	1/2	0
\bar{b}	-1/3	+1/3	0	0	1	0	1/2	0
\bar{t}	-1/3	-2/3	0	0	0	-1	1/2	0

Kwarki i antykwarki są fermionami o spinie 1/2

kwarki u, d, s



antykwaraki \bar{u} , \bar{d} , \bar{s}



Mezony = kwarkonia (*quarkonium*)

Notacja spektroskopowa $^{2S+1}\mathbf{L}_{J=L+S}$ albo J^P

Przykłady $^1\mathbf{S}_0$ 0^- (mezony pseudoskalarne)
 $L = 0, S = 0, J = 0$

$^3\mathbf{S}_1$ 1^- (mezony wektorowe)
 $L = 0, S = 1, J = 1$

$^3\mathbf{P}_2$ 2^+ (mezony tensorowe)
 $L = 1, S = 1, J = 2$

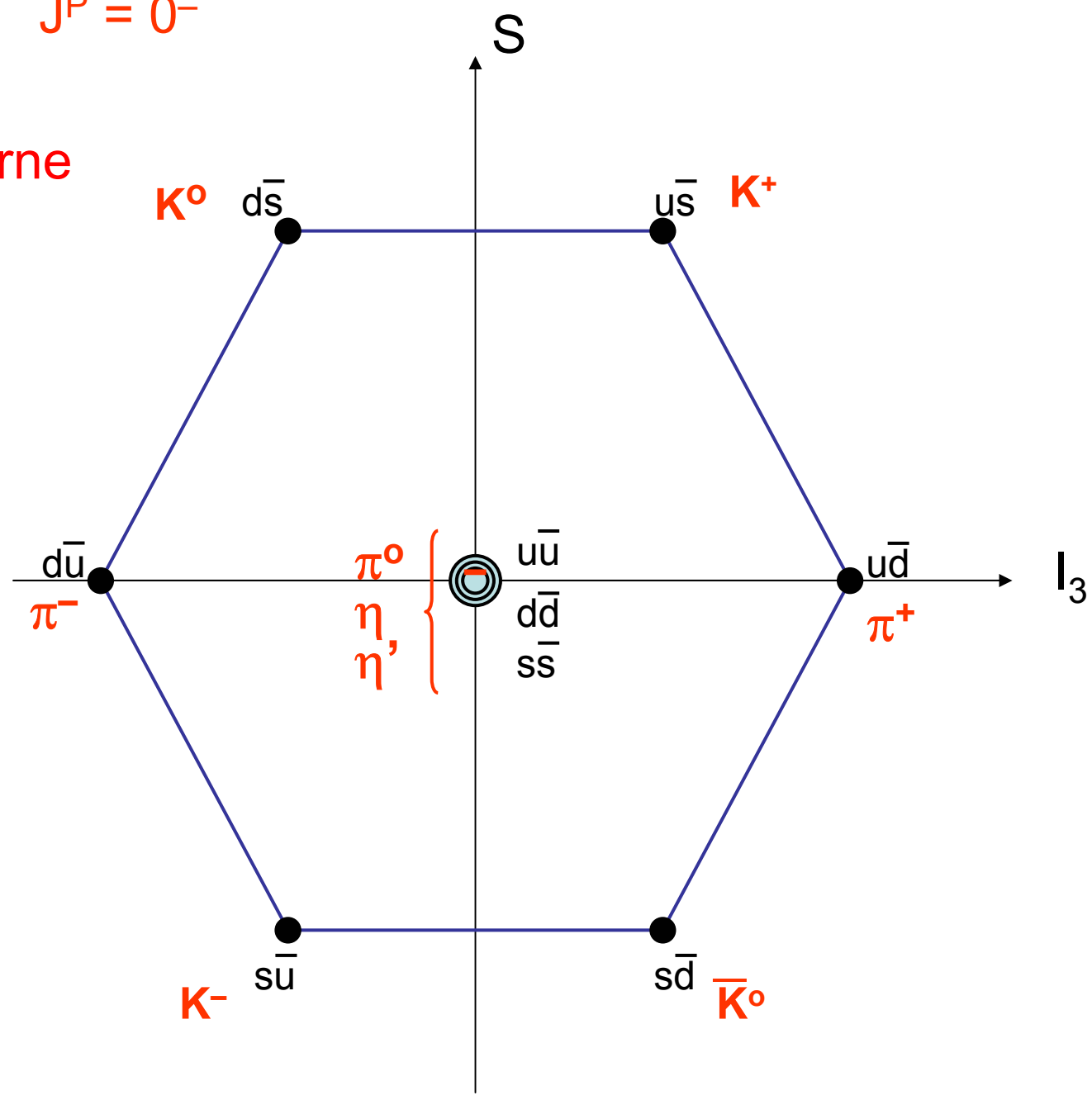
Parzystość $P = (-1)^L (-1)^L$



parzystość wewnętrzna pary fermionów

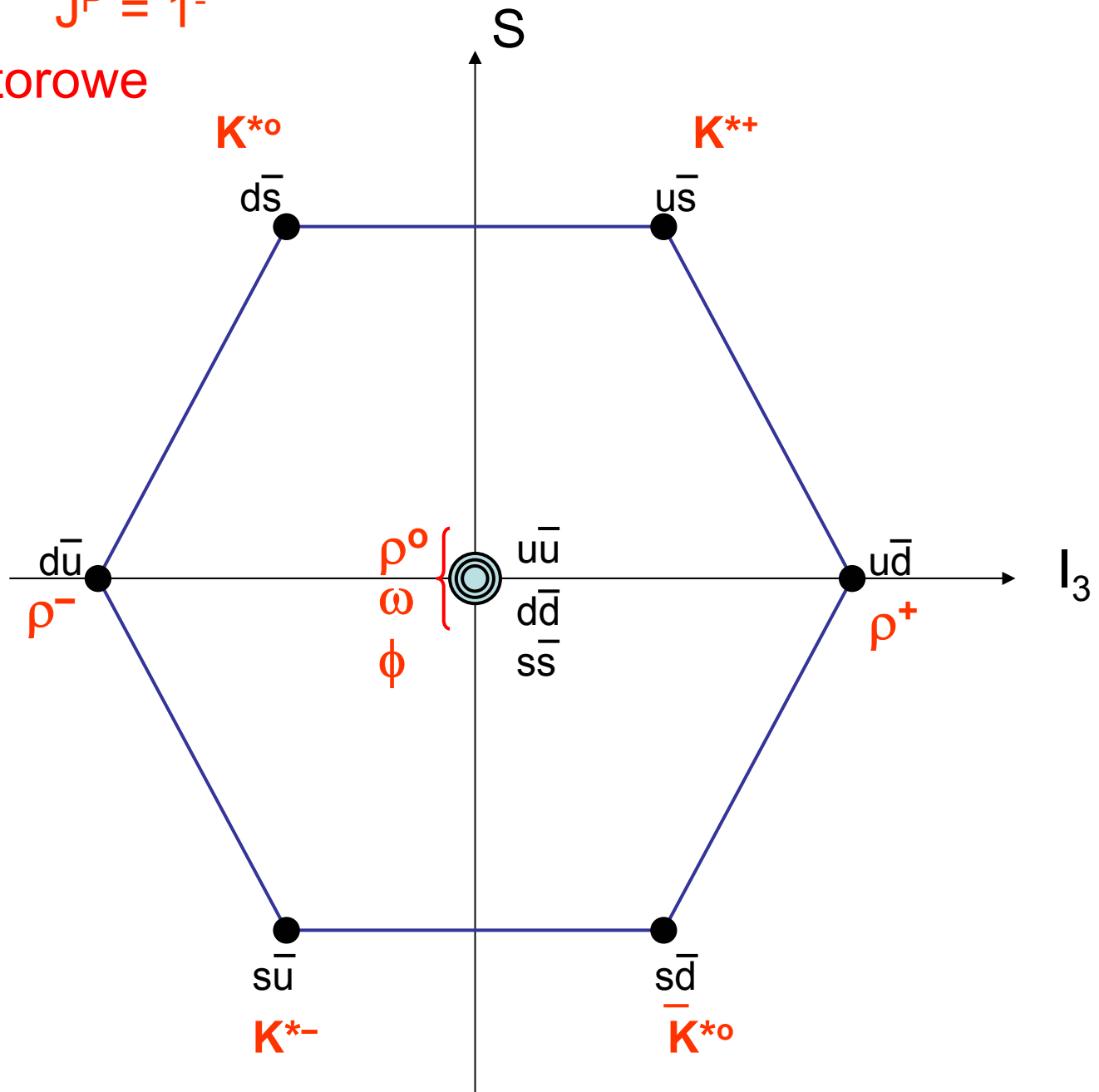
Multiplet 1S_0 $J^P = 0^-$

Mezony
pseudoskalarne



	Masa (MeV)
$\pi^+ \pi^-$	140
π^0	135
$K^0 \bar{K}^0$	498
$K^+ K^-$	494
η	548
η'	958

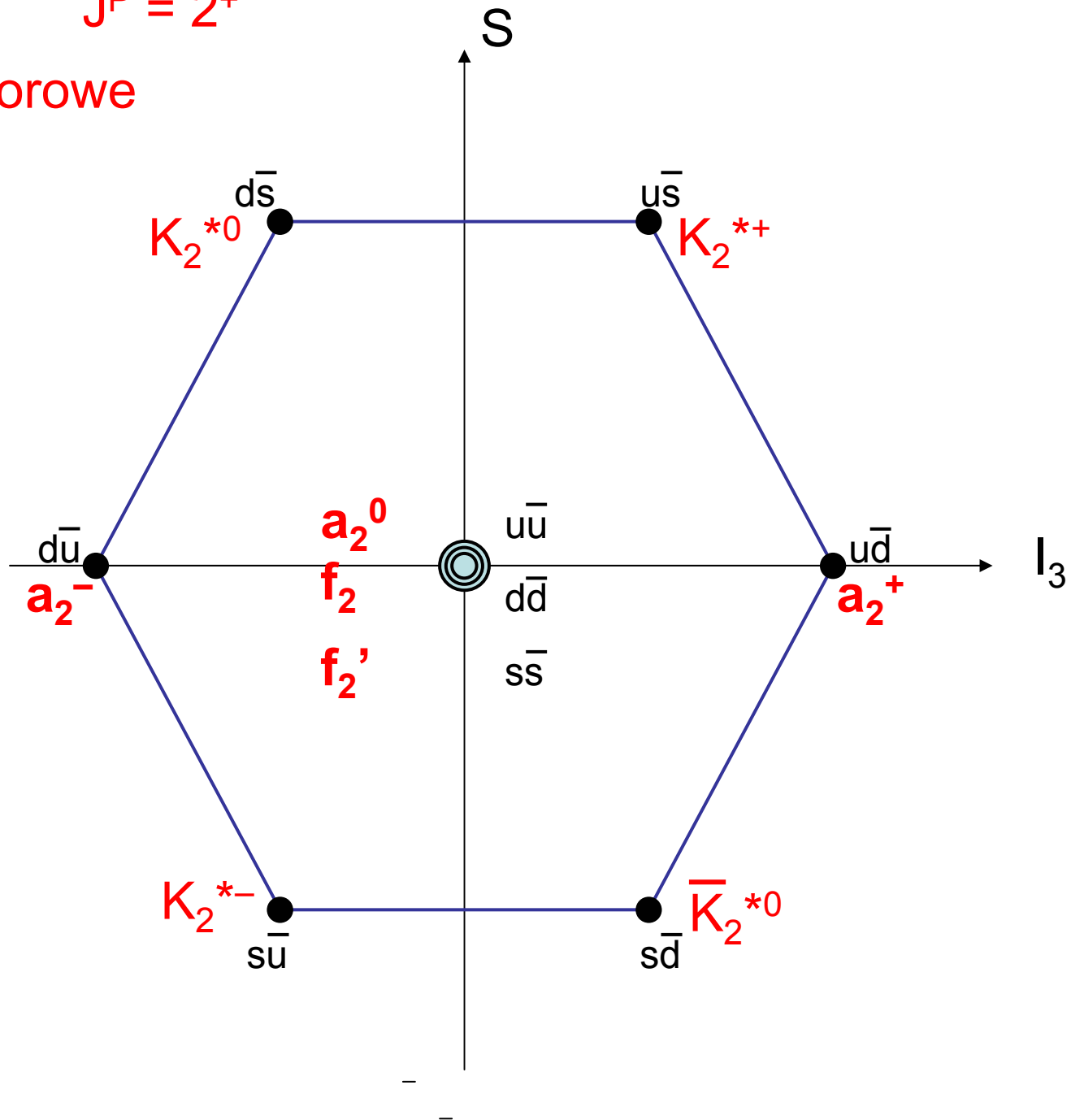
Multiplet 3S_1 $J^P = 1^-$
 Mezony wektorowe



Masa (MeV)	
$\rho^+ \rho^-$	776
ρ^0	776
$K^{*0} K^{*0}$	892
$K^{*+} K^{*-}$	892
ω	782
ϕ	1020

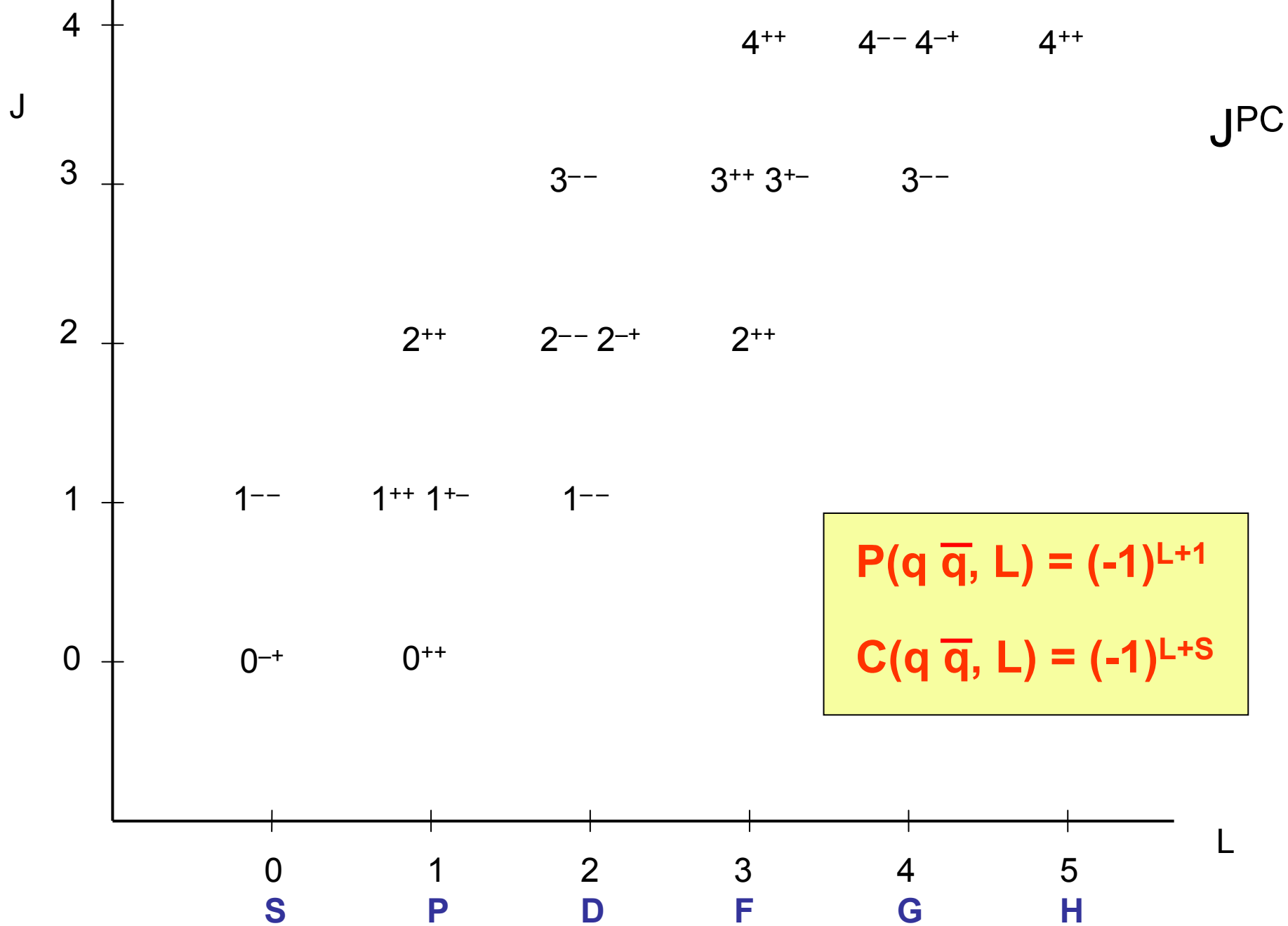
Multiplet 3P_2 $J^P = 2^+$

Mezony tensorowe



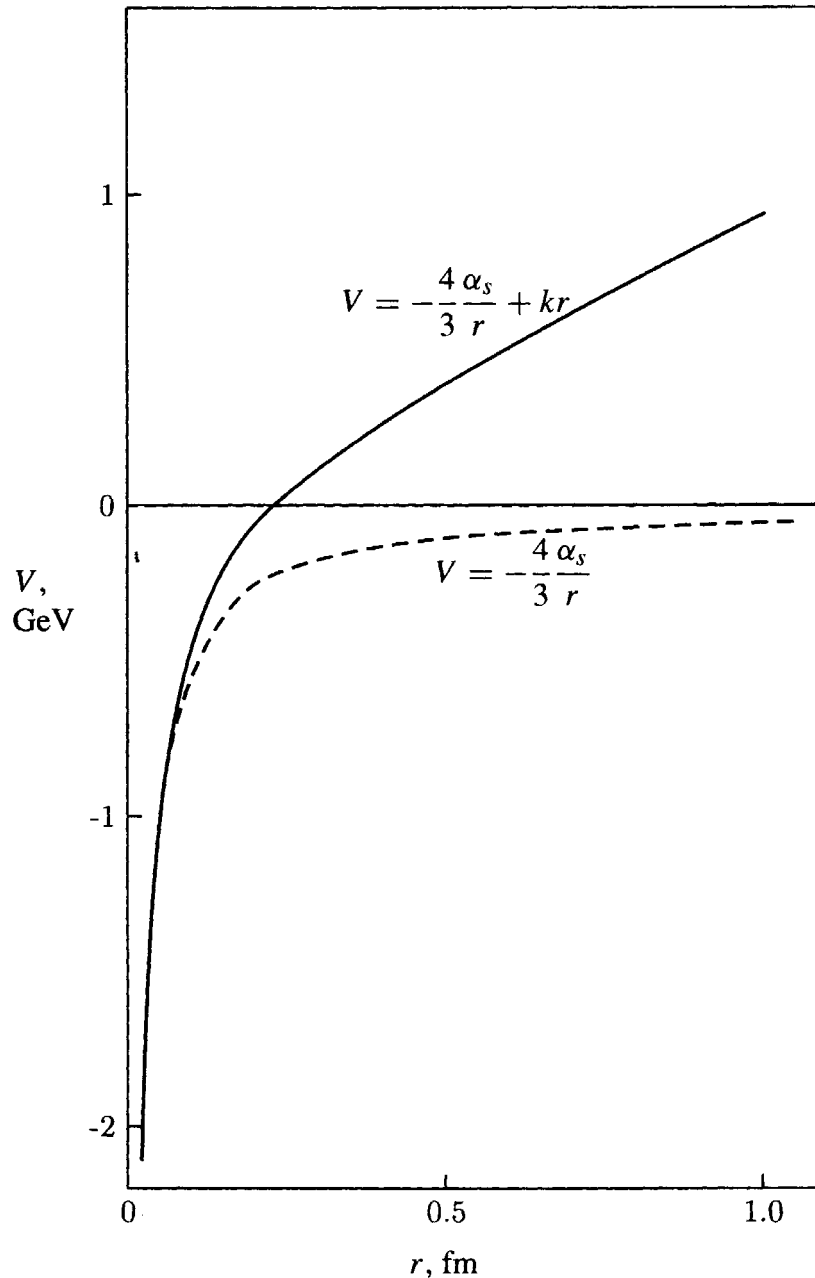
Masa
(MeV)

a_2	1318
f	1275
f'	1525
K_2^*	1430



L	S	J	J ^{PC}	2S+1L _J	przykład
0	0	0	0 ⁻⁺	¹ S ₀	π
0	1	1	1 ⁻⁺	³ S ₁	ρ
1	0	1	1 ^{+−}	¹ P ₁	
1	1	0	0 ⁺⁺	³ P ₀	
1	1	1	1 ⁺⁺	³ P ₁	
1	1	2	2 ⁺⁺	³ P ₂	a ₂ (1320)
2	0	2	2 ⁻⁺	¹ D ₂	π ₂ (1680)
2	1	1	1 ⁻⁻	³ D ₁	
2	1	2	2 ⁻⁻	³ D ₂	
2	1	3	3 ⁻⁻	³ D ₃	ρ ₃ (1690)
3	0	3	3 ^{+−}	¹ F ₃	
3	1	2	2 ⁺⁺	³ F ₂	
3	1	3	3 ⁺⁺	³ F ₃	
3	1	4	4 ⁺⁺	³ F ₄	
4	0	4	4 ⁻⁺	¹ G ₄	
4	1	3	3 ⁻⁻	³ G ₃	

.....



Wiadomo, że potencjał kwark-kwark ma wyraz malejący z odległością oraz wyraz rosnący z odległością.

Wartości parametrów tych wyrazów muszą być dopasowywane na podstawie obserwacji poziomów (tj. stanów związanych kwarków)

Zasady nazewnictwa mezonów i barionów (1984 r.)

Mezony

$J^{PC} =$	$0^{-+}, 2^{-+} \dots$	$1^{+-}, 3^{+-} \dots$	$1^{--}, 3^{--} \dots$	$0^{++}, 1^{++} \dots$
$2S+1L_J =$	$^1(L_{\text{even}})_J$	$^1(L_{\text{odd}})_J$	$^3(L_{\text{even}})_J$	$^3(L_{\text{odd}})_J$
$I = 1(u,d)$	π	ρ	ρ	a
$I = 0(u,d)$	η	h	ω	f
$s\bar{s}$	η'	h'	ϕ	f'
$c\bar{c}$	η_c	h_c	ψ	χ
$b\bar{b}$	η_b	h_b	Υ	χ_b
$t\bar{t}$	η_t	h_t	θ	χ_t

Wyjątek: $\psi (3100) = J/\psi$

Zasady nazewnictwa mezonów i barionów (1984 r.)

Mezony

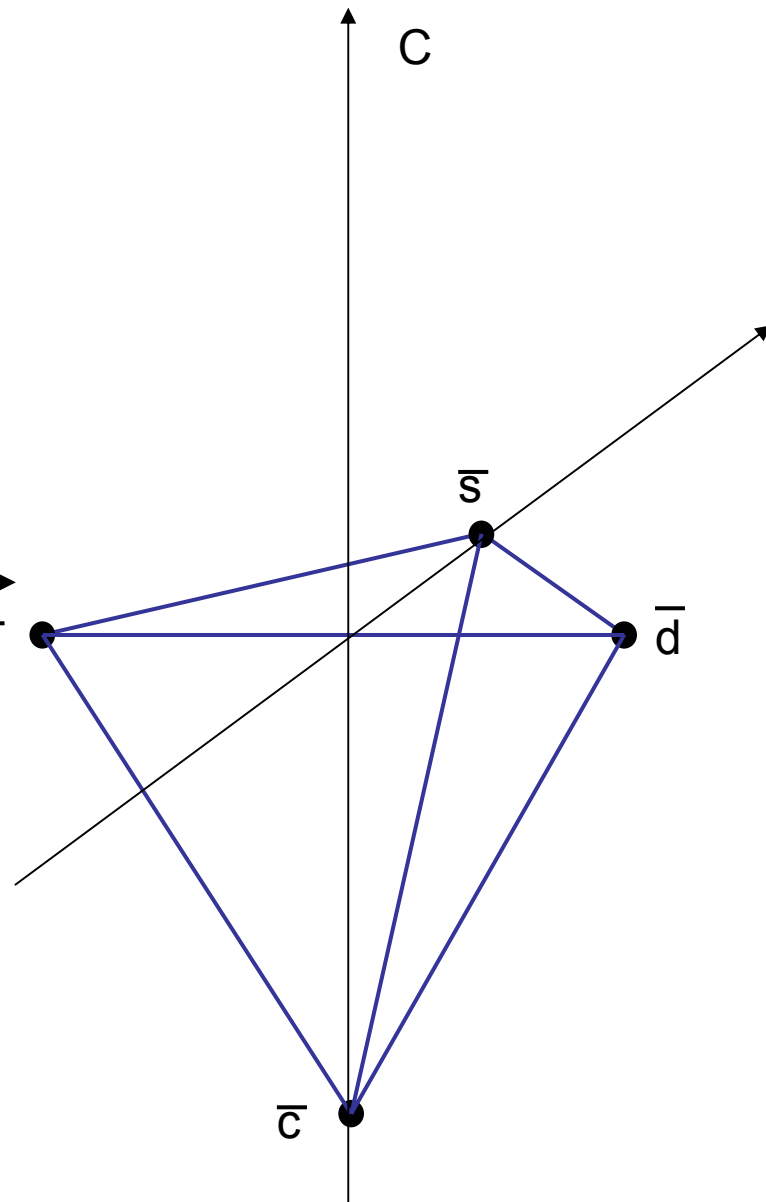
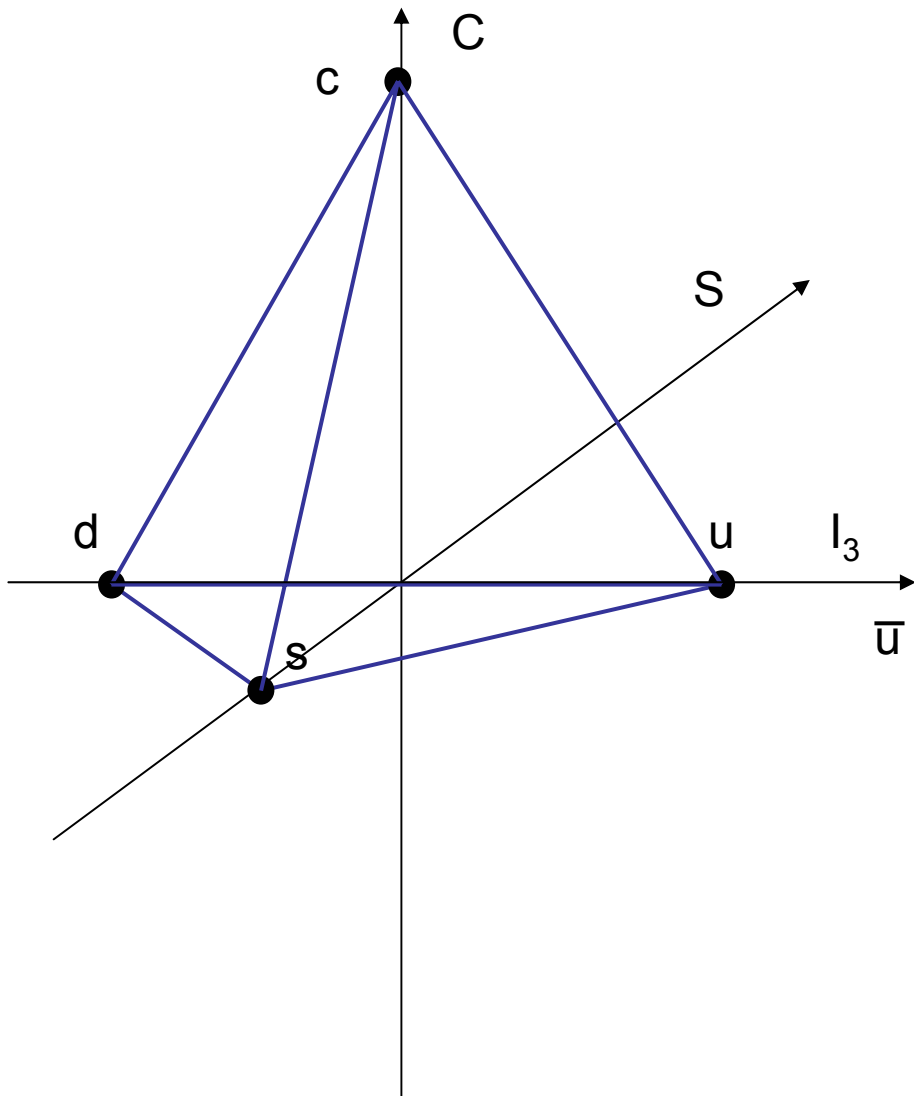
$J^P = 0^-, 1^+, 2^-, 3^+, \dots$

	s	c	b	t
u,d	\bar{K}	D	\bar{B}	T
s		D_s	\bar{B}_s	T_s
c			\bar{B}_c	T_c
b				T_b
t				

$J^P = 0^+, 1^-, 2^+, 3^-, \dots$

	s	c	b	t
u,d	\bar{K}^*	D^*	\bar{B}^*	T^*
s		D_s^*	\bar{B}_s^*	T_s^*
c			\bar{B}_c^*	T_c^*
b				T_b^*
t				

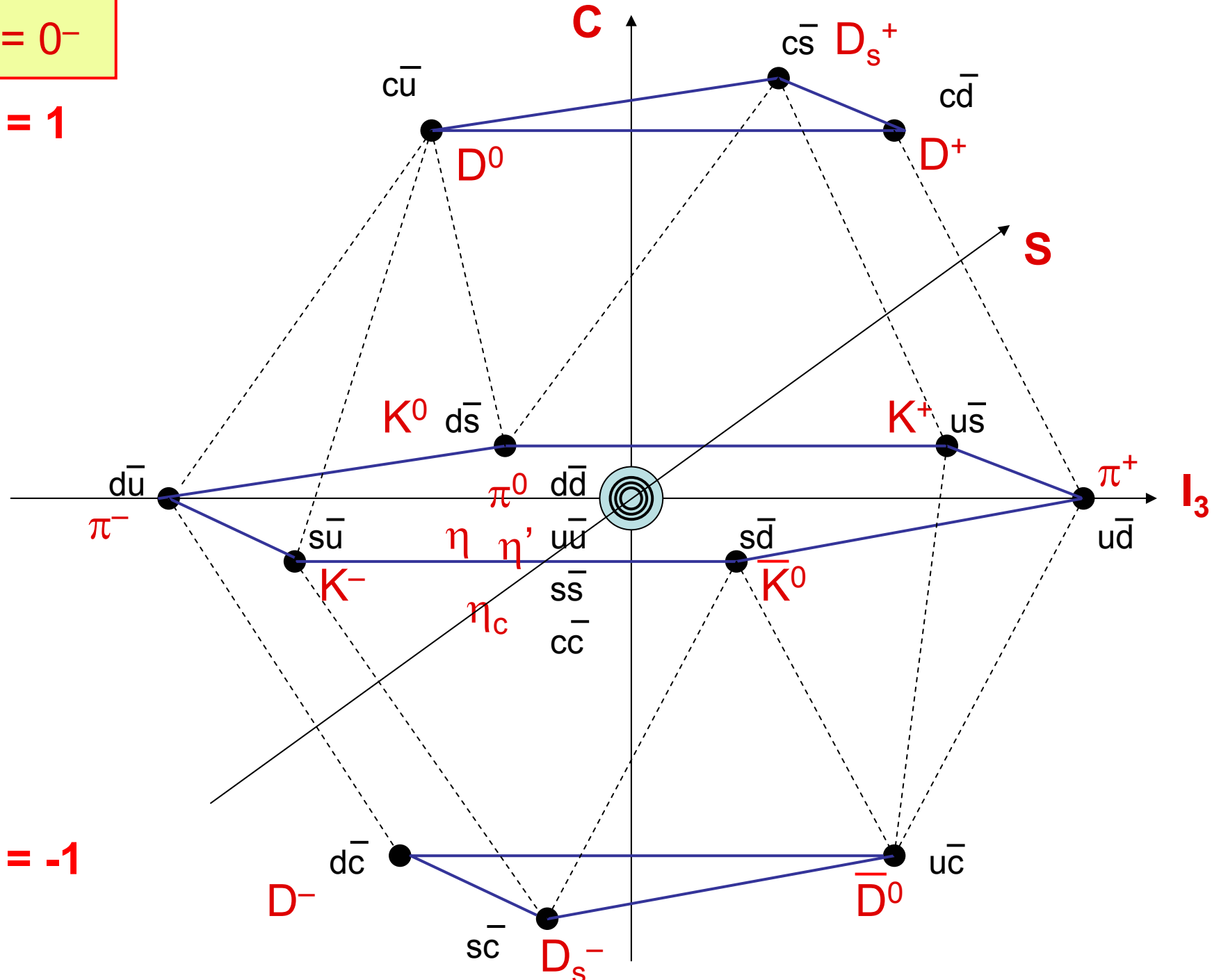
Kwarki d, u, s, c



$J^P = 0^-$

$C = 1$

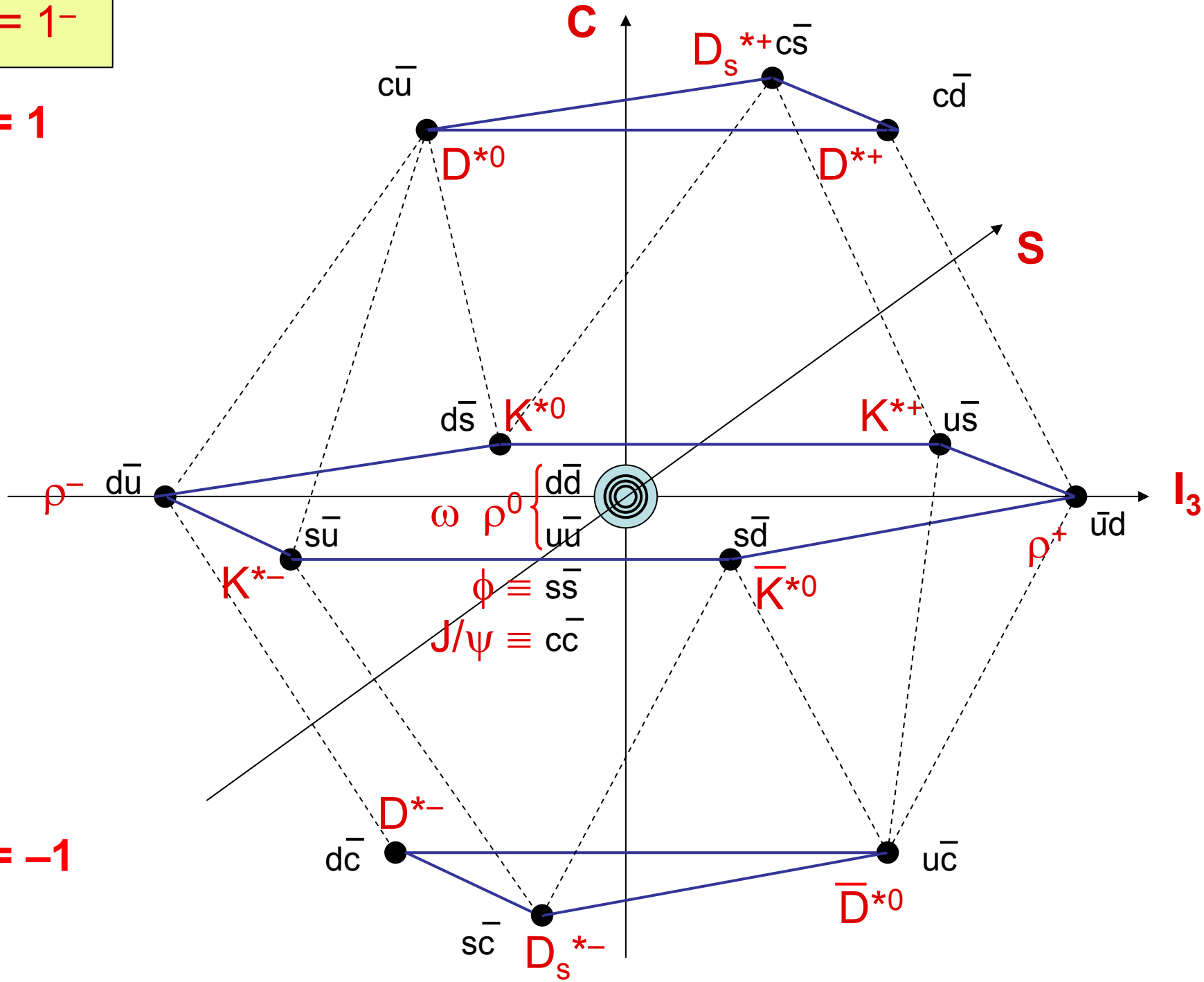
$C = -1$



$J^P = 1^-$

$C = 1$

$C = -1$



Mezony zawierające kwark c

$$D^{\pm} \quad 1869,6 \text{ MeV} \quad \tau = 1,04 \text{ ps}$$

$$D^0 \quad 1864,8 \text{ MeV} \quad \tau = 0,41 \text{ ps}$$

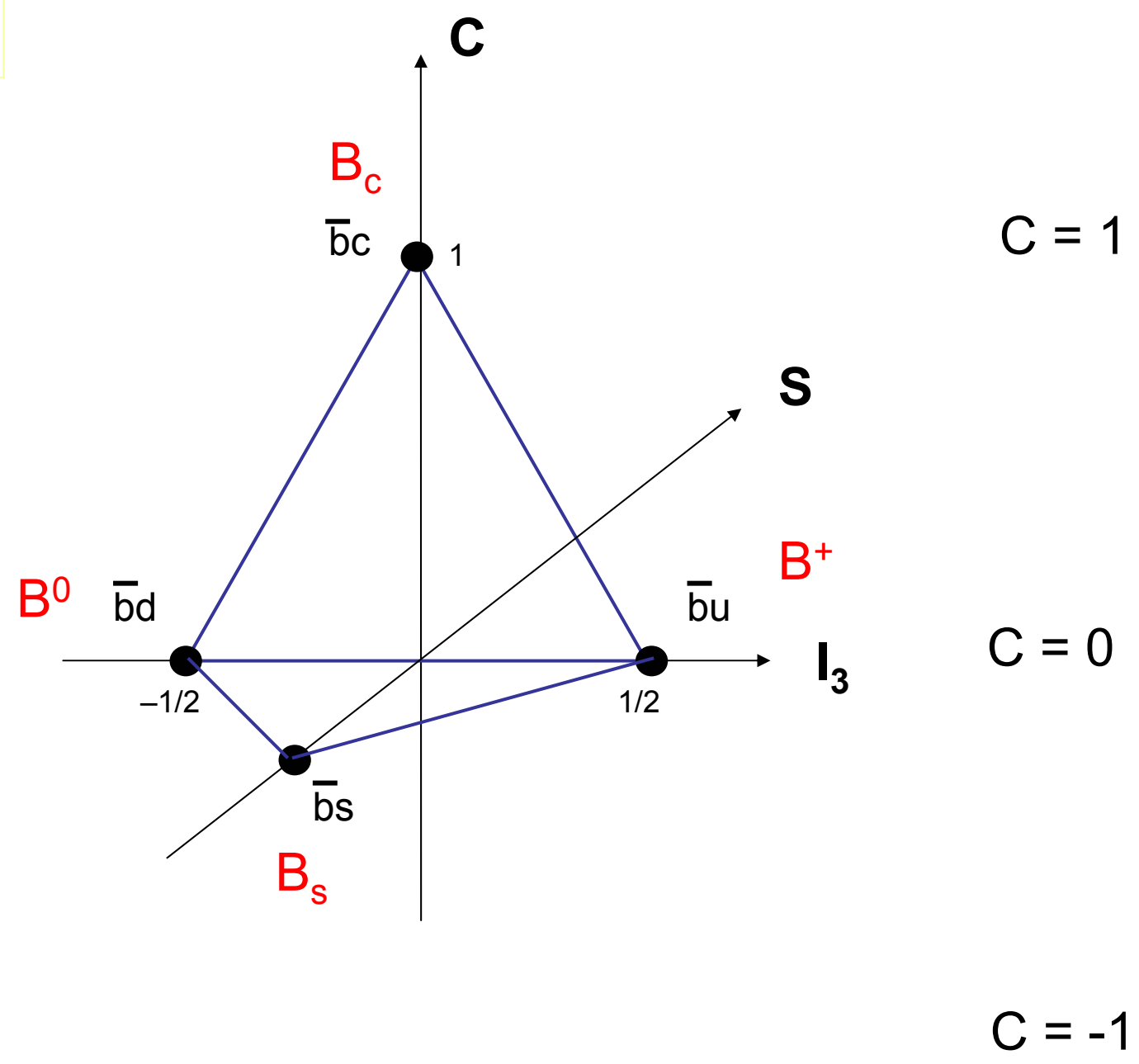
$$D_s^{\pm} \quad 1968,5 \text{ MeV} \quad \tau = 0,50 \text{ ps}$$

mezony D^* - rozpad silny

Wprowadzenie piątego kwarku oznacza konieczność kreślenia poza osiami I_3 , S i C , nowej, czwartej osi B

Nie mogąc rysować brył czterowymiarowych możemy jednak patrzeć na ich rzuty na przestrzeń trójwymiarową

Rzut B = +1

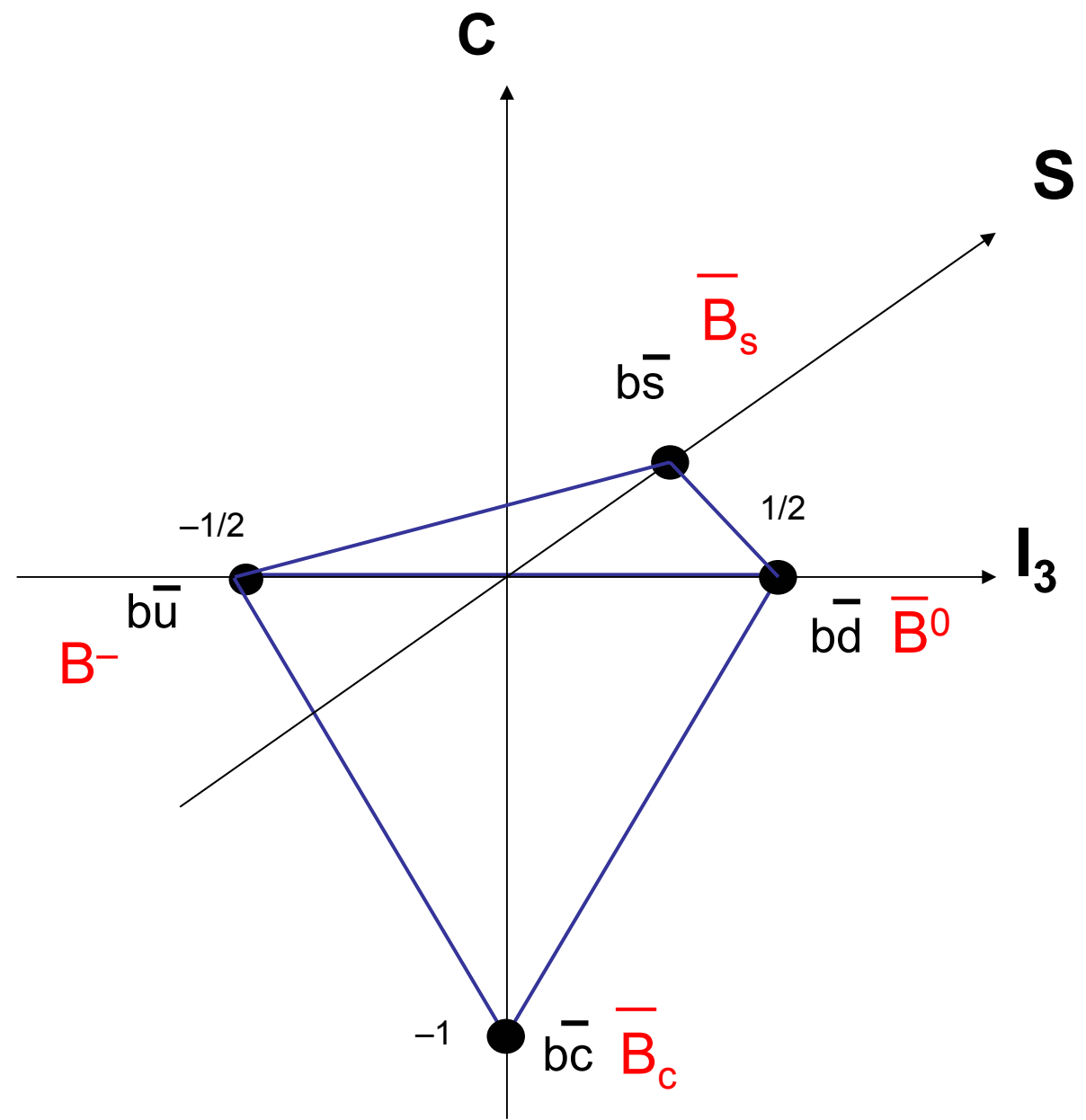


Rzut B = -1

C = 1

C = 0

C = -1





Znane są już mezony Υ (1^{--}) i χ_b (0^{++}) (masy około 10 GeV)

Mezony zawierające kwark b mają bardzo duże masy

$$B^\pm \quad 5279 \text{ MeV} \quad \tau = 1,64 \text{ ps}$$

$$B^0 \quad 5280 \text{ MeV} \quad \tau = 1,53 \text{ ps}$$

$$B_s^0 \quad 5366 \text{ MeV} \quad \tau = 1,47 \text{ ps}$$

$$B_c^\pm \quad 6276 \text{ MeV} \quad \tau = 0,46 \text{ ps}$$

(przypuszczalnie są to stany $J^P = 0^-$)

Dla każdego L, S, J możliwe są jeszcze „wzbudzenia radialne” (*radial excitations*)

(odpowiednik głównej liczby kwantowej dla potencjału kulombowskiego)

Przykład

$J^{PC} = 1^{--}$	$\Upsilon (1S)$	$M = 9460 \text{ MeV}$
	$\Upsilon (2S)$	10023
	$\Upsilon (3S)$	10355
	$\Upsilon (4S)$	10579
	Υ	10860
	Υ	11019

Przykład $J^{PC} = 1^{--}$

ρ	$M = 776 \text{ MeV}$
ρ	1465
ρ	1720

Zasady nazewnictwa mezonów i barionów (1984 r.)

Bariony

Z trzema kwarkami pierwszej generacji

$$\mathbf{N} \quad I = 1/2$$

$$\mathbf{\Delta} \quad I = 3/2$$

Z dwoma kwarkami pierwszej generacji

$$\mathbf{\Lambda} \quad I = 0$$

$$\mathbf{\Sigma} \quad I = 1$$

Z jednym kwarkiem pierwszej generacji

$$\mathbf{\Xi} \quad I = 1/2$$

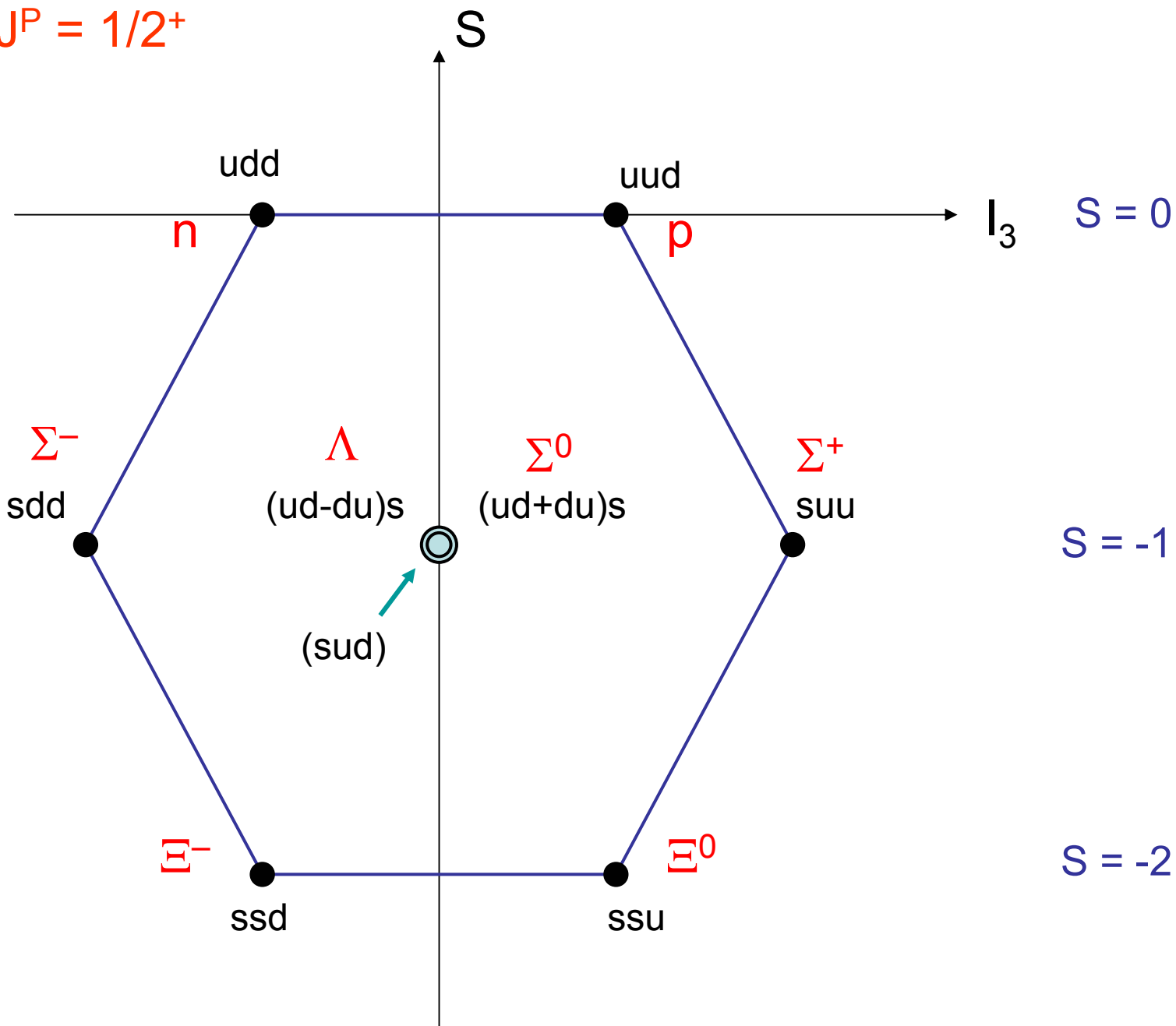
Bez kwarków pierwszej generacji

$$\mathbf{\Omega} \quad I = 0$$

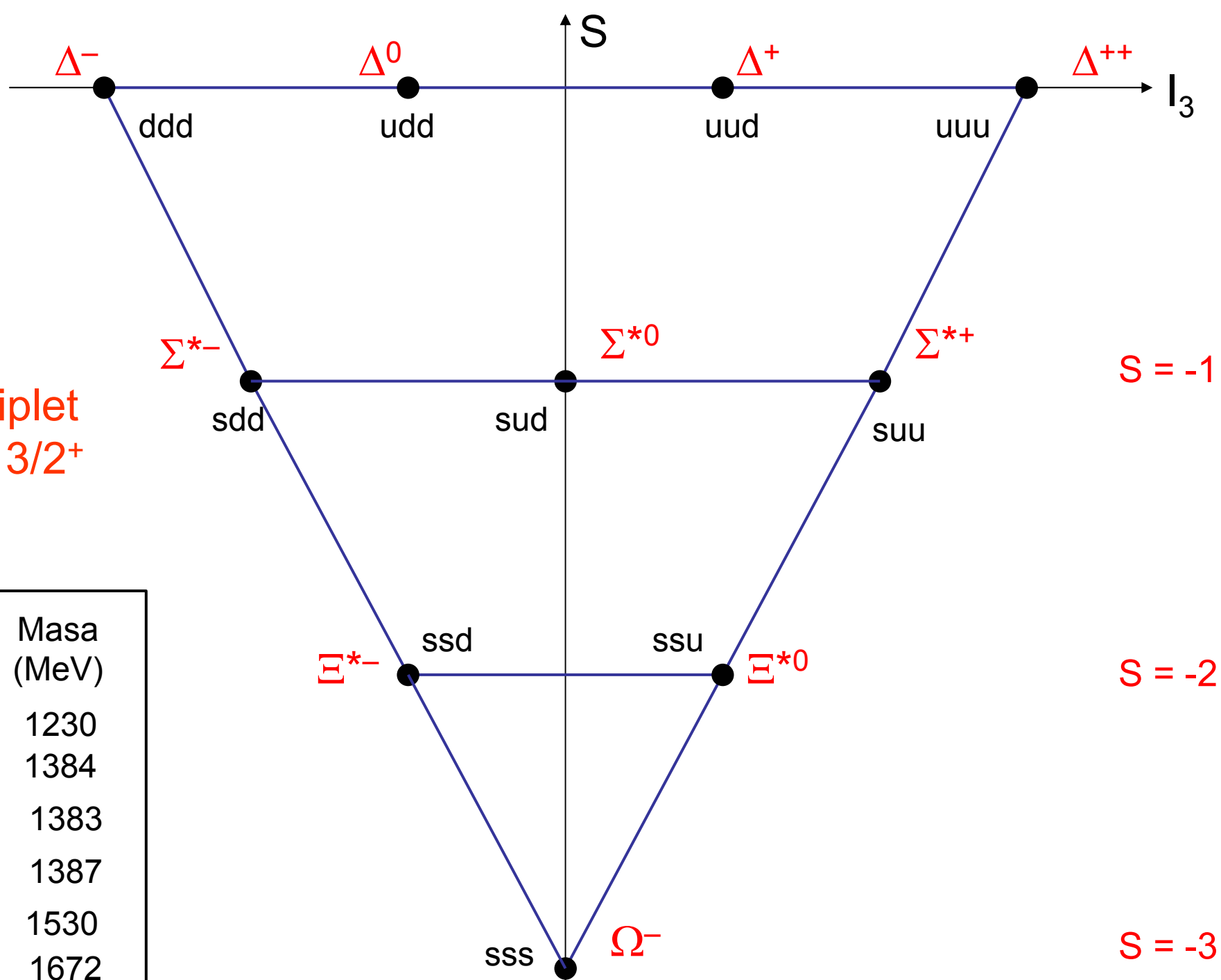
Zawartość kwarków c, b, t dana wskaźnikiem

Na przykład: $\mathbf{\Lambda}_c, \mathbf{\Sigma}_c, \mathbf{\Lambda}_b, \mathbf{\Xi}_c, \mathbf{\Xi}_{cb}, \mathbf{\Omega}_c, \mathbf{\Omega}_{ccc}$

Multiplet $J^P = 1/2^+$



	Masa (MeV)
p	938,3
n	939,6
Λ	1116
Σ^0	1193
Σ^-	1197
Σ^+	1190
Ξ^0	1315
Ξ^-	1321



Multiplet
 $J^P = 3/2^+$

	Masa (MeV)
Δ	1230
Σ^{*0}	1384
Σ^{*+}	1383
Σ^{*-}	1387
Ξ^{*0}	1530
Ω^-	1672

Całkowita funkcja falowa układu fermionów jest antysymetryczna

$$\Psi = \Psi_{\text{kolor}} (\text{singlet}) \times \Psi_{\text{zapach}} \times \left[\Psi_{\text{spin}} \left(\mathbf{S} = \frac{1}{2}, \frac{3}{2} \right) \times \Psi_{\text{orbit}} (L = 0, 1, \dots) \right]_{\text{total } J}$$

A	A	S	S ↑↑↑ (S = 3/2)	S (L = 0)	J = 3/2
A	A	A	A ↑↑↓ (S = 1/2)	S (L = 0)	J = 1/2

(opcja symetryczna
niemożliwa)

$$\Psi_{\text{kolor}} = \frac{1}{\sqrt{3!}} \begin{vmatrix} q_{1R} & q_{2R} & q_{3R} \\ q_{1B} & q_{2B} & q_{3B} \\ q_{1G} & q_{2G} & q_{3G} \end{vmatrix}$$

singlet kolorowy $q_1 q_2 q_3$

Symetryczna funkcja zapachowa dla multipletu barionowego $J^P = 3/2^+$

ddd (ddu + udd + dud) (duu + udu + uud) uuu

(dds + sdd + dsd) (dsu + uds + sud) (uus + suu + usu)

(dss + sds + ssd) (sus + ssu + uss)

sss

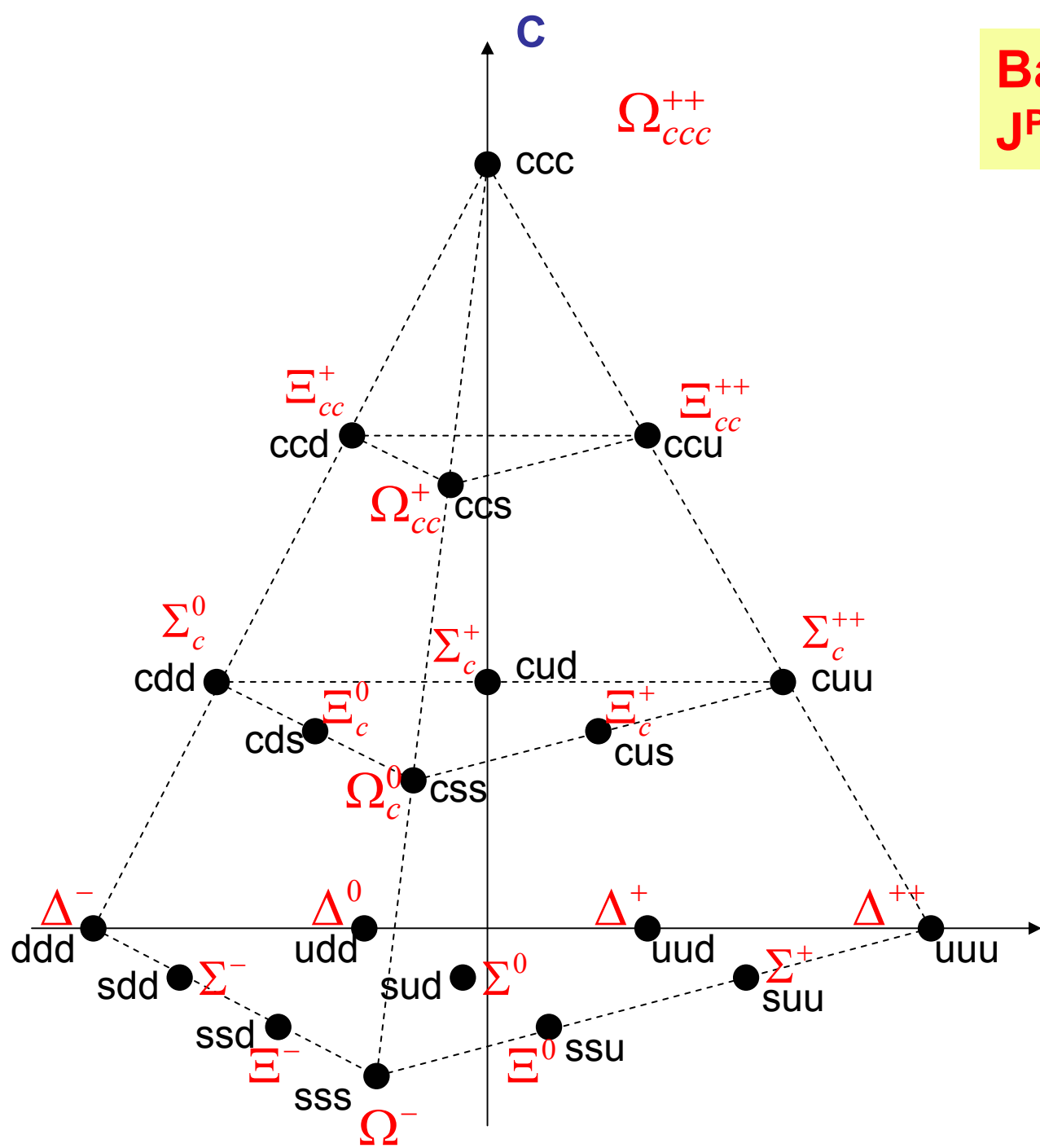
Bariony
 $J^P = 3/2^+$

C = 3

C = 2

C = 1

C = 0



I₃

Bariony
 $J^P = 1/2^+$

$C = 3$

$C = 2$

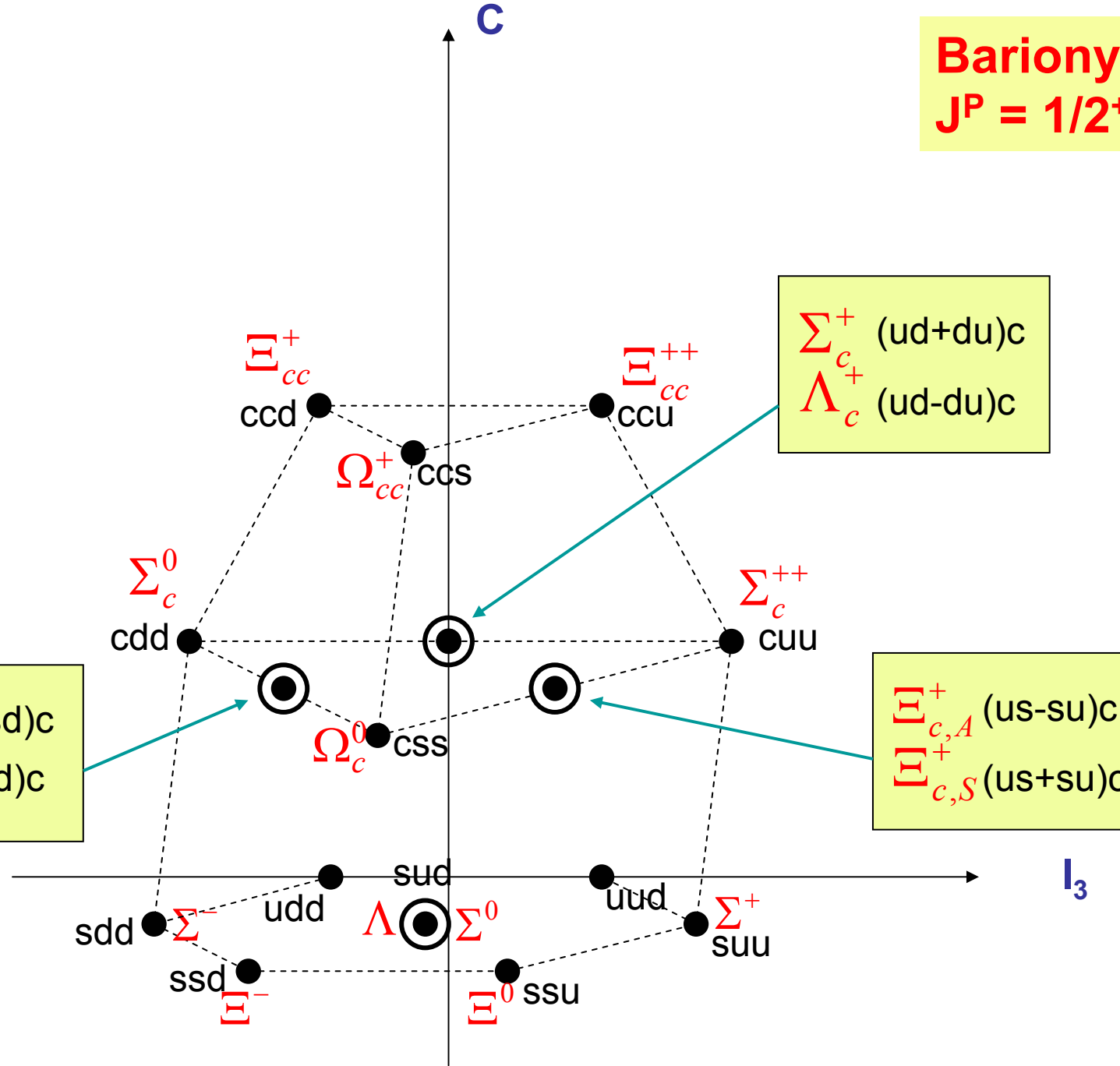
$C = 1$

$C = 0$

$\Xi_{c,S}^0$ (ds+sd)c
 $\Xi_{c,A}^0$ (ds-sd)c

Σ_c^+ (ud+du)c
 Λ_c^+ (ud-du)c

$\Xi_{c,A}^+$ (us-su)c
 $\Xi_{c,S}^+$ (us+su)c



Bariony zawierające kwark c mają duże masy

Λ_c^+	2286 MeV	$\tau = 0,20$ ps
Σ_c	2454 MeV	
Ξ_c^0	2471 MeV	$\tau = 0,11$ ps
Ξ_c^+	2468 MeV	$\tau = 0,44$ ps
Ω_c^0	2698 MeV	$\tau = 0,07$ ps

(przypuszczalnie są to stany $J^P = 1/2^+$)

**Liczba
zapachów**

**Liczba stanów barionowych
(dla $L = 0$)**

$$S = \frac{1}{2}$$

$$S = \frac{3}{2}$$

1

0

1

2

2

4

3

8

10

4

20

20

5

40

35

6

70

56

Bariony z kwarkami b

$$J^P = 3/2^+$$

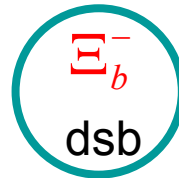
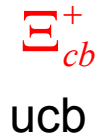
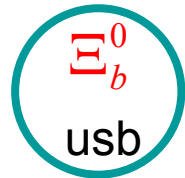
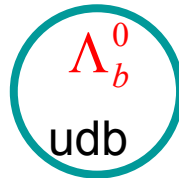
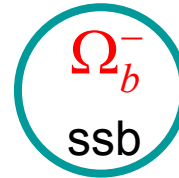
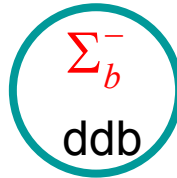
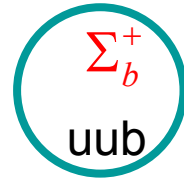
B = -1	Σ_b^+ uub	Σ_b^- ddb	Ω_b^- ssb	Ω_{ccb}^+ ccb		
	Λ_b^0 udb	Ξ_b^0 usb	Ξ_{cb}^+ ucb	Ξ_b^- dsb	Ξ_{cb}^0 dcb	Ω_{cb}^- scb
B = -2	Ξ_{bb}^0 ubb	Ξ_{bb}^- dbb	Ω_{bb}^- sbb	Ω_{cbb}^0 cbb		
B = -3	Ω_{bbb}^- bbb					

Jest to łącznie 15 stanów, które wraz z rozpatrywanymi wcześniej 20 stanami dla $B = 0$ daje liczbę 35 barionów $J^P = 3/2^+$

Bariony z kwarkami b

$$J^P = 1/2^+$$

B = -1



każdy z tych stanów istnieje jako **A** i jako **S**

B = -2



B = -3



stan niemożliwy ze względu na warunek antysymetryzacji funkcji falowej

Jest to łącznie 20 stanów, które wraz z rozpatrywanymi wcześniej 20 stanami dla B = 0 daje liczbę 40 barionów $J^P = 1/2^+$

Dotychczas zaobserwowano 6 barionów z kwarkiem b (założenie $J^P = 1/2^+$)

Zidentyfikowane bariony z kwarkiem b

Λ_b^0 5620 MeV $\tau = 1,38$ ps

Σ_b^+ 5608 MeV

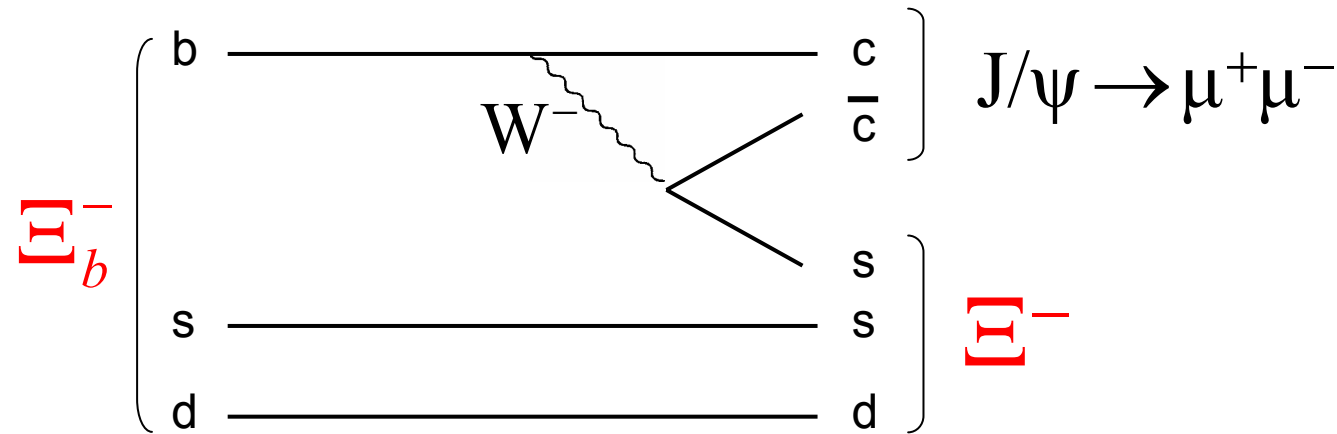
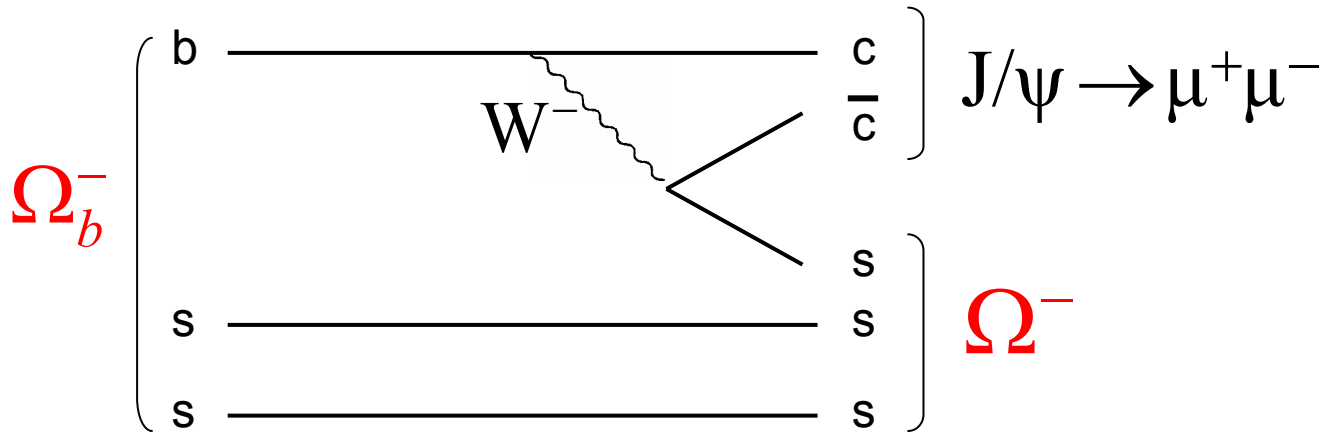
Σ_b^- 5615 MeV

Ξ_b^0 Ξ_b^- 5794 MeV $\tau = 1,42$ ps

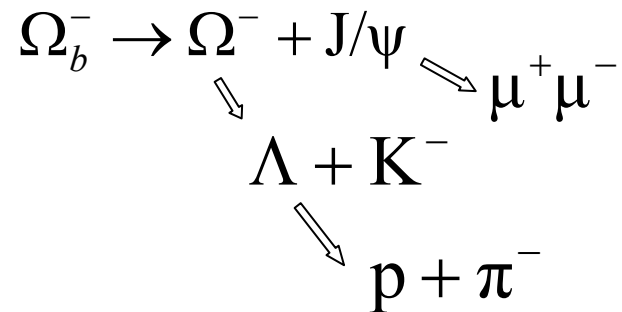
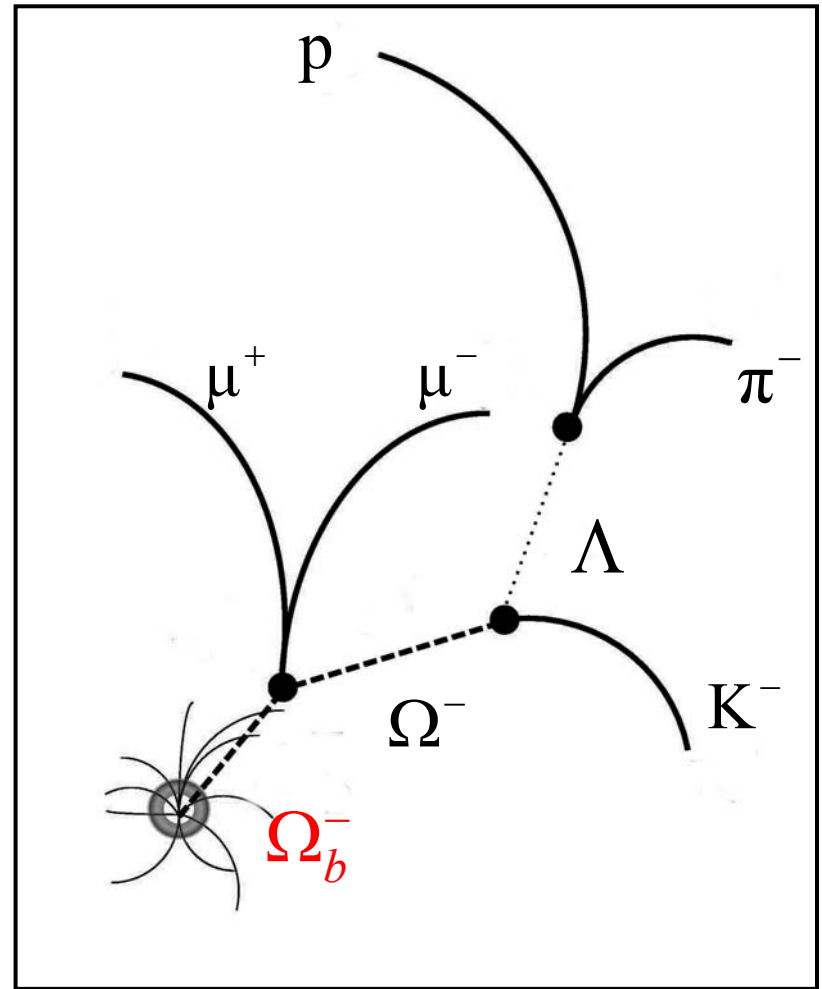
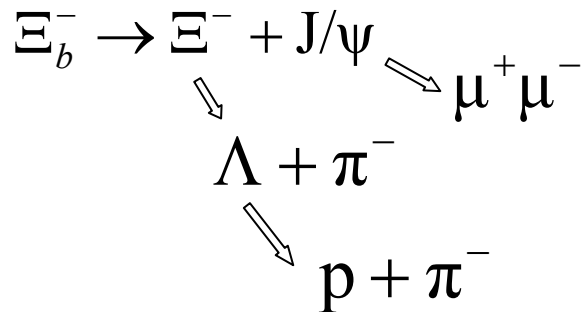
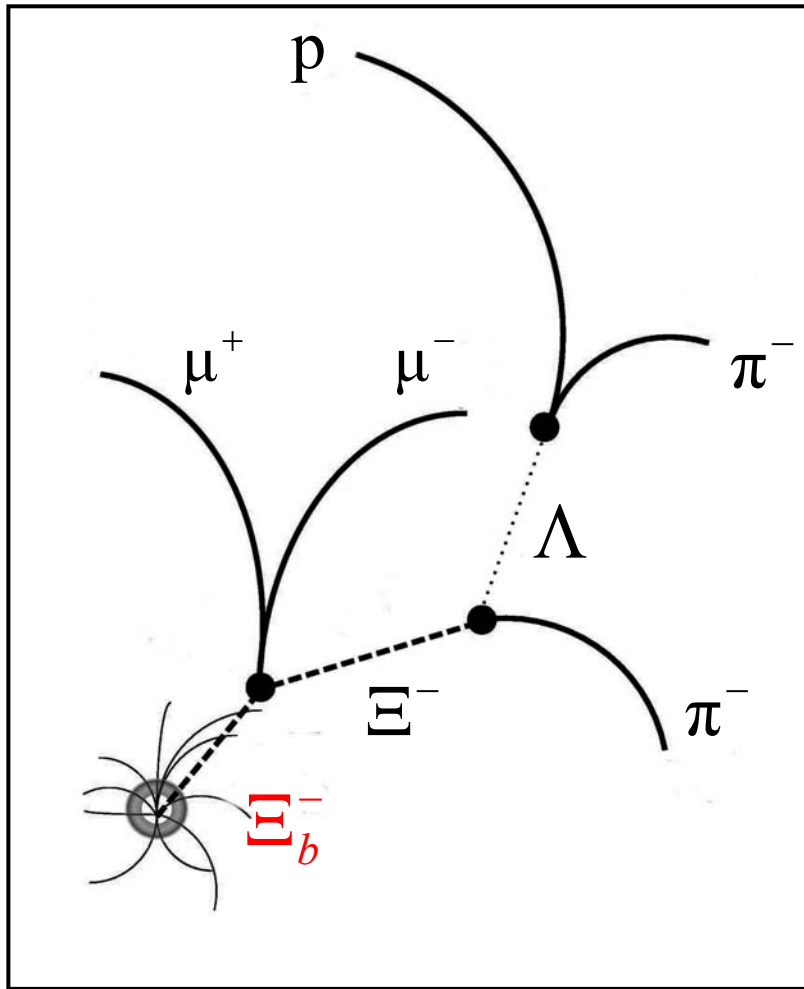
Ω_b^- 6165 MeV

doniesienie o odkryciu
przez D0 Collaboration
29 sierpnia 2008 r. !

Rozpady barionów z kwarkiem b



Rozpady barionów z kwarkiem b



Przykład analizy w celu wykrycia hiperonu Ω_b^-

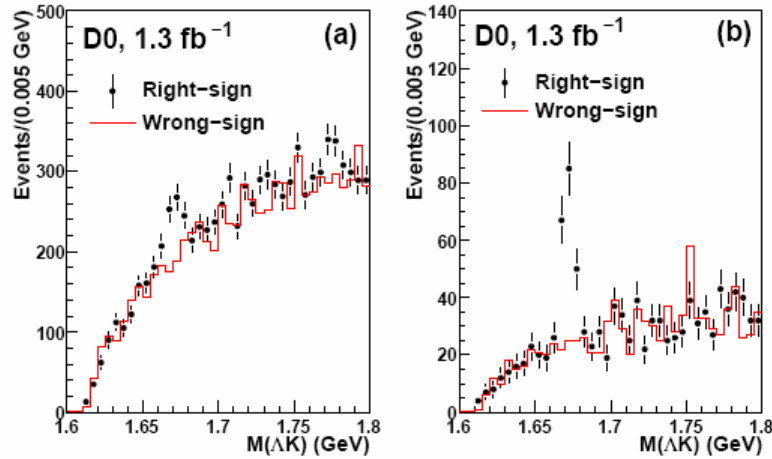


FIG. 1: The invariant mass distribution of the ΛK pair before (a) and after (b) the BDT selection. Filled circles are from the right-sign ΛK^- events while the histogram is from the wrong-sign ΛK^+ events without any additional normalization.

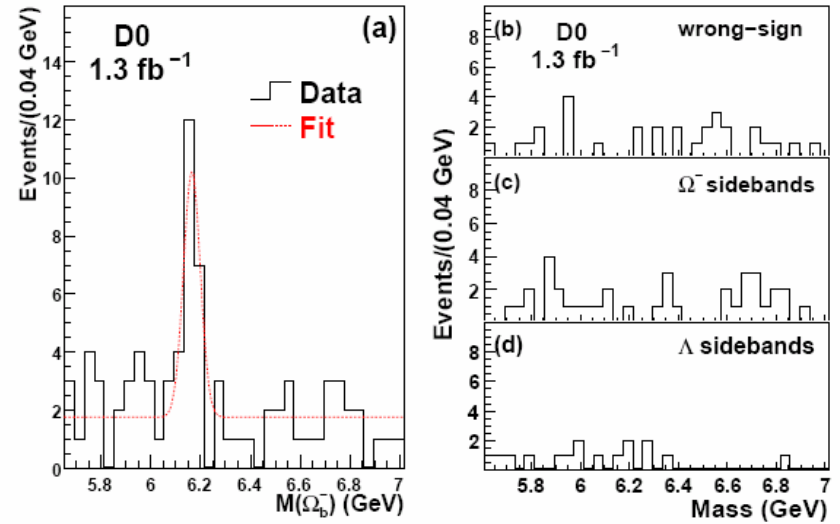


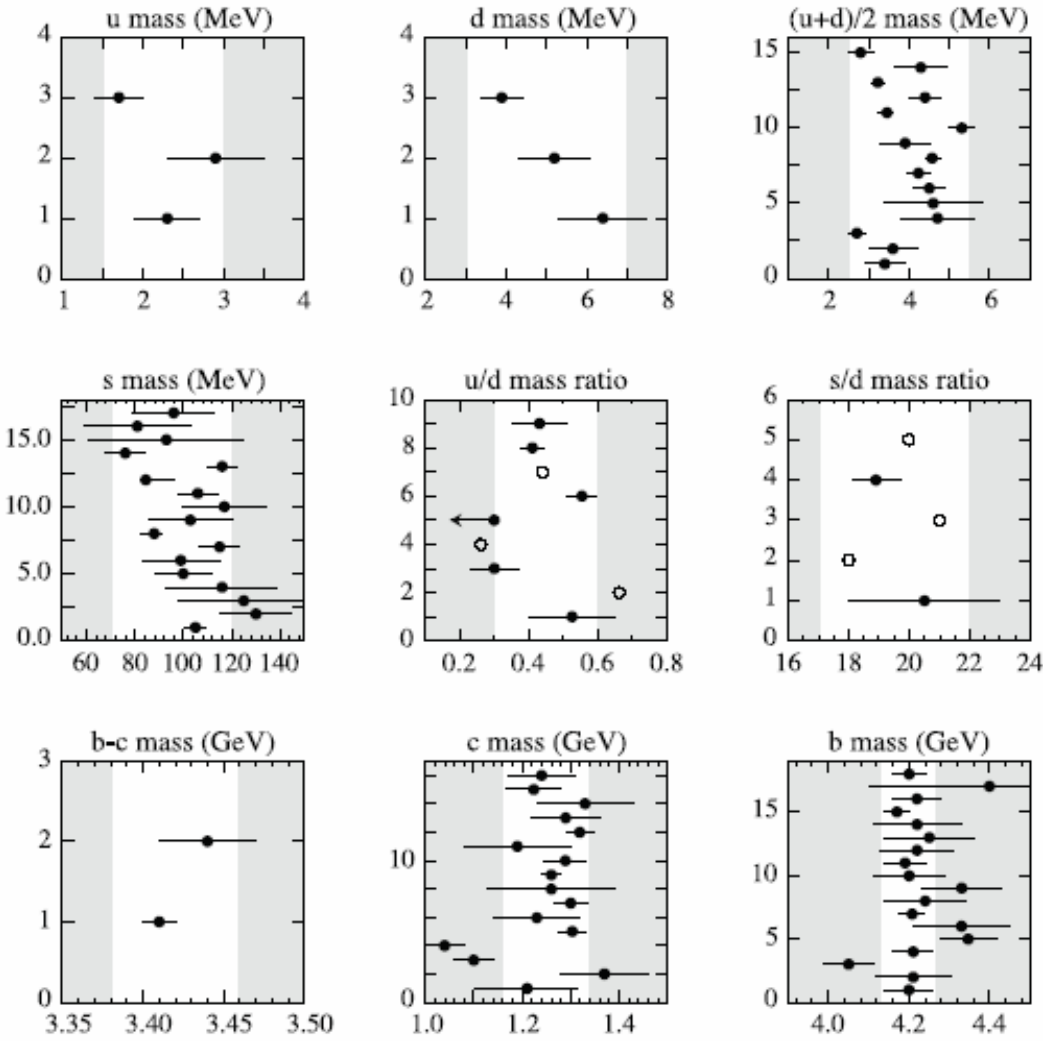
FIG. 2: (a) The $M(\Omega_b^-)$ distribution of the Ω_b^- candidates after all selection criteria. The dotted curve is an unbinned likelihood fit to the model of a constant background plus a Gaussian signal. The mass distributions for the wrong-sign background (b), the Ω^- sideband events (c), and the Λ sideband events (d).

Bariony – PDG 2006

p	P_{11}	****	$\Delta(1232)$	P_{33}	****	Λ	P_{01}	***	Σ^+	P_{11}	****	Ξ^0	P_{11}	****
n	P_{11}	****	$\Delta(1600)$	P_{33}	***	$\Lambda(1405)$	S_{01}	****	Σ^0	P_{11}	****	Ξ^-	P_{11}	****
$N(1440)$	P_{11}	****	$\Delta(1620)$	S_{31}	****	$\Lambda(1520)$	D_{03}	***	Σ^-	P_{11}	****	$\Xi(1530)$	P_{13}	****
$N(1520)$	D_{13}	****	$\Delta(1700)$	D_{33}	****	$\Lambda(1600)$	P_{01}	**	$\Sigma(1385)$	P_{13}	****	$\Xi(1620)$		*
$N(1535)$	S_{11}	****	$\Delta(1750)$	P_{31}	*	$\Lambda(1670)$	S_{01}	****	$\Sigma(1480)$		*	$\Xi(1690)$		***
$N(1650)$	S_{11}	****	$\Delta(1900)$	S_{31}	**	$\Lambda(1690)$	D_{03}	****	$\Sigma(1560)$		**	$\Xi(1820)$	D_{13}	***
$N(1675)$	D_{15}	****	$\Delta(1905)$	F_{35}	****	$\Lambda(1800)$	S_{01}	**	$\Sigma(1580)$	D_{13}	*	$\Xi(1950)$		***
$N(1680)$	F_{15}	****	$\Delta(1910)$	P_{31}	****	$\Lambda(1810)$	P_{01}	**	$\Sigma(1620)$	S_{11}	**	$\Xi(2030)$		***
$N(1700)$	D_{13}	***	$\Delta(1920)$	P_{33}	***	$\Lambda(1820)$	F_{05}	****	$\Sigma(1660)$	P_{11}	***	$\Xi(2120)$		*
$N(1710)$	P_{11}	***	$\Delta(1930)$	D_{35}	***	$\Lambda(1830)$	D_{05}	****	$\Sigma(1670)$	D_{13}	****	$\Xi(2250)$		**
$N(1720)$	P_{13}	****	$\Delta(1940)$	D_{33}	*	$\Lambda(1890)$	P_{03}	****	$\Sigma(1690)$		**	$\Xi(2370)$		**
$N(1900)$	P_{13}	**	$\Delta(1950)$	F_{37}	****	$\Lambda(2000)$		*	$\Sigma(1750)$	S_{11}	***	$\Xi(2500)$		*
$N(1990)$	F_{17}	**	$\Delta(2000)$	F_{35}	**	$\Lambda(2020)$	F_{07}	*	$\Sigma(1770)$	P_{11}	*			
$N(2000)$	F_{15}	**	$\Delta(2150)$	S_{31}	*	$\Lambda(2100)$	G_{07}	****	$\Sigma(1775)$	D_{15}	****	Ω^-		****
$N(2080)$	D_{13}	**	$\Delta(2200)$	G_{37}	*	$\Lambda(2110)$	F_{05}	***	$\Sigma(1840)$	P_{13}	*	$\Omega(2250)^-$		***
$N(2090)$	S_{11}	*	$\Delta(2300)$	H_{39}	**	$\Lambda(2325)$	D_{03}	*	$\Sigma(1880)$	P_{11}	**	$\Omega(2380)^-$		**
$N(2100)$	P_{11}	*	$\Delta(2350)$	D_{35}	*	$\Lambda(2350)$	H_{09}	***	$\Sigma(1915)$	F_{15}	****	$\Omega(2470)^-$		**
$N(2190)$	G_{17}	****	$\Delta(2390)$	F_{37}	*	$\Lambda(2585)$		**	$\Sigma(1940)$	D_{13}	***			
$N(2200)$	D_{15}	**	$\Delta(2400)$	G_{39}	**				$\Sigma(2000)$	S_{11}	*	Λ_c^+		****
$N(2220)$	H_{19}	****	$\Delta(2420)$	$H_{3,11}$	****				$\Sigma(2030)$	F_{17}	****	$\Lambda_c(2593)^+$		***
$N(2250)$	G_{19}	****	$\Delta(2750)$	$h_{3,13}$	**				$\Sigma(2070)$	F_{15}	*	$\Lambda_c(2625)^+$		***
$N(2500)$	$h_{1,11}$	***	$\Delta(2950)$	$K_{3,15}$	**				$\Sigma(2080)$	P_{13}	**	$\Lambda_c(2765)^+$		*
$N(2700)$	$K_{1,13}$	**							$\Sigma(2100)$	G_{17}	*	$\Lambda_c(2880)^+$		**
			$\Theta(1540)^+$	*					$\Sigma(2250)$		***	$\Sigma_c(2455)$		****
									$\Sigma(2455)$		**	$\Sigma_c(2520)$		***
									$\Sigma(2620)$		**	$\Sigma_c(2520)$		***
									$\Sigma(3000)$		*	$\Sigma_c(2645)$		***
									$\Sigma(3170)$		*	$\Sigma_c(2790)$		***
												$\Sigma_c(2815)$		***
												Ω_c^0		***
												Ξ_c^+		*
												Λ_b^0		***
												Ξ_b^-		*

Kwarki są obiektami związanymi, toteż ich masa ma charakter masy efektywnej (podobnie jak np. masa elektronów w ciele stałym) i zależy od modelu obliczeń

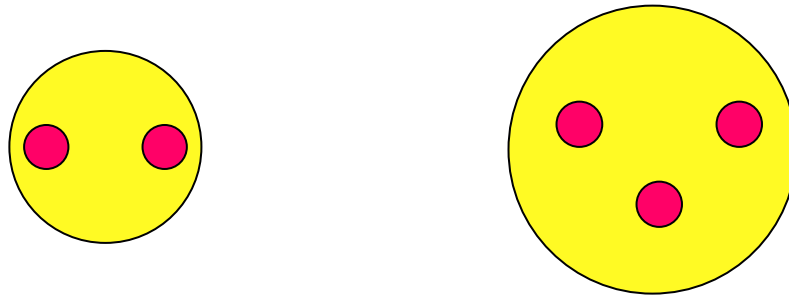
Particle Data Group
2006



Addytywny model kwarków

Tylko kwarki walencyjne, bez gluonów, kwarków morza, potencjału wiązania;

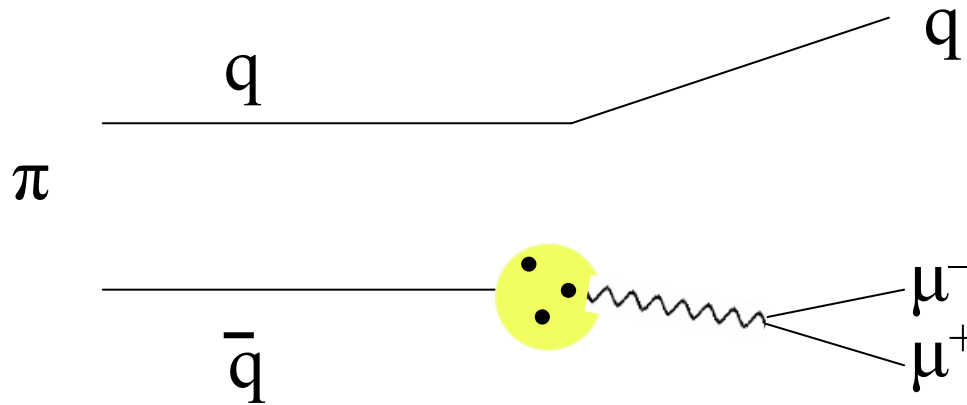
Amplituda oddziaływania hadron-hadron = suma amplitud oddziaływań kwark-kwark



$$\sigma(\pi p) / \sigma(pp) \cong 6/9 = 2/3$$

Levin & Frankfurt (1965)

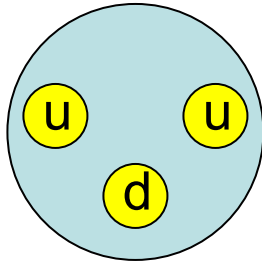
Proces Drella-Yana



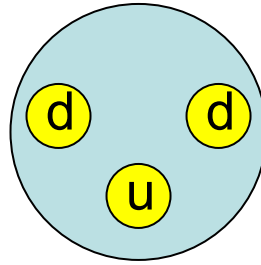
$\pi^- (\bar{u}d)$	$^{12}\text{C} (18u + 18d)$	}	$\sigma = 18 e_u^2 = 18 (4/9)$
$\pi^+ (u\bar{d})$			$\sigma = 18 e_d^2 = 18 (1/9)$

$\sigma(\pi^-) / \sigma(\pi^+) = 4$ zgodnie z doświadczeniem

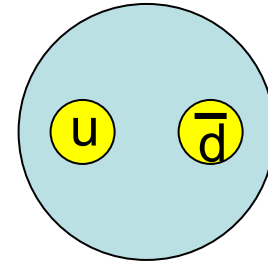
Kłopoty modelu kwarków



proton



neutron



mezon π^+

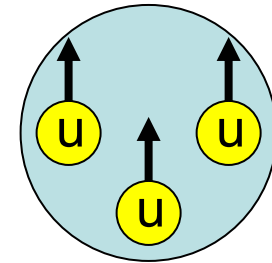
itd.

ALE!

Doświadczenie:

Stan rezonansowy Δ^{++} o spinie $3/2$

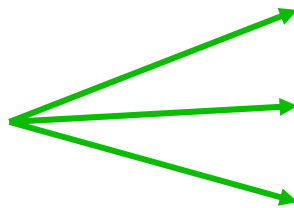
Spiny trzech kwarków u muszą być ustawione tak samo



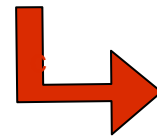
Hiperon $\Omega^- \equiv (s\uparrow s\uparrow s\uparrow)$
(oraz inne przykłady)

Kłopoty modelu kwarków

Wniosek: prosty model kwarków niezgodny z zakazem Pauliego

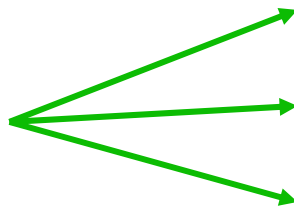


Model kwarków nie ma sensu
Kwarki są parafermionami
Kwarki mają dodatkową liczbę kwantową

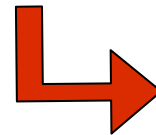


ładunek kolorowy

Poszukiwania kwarków swobodnych są bezskuteczne



Model kwarków nie ma sensu
Nie umiemy ich szukać
Kwarki nie mogą być swobodne



uwięzienie kwarków

Produkcja hadronów w oddziaływaniach elektron-pozyton

$$R = \frac{\sigma \left[\begin{array}{c} e^+ \\ e^- \end{array} \rightarrow \begin{array}{c} q \\ \bar{q} \end{array} \right]}{\sigma \left[\begin{array}{c} e^+ \\ e^- \end{array} \rightarrow \begin{array}{c} \mu^+ \\ \mu^- \end{array} \right]}$$

The image shows two Feynman diagrams representing the annihilation of an electron-positron pair into a quark-antiquark pair and a muon-antimuon pair. In both diagrams, an electron (e^-) and a positron (e^+) enter from the left and meet at a vertex. A wavy line representing a virtual photon connects this vertex to another vertex on the right. From the second vertex, a quark (q) and an antiquark (\bar{q}) emerge in the top diagram, and a muon (μ^-) and an antimuon (μ^+) emerge in the bottom diagram. The diagrams are enclosed in large square brackets, and the Greek letter sigma (σ) is placed to the left of each bracket. A horizontal line is drawn below the first diagram, and the letter R is placed to the left of this line, indicating that the ratio of the two cross-sections is R.

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrony})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = \sum e_{q_i}^2 \quad \text{jeśli bez koloru}$$

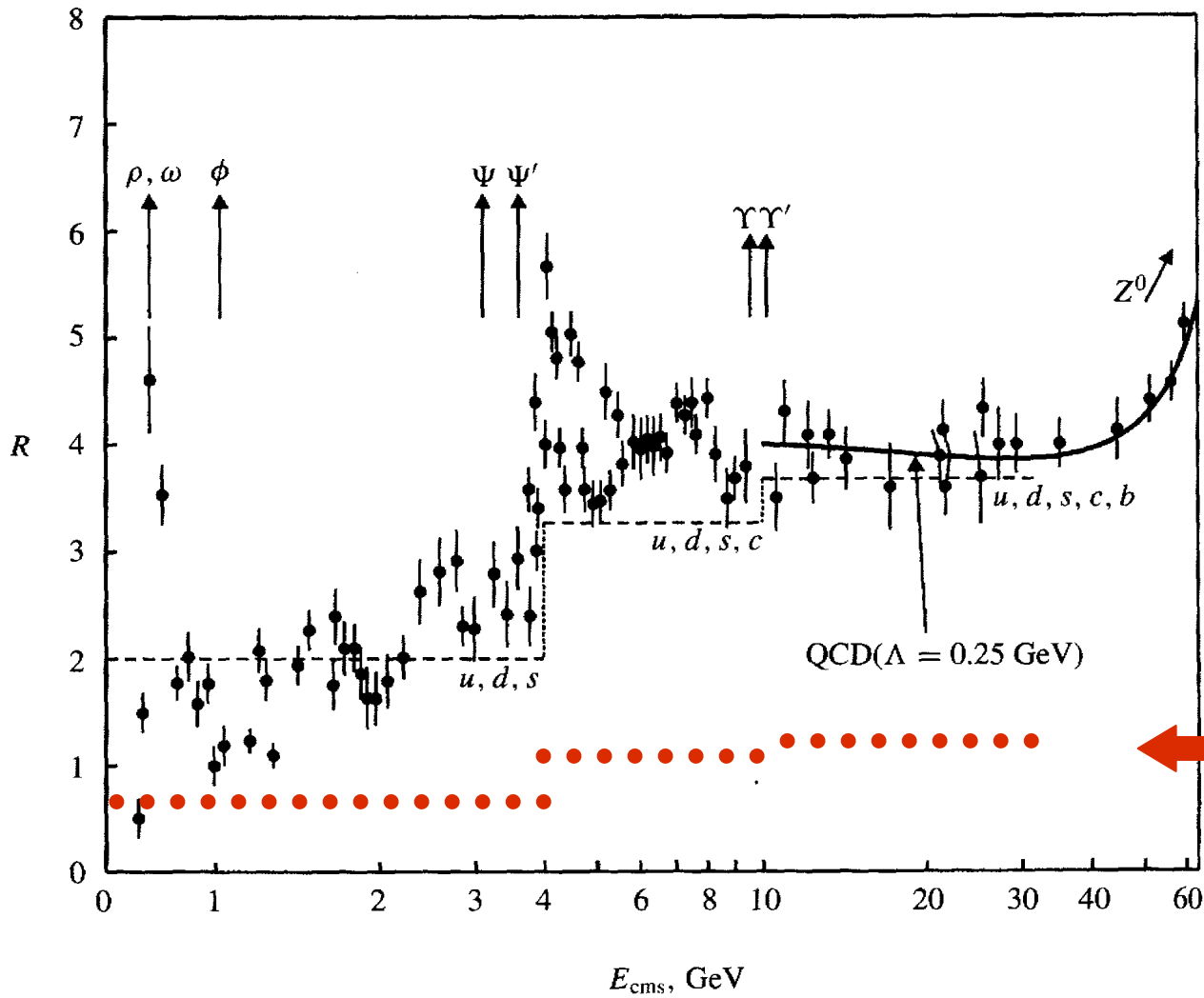
$$R = \left(\frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \frac{4}{9} \right)$$

d u s c b t

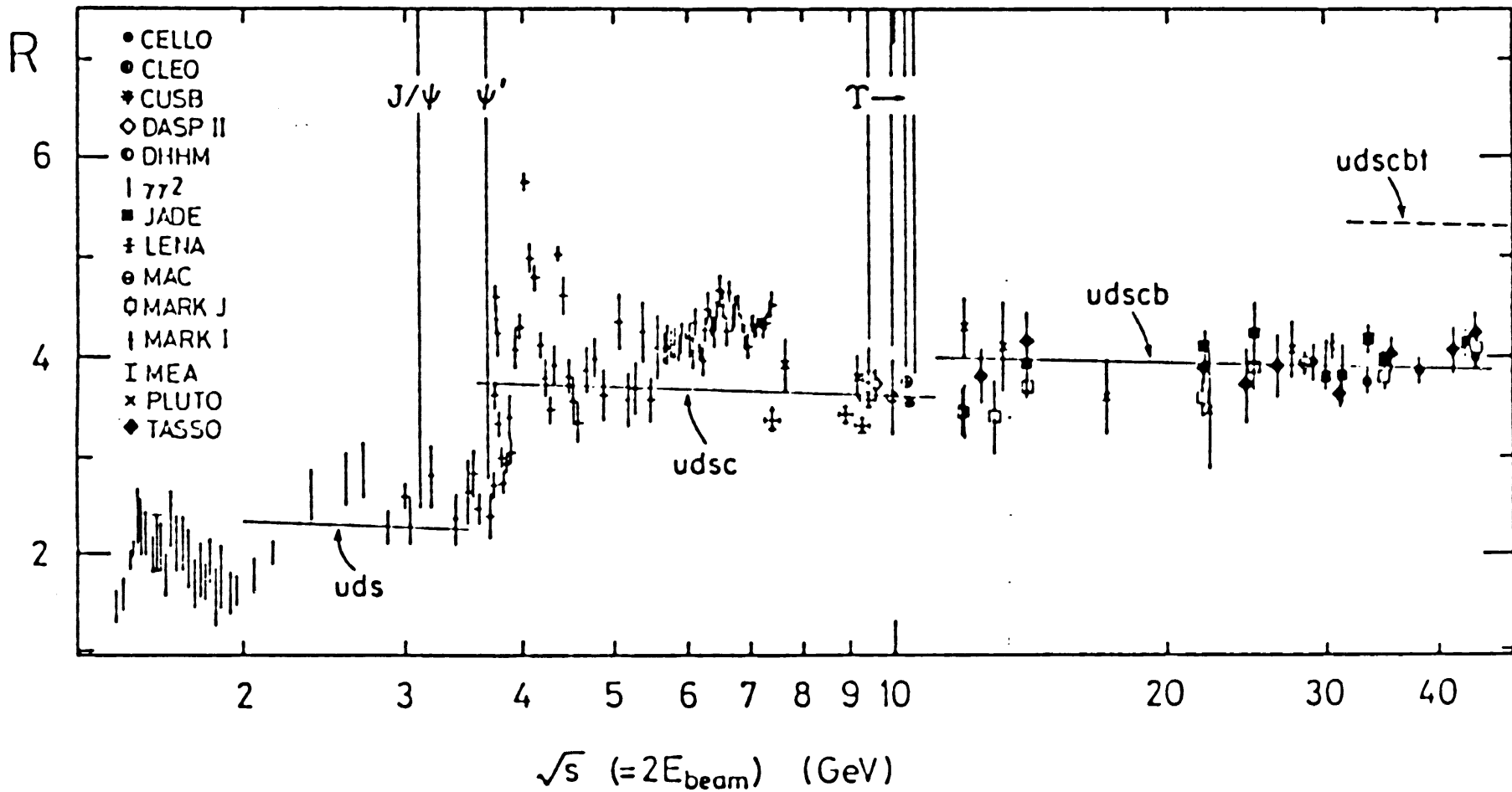
$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrony})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = 3 \sum e_{q_i}^2 \quad \text{jeśli 3 kolory}$$

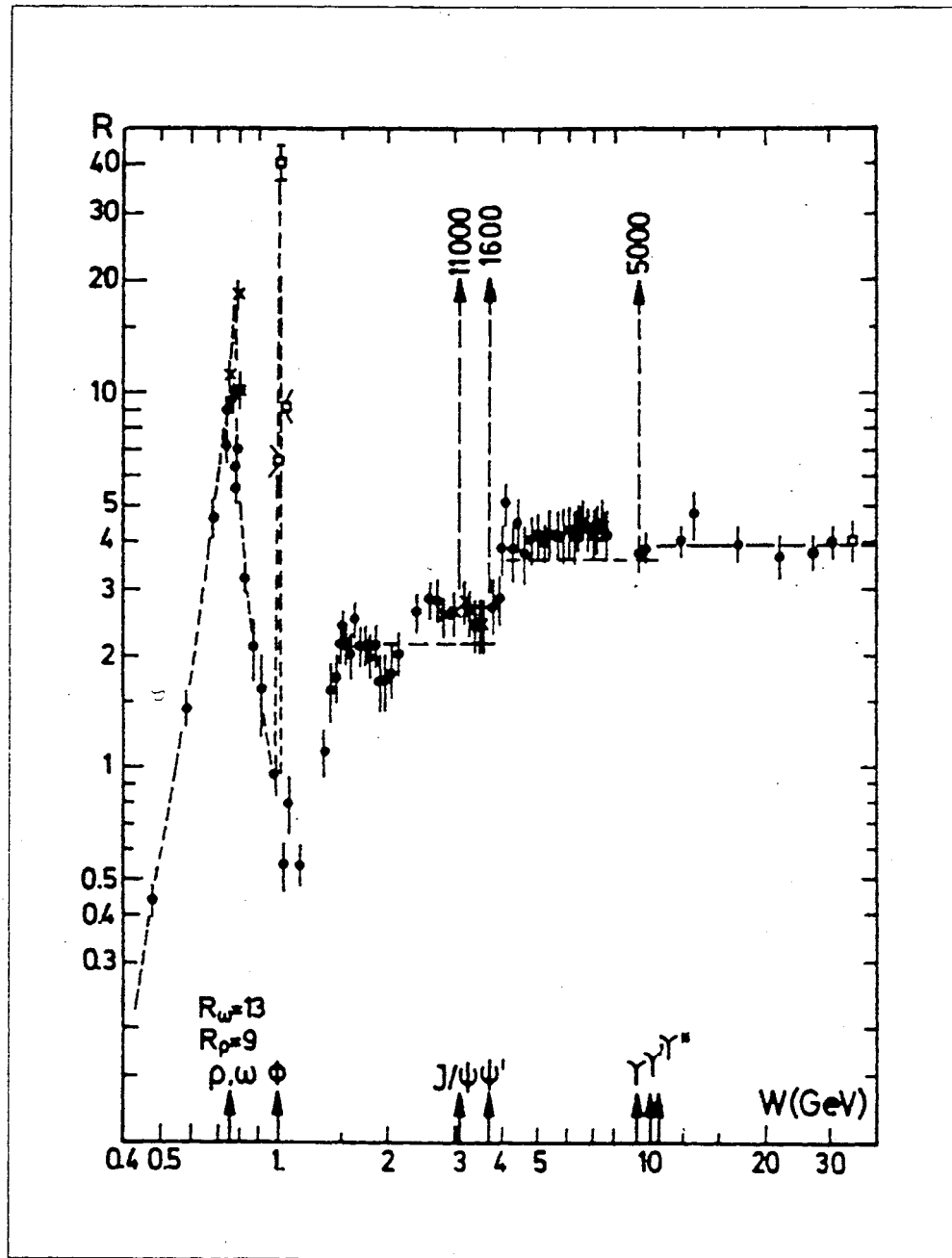
$$R = 3 \left(\frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \frac{4}{9} \right)$$

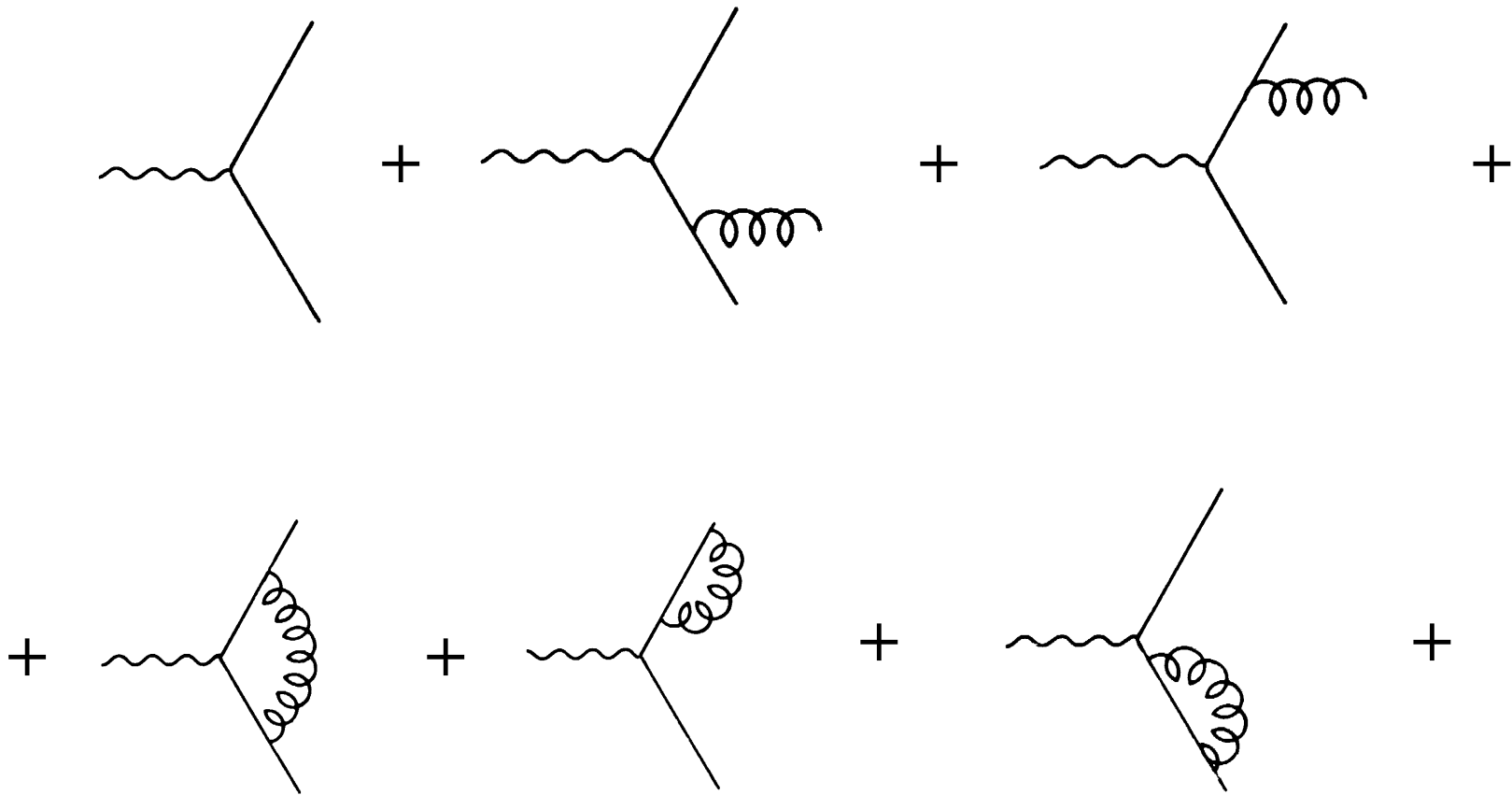
d u s c b t



**bez
koloru**

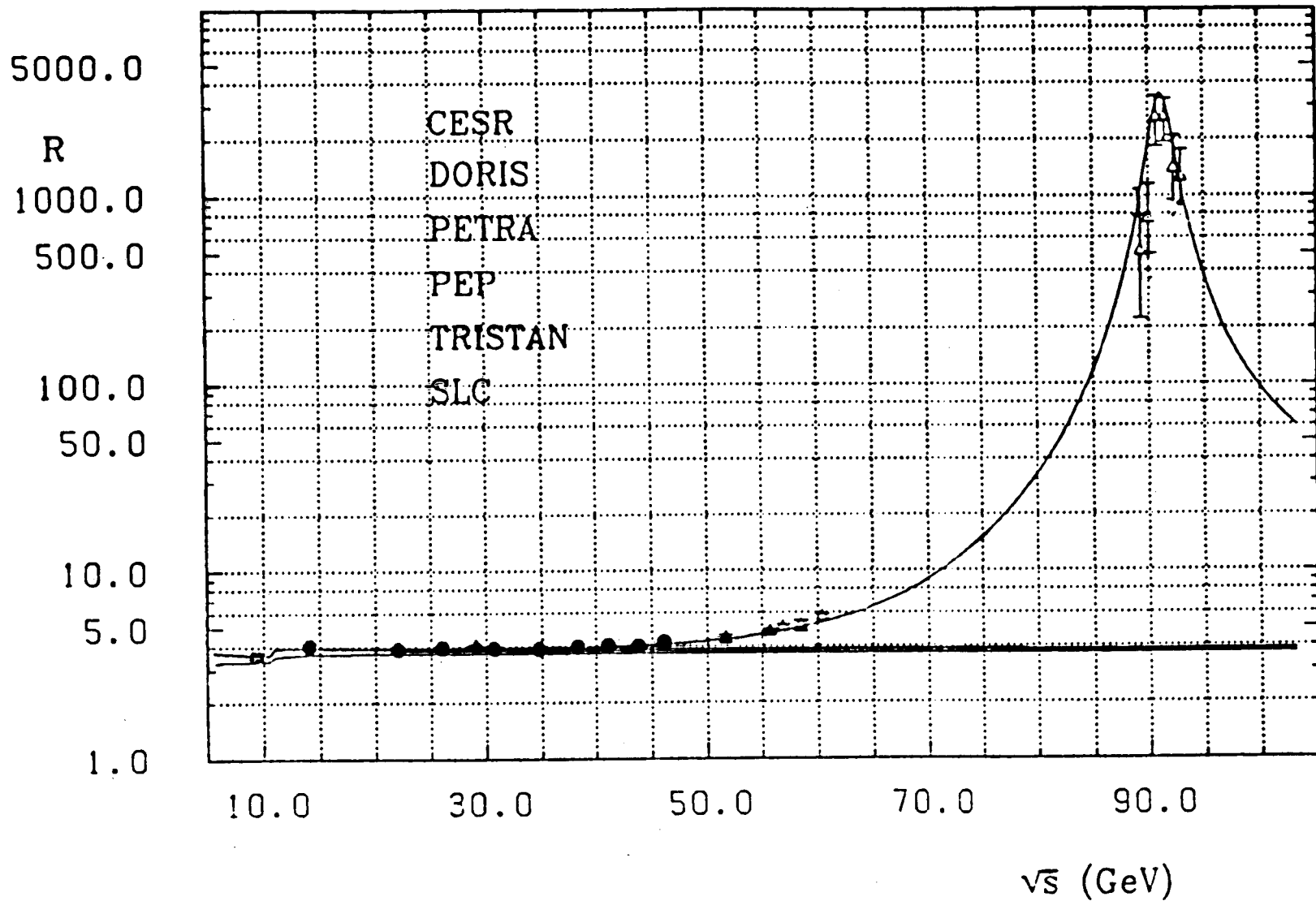






$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = 3 \sum e_{q_i}^2 \left(1 + \frac{\alpha_s(Q^2)}{\pi} + \dots \right)$$

Wartości R w obszarze Z^0



Ładunek kolorowy ma trzy wartości α , β , γ

$$\alpha + \beta + \gamma = 0$$

$$\alpha + \bar{\alpha} = 0$$

$$\beta + \bar{\beta} = 0$$

$$\gamma + \bar{\gamma} = 0$$

Nasuwa się analogia z optyką, gdzie





































niebieski + zielony + czerwony = biel

niebieski + kolor dopełniający = biel itd.

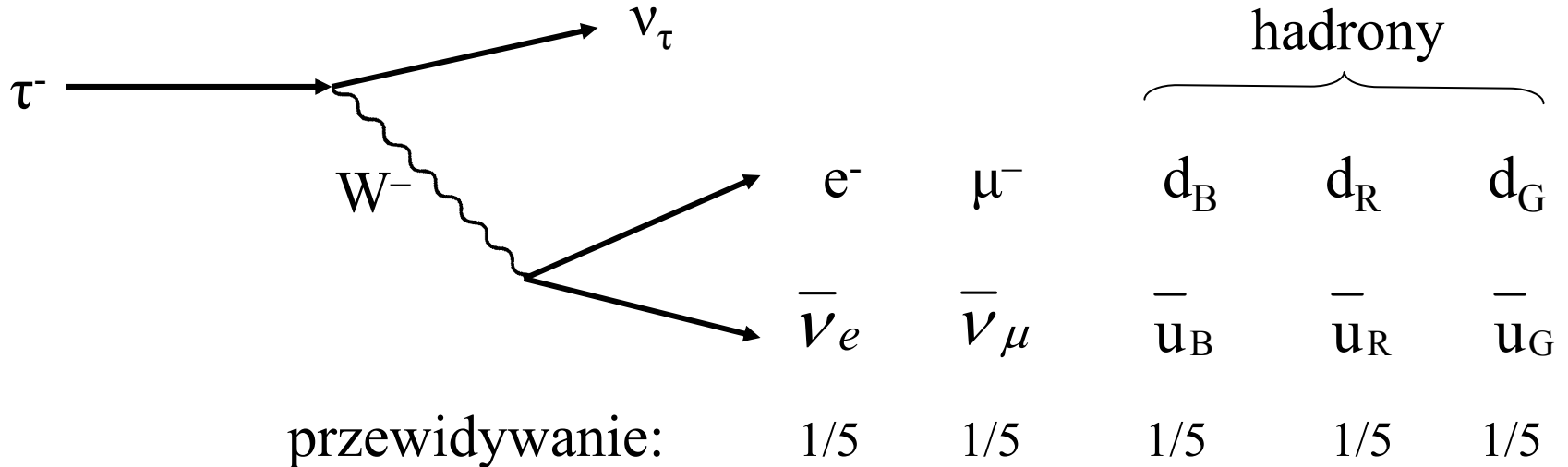
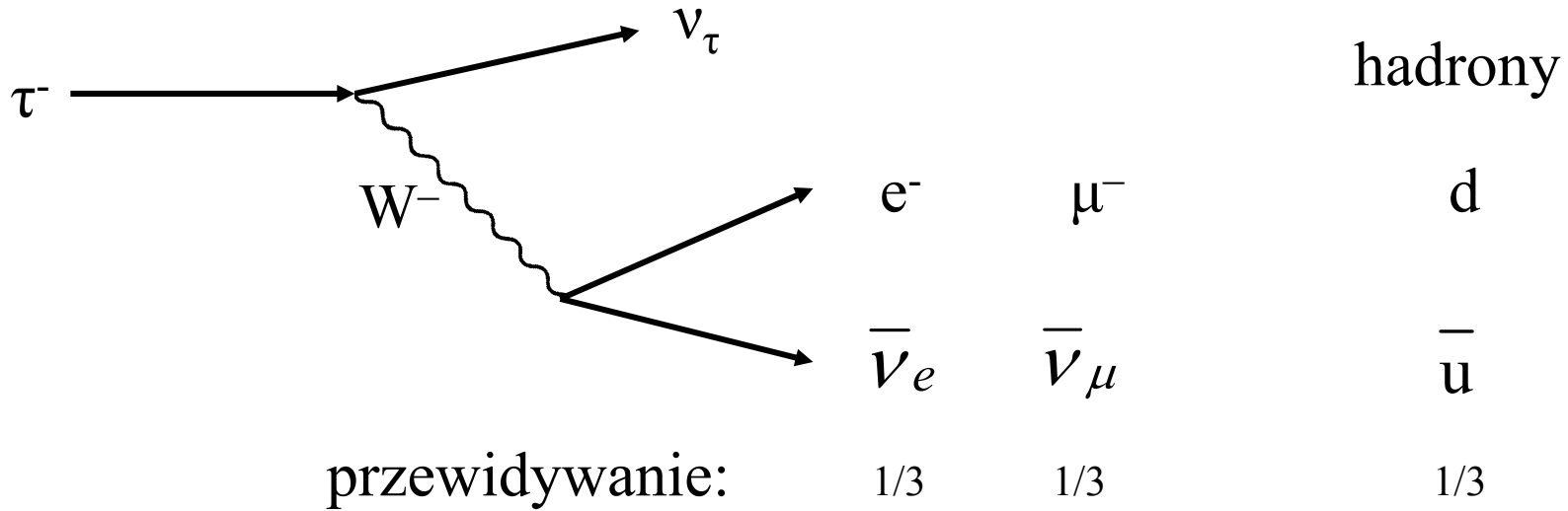
Dlatego zamiast ładunków α β γ mówimy o trzech kolorach zasadniczych **B G R**

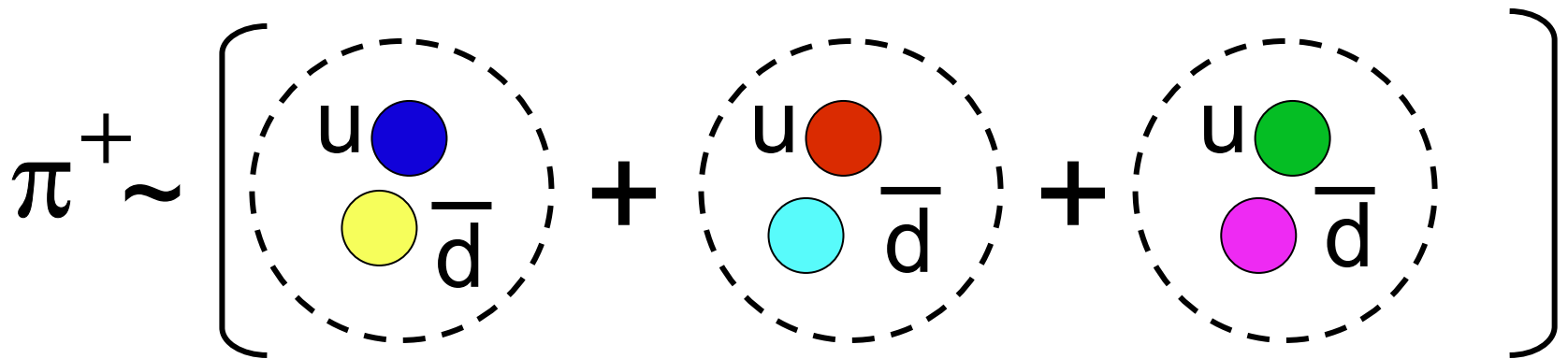
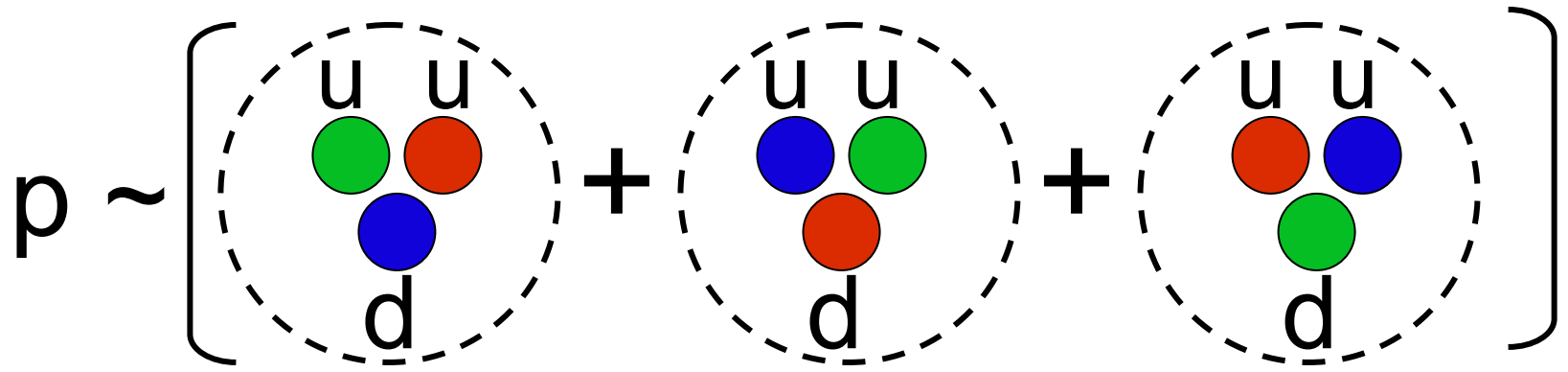
kwarki

antykwaraki

	R	G	B		\bar{R}	\bar{G}	\bar{B}	
u								u
d								d
c								c
s								s
t								t
b								b

Rozpad leptonu τ i liczba kolorów





etc.

Leptony (umowa)

	e_q	m (MeV)	τ	L_e	L_μ	L_τ
e^-	-1	0,51..	$>4,6 \times 10^{26}$ lat	1	0	0
ν_e	0	(< 2 eV)		1	0	0
μ^-	-1	105,65	2,197 μs	0	1	0
ν_μ	0			0	1	0
τ^-	-1	1777,0	290,6 fs	0	0	1
ν_τ	0			0	0	1

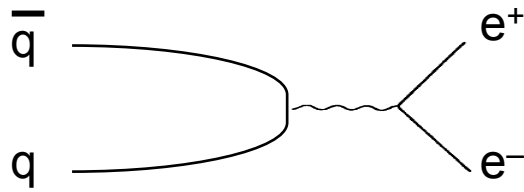
Leptony są fermionami o spinie 1/2

Antyleptony (umowa)

	e_q	m (MeV)	τ	L_e	L_μ	L_τ
e^+	+1	0,51..	$>4,6 \times 10^{26}$ lat	-1	0	0
$\bar{\nu}_e$	0	(< 2 eV)		-1	0	0
μ^+	+1	105,65	2,197 μ s	0	-1	0
$\bar{\nu}_\mu$	0			0	-1	0
τ^+	+1	1777,0	290,6 fs	0	0	-1
$\bar{\nu}_\tau$	0			0	0	-1

Antyleptony są fermionami o spinie 1/2

Rozpady leptonowe mezonów wektorowych



(Model Van Royena-Weisskopf)

$$\Gamma(q\bar{q} \rightarrow l^+l^-) \cong |\psi(0)|^2 e_{qi}^2$$

	Γ_{ee} (keV)
ρ	$7,04 \pm 0,06$
ω	$0,60 \pm 0,02$
ϕ	$1,27 \pm 0,02$
J/ψ	$5,55 \pm 0,14$
Υ	$1,34 \pm 0,02$

$$\Gamma_{\rho} \sim \left[\frac{1}{\sqrt{2}} \left(\frac{2}{3} - \left(-\frac{1}{3} \right) \right) \right]^2 e_{qi}^2 = \frac{1}{2}$$

$$\Gamma_{\omega} \sim \left[\frac{1}{\sqrt{2}} \left(\frac{2}{3} + \left(-\frac{1}{3} \right) \right) \right]^2 e_{qi}^2 = \frac{1}{18}$$

$$\Gamma_{\phi} = \Gamma_{\Upsilon} \sim \left(-\frac{1}{3} \right)^2 e_{qi}^2 = \frac{1}{9}$$

$$\Gamma_{J/\psi} \sim \left(\frac{2}{3} \right)^2 e_{qi}^2 = \frac{4}{9}$$

9

1

2

4

$$\Gamma(q\bar{q} \rightarrow l^+l^-) \cong |\psi(0)|^2 e_{qi}^2$$

	M (MeV)	Γ_{ee} (keV)
Υ (1S)	9460	1,340 ± 0,018
Υ (2S)	10023	0,612 ± 0,011
Υ (3S)	10355	0,443 ± 0,008
Υ (4S)	10579	0,272 ± 0,029
Υ (10860)		0,31 ± 0,07
Υ (11019)		0,130 ± 0,030

Wpływ różnic w $\psi(0)$