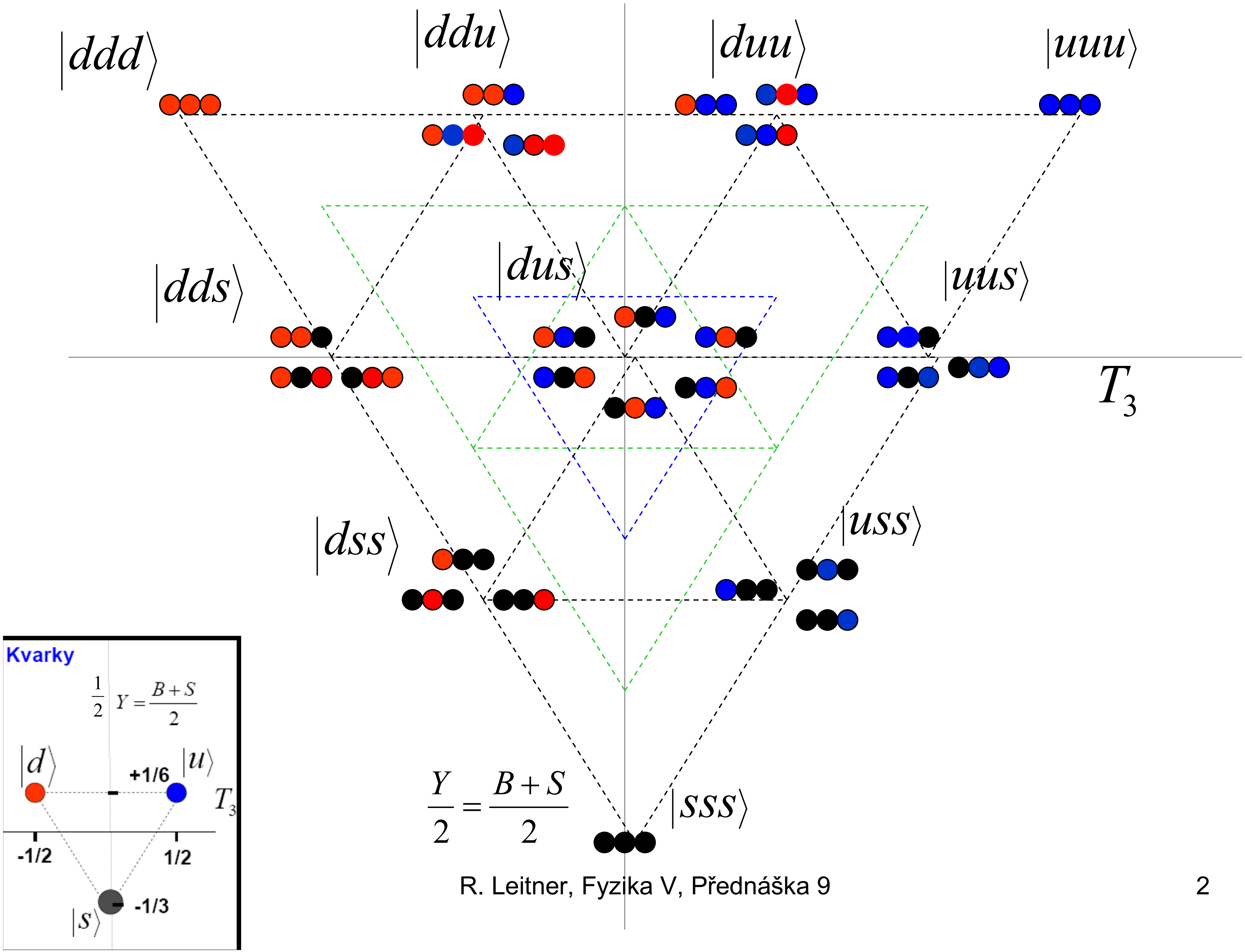
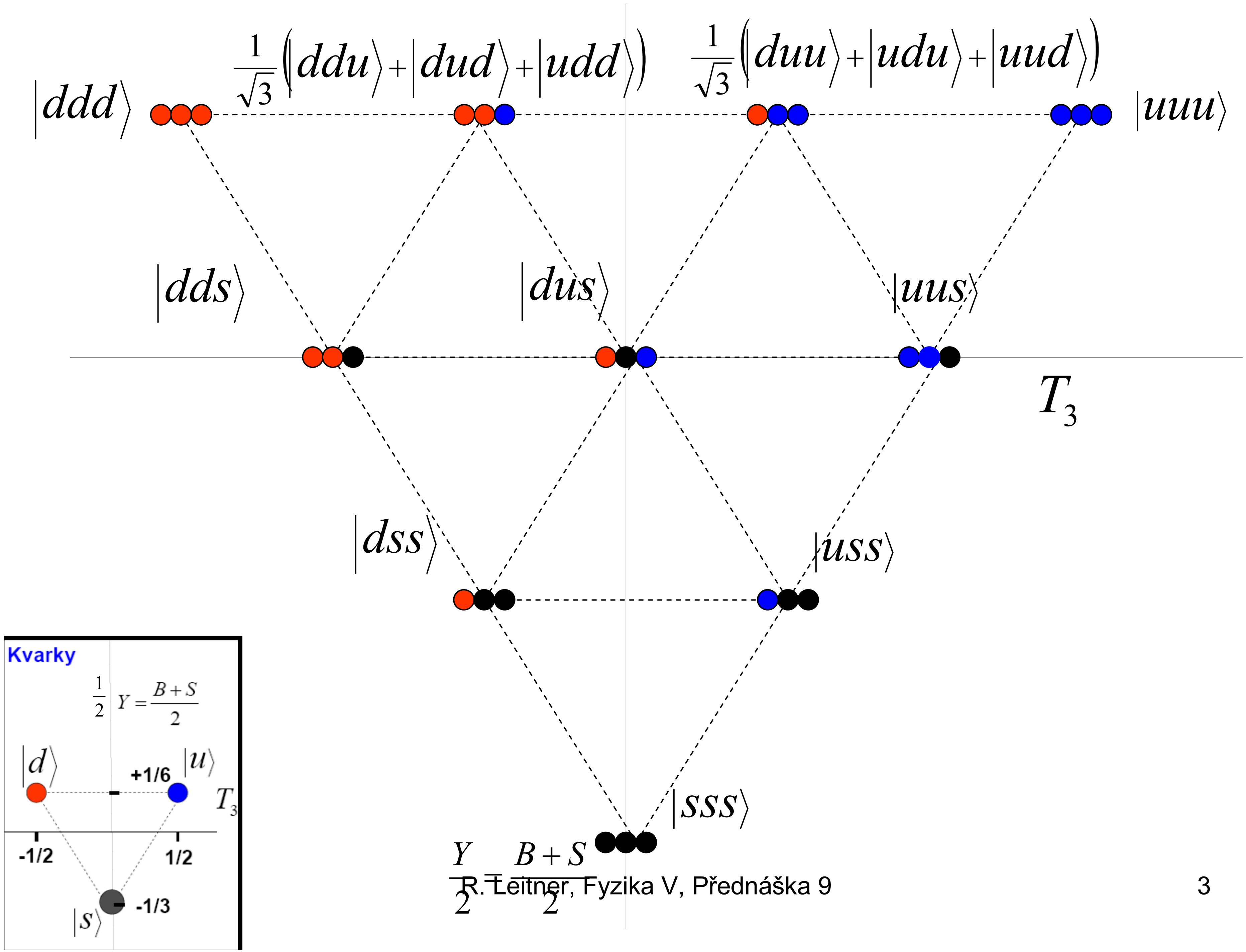
Přednáška 9. (3.12.2007)

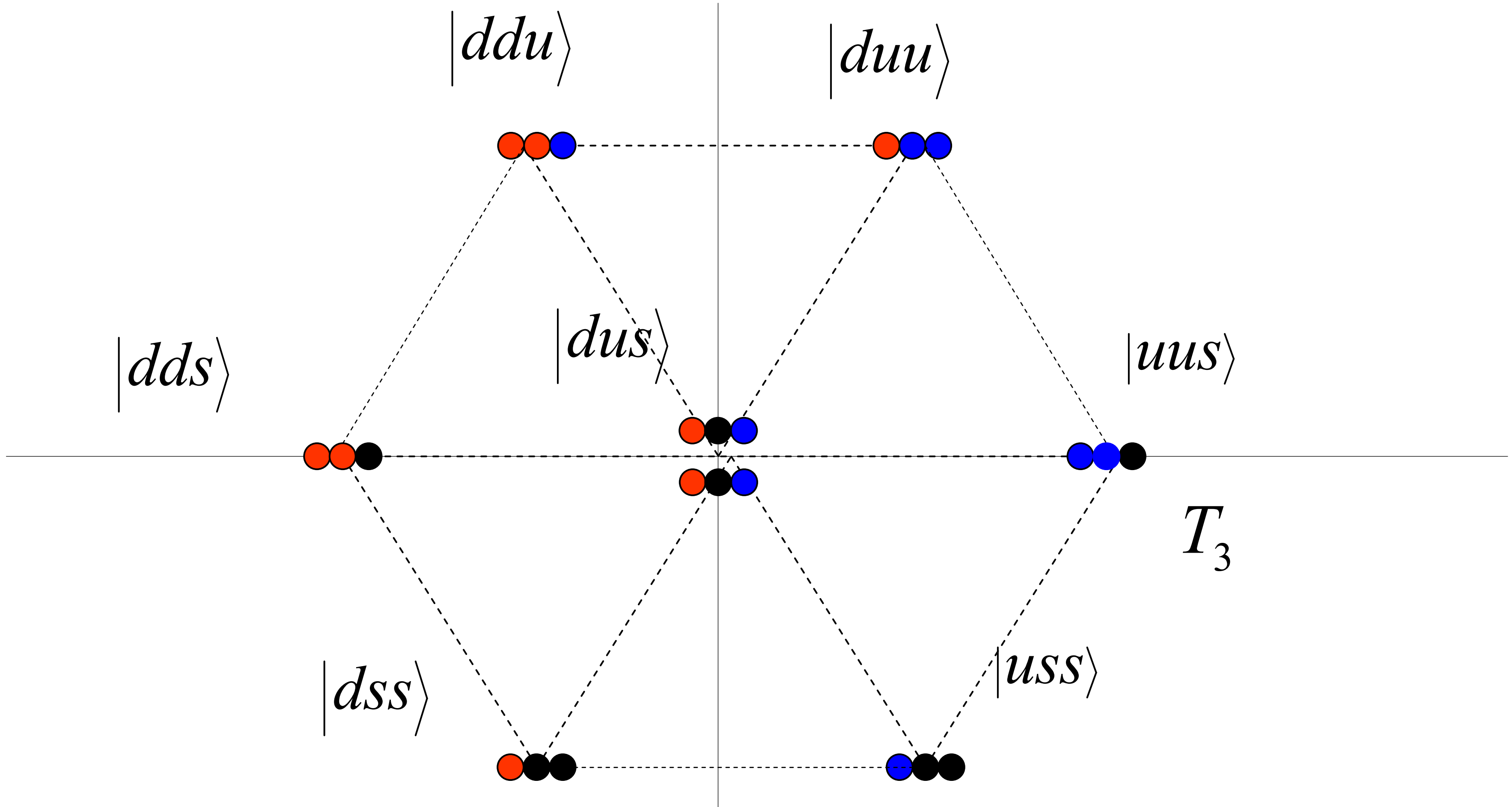
- Vlnové funkce baryonů a magnetické momenty.
- Kvantové číslo barva. Nejlehčí baryony.
- Silná interakce jako výměna barevných gluonů.
- Vektorové mezony. Mezon Φ a Zweigovo pravidlo.
- Některé důkazy existence kvarků a barvy
  Nové kvarky.



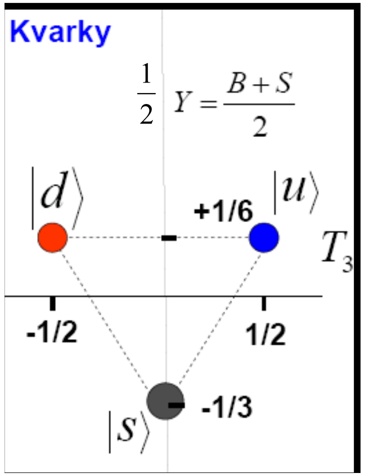
$|ddd\rangle$
$|ddu\rangle$
$|duu\rangle$
$|uuu\rangle$
$|dds\rangle$
$|dus\rangle$
$|uus\rangle$
T_3
$|dss\rangle$
$|uss\rangle$
$|sss\rangle$
$\frac{Y}{2} = \frac{B+S}{2}$
Kvarky
$\frac{1}{2}\ Y = \frac{B+S}{2}$
$|d\rangle$
+1/6
$|u\rangle$
T_3
-1/2
1/2
$|s\rangle$
-1/3



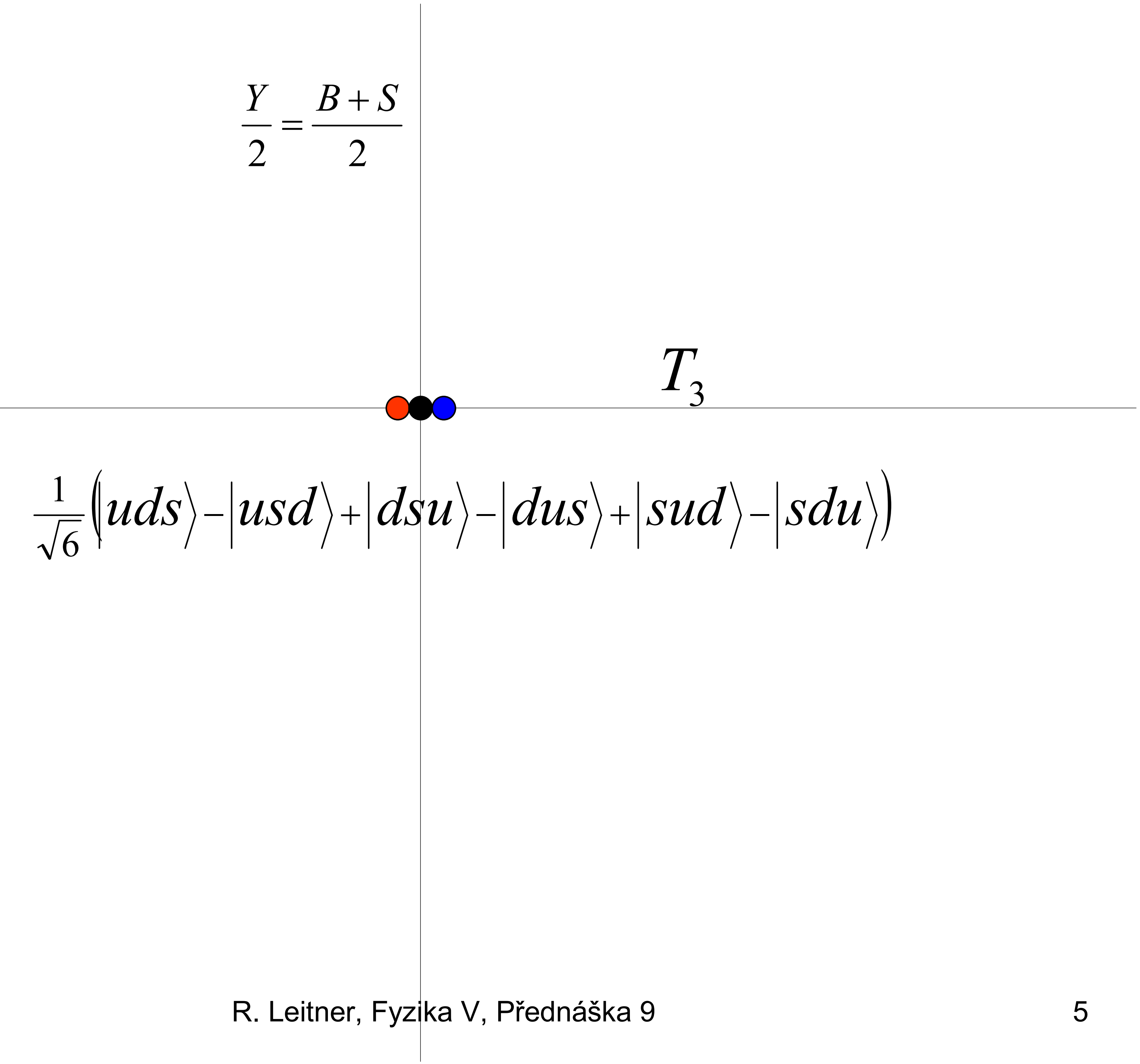
$|ddd\rangle$
$\frac{1}{\sqrt{3}}\left(|ddu\rangle+|dud\rangle+|udd\rangle\right)$
$\frac{1}{\sqrt{3}}\left(|duu\rangle+|udu\rangle+|uud\rangle\right)$
$|uuu\rangle$
$|dds\rangle$
$|dus\rangle$
$|uus\rangle$
T_3
$|dss\rangle$
$|uss\rangle$
$|sss\rangle$
$\frac{Y}{2}=\frac{B+S}{2}$
Kvarky
$\frac{1}{2}Y=\frac{B+S}{2}$
$|d\rangle$
+1/6
$|u\rangle$
T_3
-1/2
1/2
$|s\rangle$
-1/3



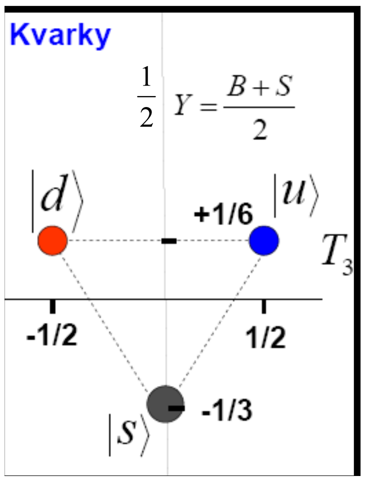
$$\frac{Y}{2} = \frac{B+S}{2}$$



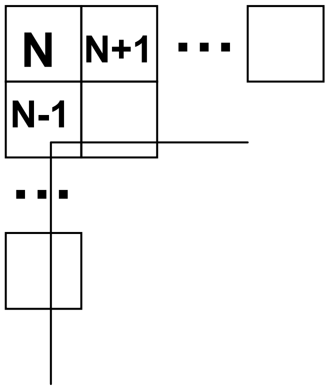
$$\frac{Y}{2}=\frac{B+S}{2}$$



$$\frac{1}{\sqrt{6}}\left(|uds\rangle-|usd\rangle+|dsu\rangle-|dus\rangle+|sud\rangle-|sdu\rangle\right)$$

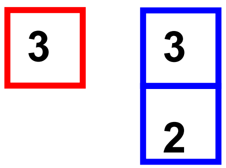


Youngovy symboly a multiplety



$$MULT = \frac{(N\cdot(N+1)\cdot\ldots)\cdot((N-1)\cdot\ldots)\cdot\ldots}{NH_1\cdot\ldots\cdot NH_n}$$

$3\otimes\bar{3}$



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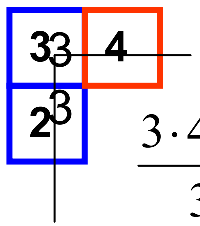
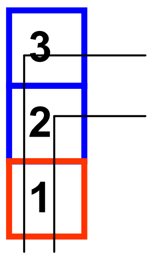


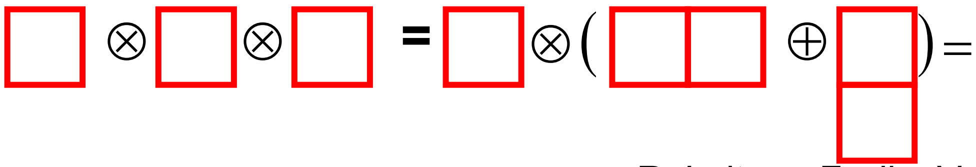
$$\frac{3\cdot4\cdot2}{3}=8$$

1

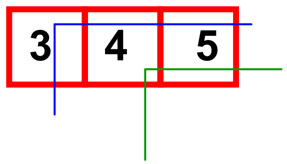


$$\frac{3\cdot2\cdot1}{2\cdot3}=1$$

$3\otimes3\otimes3$



10 $\frac{3\cdot4\cdot5}{3\cdot2}=10$



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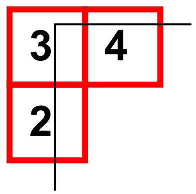

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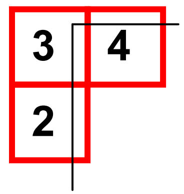
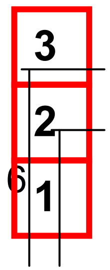
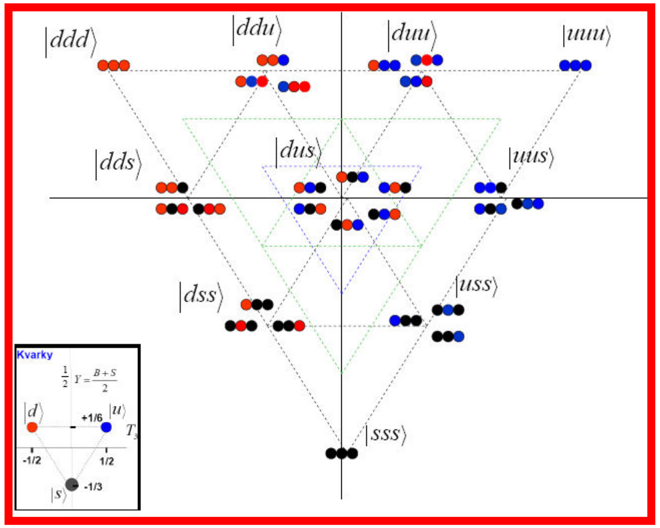
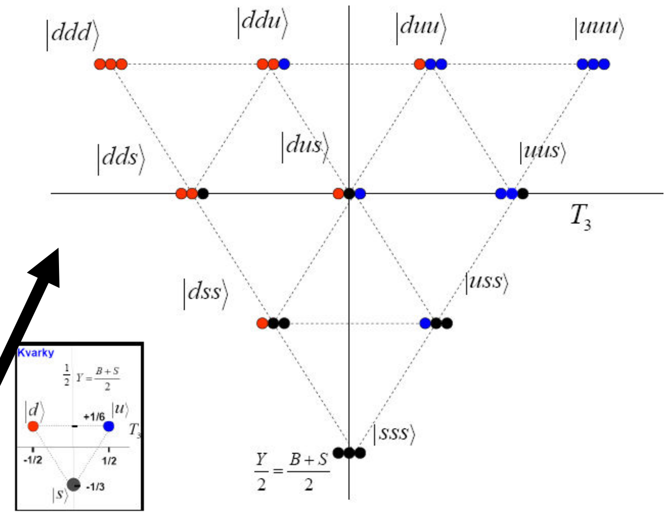


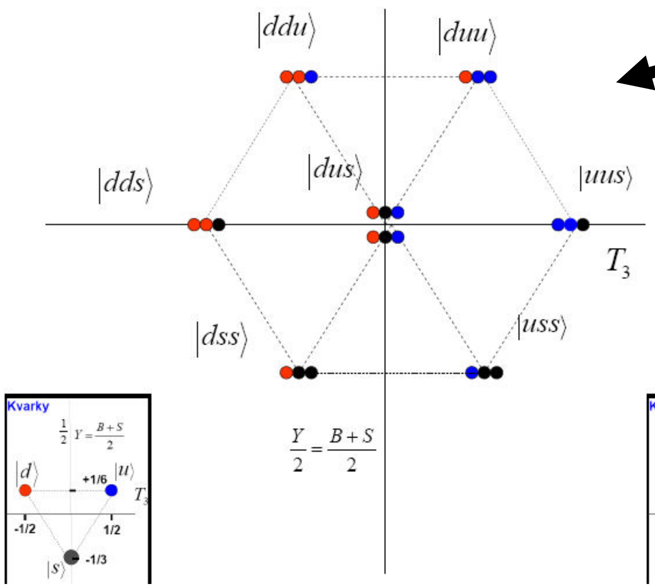
1

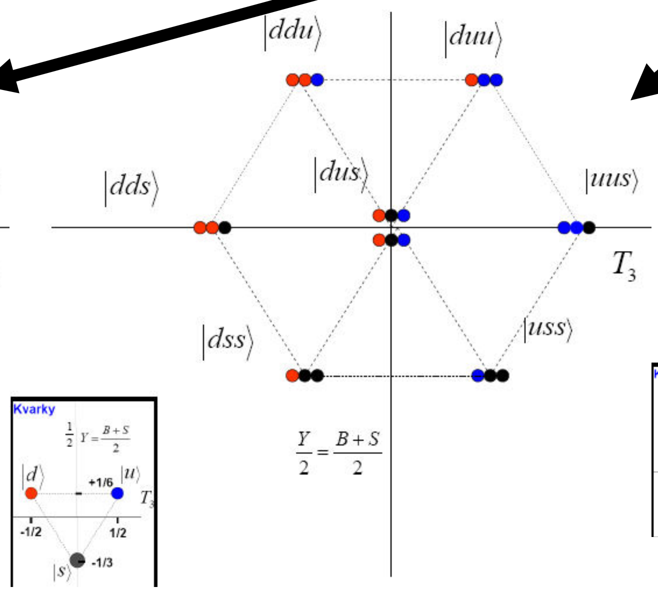


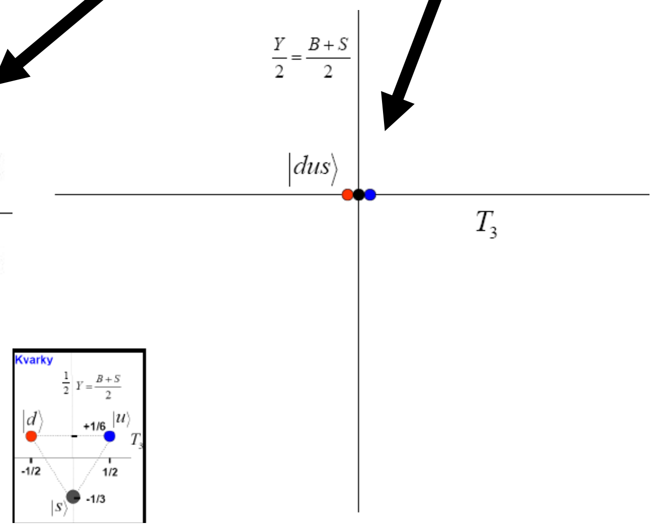




$$3 \otimes 3 \otimes 3 = 10^{S} \oplus 8^{MA} \oplus 8^{MS} \oplus 1^{A}$$







$$1/2 \otimes 1/2 \otimes 1/2:$$

$$1/2 \otimes 1/2 = 1 \oplus 0;$$

$$1:$$

$$\left|1,-1\right\rangle = \left|\downarrow\downarrow\right\rangle;$$

$$\left|1,0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle\right);$$

$$\left|1,1\right\rangle = \left|\uparrow\uparrow\right\rangle$$

$$0:$$

$$\left|0,0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

$$1\otimes 1/2 = 3/2 \oplus 1/2$$

$3/2:$

$$\left|3/2,-3/2\right\rangle = |1,-1\rangle\left|\downarrow\right\rangle = \left|\downarrow\downarrow\right\rangle\left|\downarrow\right\rangle = \left|\downarrow\downarrow\downarrow\right\rangle;$$

$$\left|3/2,-1/2\right\rangle = \sqrt{\frac{2}{3}}|1,0\rangle\left|\downarrow\right\rangle + \sqrt{\frac{1}{3}}|1,-1\rangle\left|\uparrow\right\rangle = \sqrt{\frac{2}{3}}\frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle\right)\left|\downarrow\right\rangle + \sqrt{\frac{1}{3}}\left|\downarrow\downarrow\right\rangle\left|\uparrow\right\rangle = \sqrt{\frac{1}{3}}\left(\left|\uparrow\downarrow\downarrow\right\rangle + \left|\downarrow\uparrow\downarrow\right\rangle + \left|\downarrow\downarrow\uparrow\right\rangle\right)$$

$$\left|3/2,+1/2\right\rangle = \sqrt{\frac{2}{3}}|1,0\rangle\left|\uparrow\right\rangle + \sqrt{\frac{1}{3}}|1,+1\rangle\left|\downarrow\right\rangle = \sqrt{\frac{2}{3}}\frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle\right)\left|\uparrow\right\rangle + \sqrt{\frac{1}{3}}\left|\uparrow\uparrow\right\rangle\left|\downarrow\right\rangle = \sqrt{\frac{1}{3}}\left(\left|\uparrow\downarrow\uparrow\right\rangle + \left|\downarrow\uparrow\uparrow\right\rangle + \left|\uparrow\uparrow\downarrow\right\rangle\right)$$

$$\left|3/2,+3/2\right\rangle = \left|\uparrow\uparrow\right\rangle\left|\uparrow\right\rangle = \left|\uparrow\uparrow\uparrow\right\rangle$$

$1/2:$

$$\left|1/2,-1/2\right\rangle = \sqrt{\frac{1}{3}}|1,0\rangle\left|\downarrow\right\rangle - \sqrt{\frac{2}{3}}|1,-1\rangle\left|\uparrow\right\rangle = \sqrt{\frac{1}{3}}\frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle\right)\left|\downarrow\right\rangle - \sqrt{\frac{2}{3}}\left|\downarrow\downarrow\right\rangle\left|\uparrow\right\rangle = \sqrt{\frac{1}{6}}\left(\left|\uparrow\downarrow\downarrow\right\rangle + \left|\downarrow\uparrow\downarrow\right\rangle - 2\left|\downarrow\downarrow\uparrow\right\rangle\right)$$

$$\left|1/2,+1/2\right\rangle = -\sqrt{\frac{1}{3}}|1,0\rangle\left|\uparrow\right\rangle + \sqrt{\frac{2}{3}}|1,+1\rangle\left|\downarrow\right\rangle = -\sqrt{\frac{1}{3}}\frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle\right)\left|\uparrow\right\rangle + \sqrt{\frac{2}{3}}\left|\uparrow\uparrow\right\rangle\left|\downarrow\right\rangle = \sqrt{\frac{1}{6}}\left(-\left|\uparrow\downarrow\uparrow\right\rangle - \left|\downarrow\uparrow\uparrow\right\rangle + 2\left|\uparrow\uparrow\downarrow\right\rangle\right)$$

$$0 \otimes 1/2 = 1/2$$

$$1/2:$$

$$\left|1/2,-1/2\right\rangle = \left|0,0\right\rangle\left|\downarrow\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)\left|\downarrow\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\downarrow\right\rangle - \left|\downarrow\uparrow\downarrow\right\rangle\right)$$

$$\left|1/2,+1/2\right\rangle = \left|0,0\right\rangle\left|\uparrow\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)\left|\uparrow\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\uparrow\right\rangle - \left|\downarrow\uparrow\uparrow\right\rangle\right)$$

$$\left|3/2,+1/2\right\rangle_{SPIN} = \sqrt{\frac{1}{3}}\left(\left|\uparrow\downarrow\uparrow\right\rangle + \left|\downarrow\uparrow\uparrow\right\rangle + \left|\uparrow\uparrow\downarrow\right\rangle\right)$$

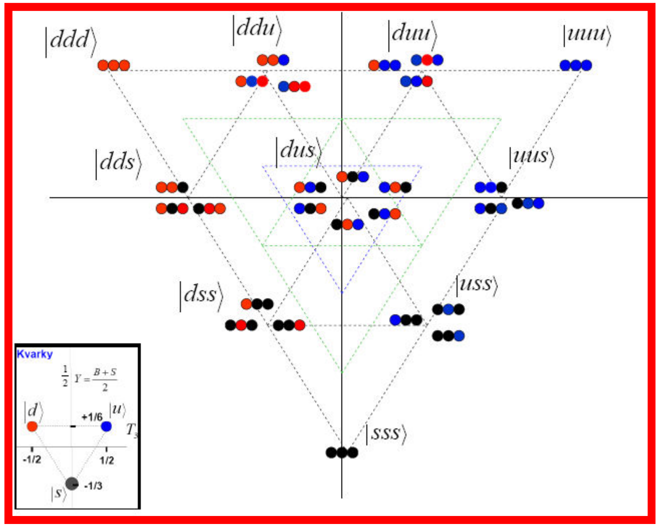
$$\left|1/2,+1/2\right\rangle_{SPIN} = \sqrt{\frac{1}{6}}\left(-\left|\uparrow\downarrow\uparrow\right\rangle - \left|\downarrow\uparrow\uparrow\right\rangle + 2\left|\uparrow\uparrow\downarrow\right\rangle\right)$$

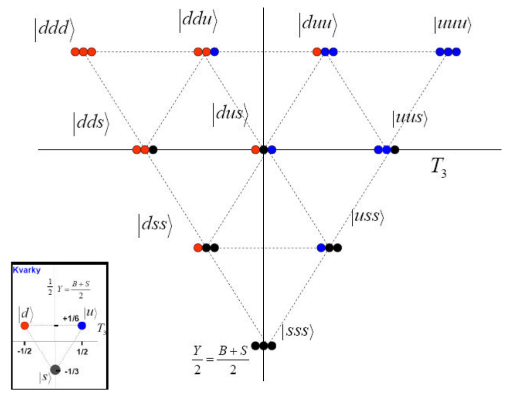
$$\left|1/2,+1/2\right\rangle_{SPIN} = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\uparrow\right\rangle - \left|\downarrow\uparrow\uparrow\right\rangle\right)$$

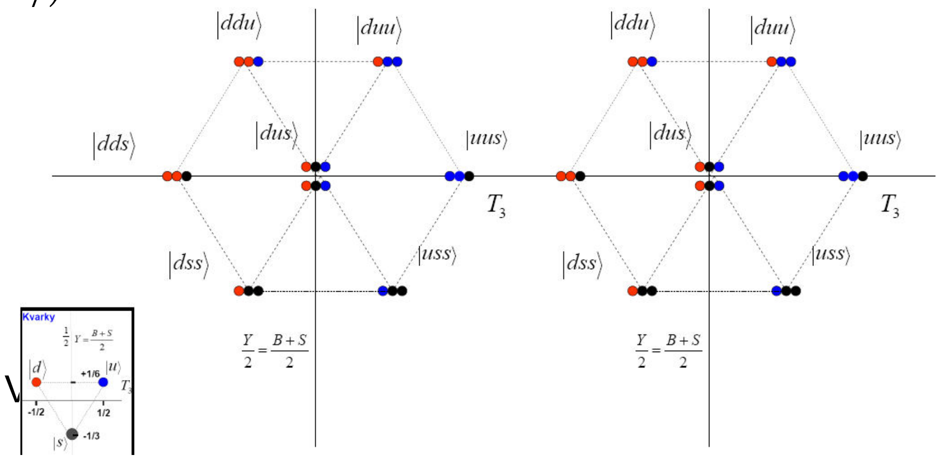
$$\left|3/2,+1/2\right\rangle_{FLAVOUR} = \sqrt{\frac{1}{3}}\left(\left|udu\right\rangle + \left|duu\right\rangle + \left|uud\right\rangle\right) \in 10^{S}$$

$$\left|1/2,+1/2\right\rangle_{FLAVOUR} = \sqrt{\frac{1}{6}}\left(-\left|udu\right\rangle - \left|duu\right\rangle + 2\left|uud\right\rangle\right) \in 8^{MS}$$

$$\left|1/2,+1/2\right\rangle_{FLAVOUR} = \frac{1}{\sqrt{2}}\left(\left|udu\right\rangle - \left|duu\right\rangle\right) \in 8^{MA}$$







$$|qqq\rangle_A = |\text{color}\rangle_A \times |\text{space, spin, flavor}\rangle_S$$

		SPIN		
		$1/2_{MS}$	$1/2_{MA}$	$3/2_S$
FLAVOUR	10_S	M	M	S
	8_{MS}		M	M
	8_{MA}	M		M
	1_A	M	M	A

$$\frac{1}{\sqrt{2}}\left(8_{MS}\cdot 1/2_{MS} + 8_{MA}\cdot 1/2_{MA}\right) = S$$

$$\frac{1}{\sqrt{2}}\left(8_{MS}\cdot 1/2_{MS} - 8_{MA}\cdot 1/2_{MA}\right) = A$$

Baryony mají symetrickou vlnovou funkci. Důvodem je správné vysvětlení magnetických momentů protonu a neutronu. Vlnová funkce fermionů ale musí být antisymetrická. To se vysvětluje kvantovým číslem barva – viz dále.

Nejlehčí baryony s orbitálním momentem hybnosti L=0 jsou:
Oktet se spinem 1/2
Dekuplet se spinem 3/2

Vlnová funkce Δ+ baryonu, spin 3/2, projekce spinu 1/2

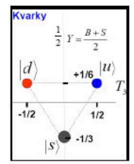
$$\left|3/2,+1/2\right\rangle_{SPIN} = \sqrt{\frac{1}{3}}\left(\left|\uparrow\downarrow\uparrow\right\rangle + \left|\downarrow\uparrow\uparrow\right\rangle + \left|\uparrow\uparrow\downarrow\right\rangle\right)$$

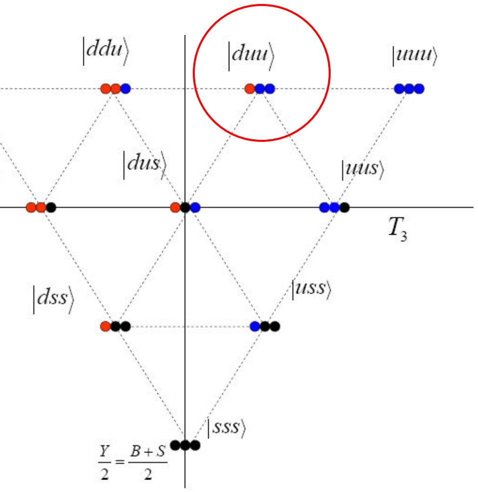
$$\left|3/2,+1/2\right\rangle_{FLAVOUR} = \sqrt{\frac{1}{3}}\left(\left|udu\right\rangle + \left|duu\right\rangle + \left|uud\right\rangle\right) \in 10_F$$

$$\left|3/2,+1/2\right\rangle_{FLAVOUR} \cdot \left|3/2,+1/2\right\rangle_{SPIN} =$$

$$\sqrt{\frac{1}{3}}\begin{pmatrix} \left|udu\right\rangle\sqrt{\frac{1}{3}}\left(\left|\uparrow\downarrow\uparrow\right\rangle + \left|\downarrow\uparrow\uparrow\right\rangle + \left|\uparrow\uparrow\downarrow\right\rangle\right) + \\ \left|duu\right\rangle\sqrt{\frac{1}{3}}\left(\left|\uparrow\downarrow\uparrow\right\rangle + \left|\downarrow\uparrow\uparrow\right\rangle + \left|\uparrow\uparrow\downarrow\right\rangle\right) + \\ \left|uud\right\rangle\sqrt{\frac{1}{3}}\left(\left|\uparrow\downarrow\uparrow\right\rangle + \left|\downarrow\uparrow\uparrow\right\rangle + \left|\uparrow\uparrow\downarrow\right\rangle\right) \end{pmatrix} =$$

$$\frac{1}{3}\begin{pmatrix} \left|u\uparrow d\downarrow u\uparrow\right\rangle + \left|u\downarrow d\uparrow u\uparrow\right\rangle + \left|u\uparrow d\uparrow u\downarrow\right\rangle + \\ \left|d\uparrow u\downarrow u\uparrow\right\rangle + \left|d\downarrow u\uparrow u\uparrow\right\rangle + \left|d\uparrow u\uparrow u\downarrow\right\rangle + \\ \left|u\uparrow u\downarrow d\uparrow\right\rangle + \left|u\downarrow u\uparrow d\uparrow\right\rangle + \left|u\uparrow u\uparrow d\downarrow\right\rangle \end{pmatrix}$$



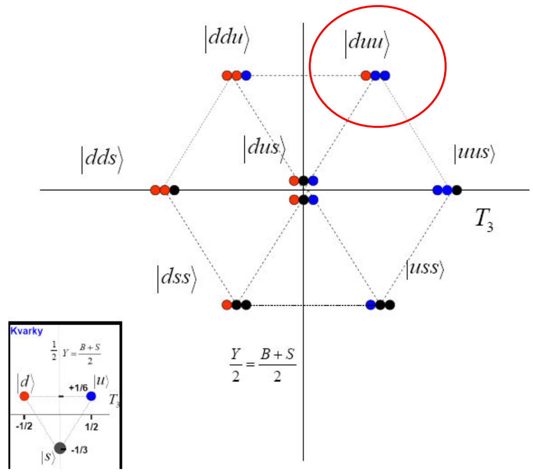


Částice se spinem 3/2, člen Izotopického kvartetu, tj. dekupletu hadronů.

Vlnová funkce protnu, spin 1/2, projekce spinu 1/2

$$|1/2,+1/2\rangle^{MS}_{SPIN} = \sqrt{\frac{1}{6}}\left(-|\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\rangle + 2|\uparrow\uparrow\downarrow\rangle\right)$$

$$|1/2,+1/2\rangle^{MA}_{SPIN} = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\rangle\right)$$



$$|1/2,+1/2\rangle^{MS}_{FLAVOUR} = \sqrt{\frac{1}{6}}\left(-|udu\rangle - |duu\rangle + 2|uud\rangle\right)$$

$$|1/2,+1/2\rangle^{MA}_{FLAVOUR} = \frac{1}{\sqrt{2}}\left(|udu\rangle - |duu\rangle\right)$$

$$\sqrt{\frac{1}{2}}\left(|1/2,+1/2\rangle^{MS}_{FLAVOUR}|1/2,+1/2\rangle^{MS}_{SPIN} + |1/2,+1/2\rangle^{MA}_{FLAVOUR}|1/2,+1/2\rangle^{MA}_{SPIN}\right) =$$

$$\sqrt{\frac{1}{2}}\begin{pmatrix} \sqrt{\frac{1}{6}}\left(-|udu\rangle - |duu\rangle + 2|uud\rangle\right)\sqrt{\frac{1}{6}}\left(-|\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\rangle + 2|\uparrow\uparrow\downarrow\rangle\right) + \\ \frac{1}{\sqrt{2}}\left(|udu\rangle - |duu\rangle\right)\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\rangle\right) \end{pmatrix} =$$

$$\sqrt{\frac{1}{2}}\begin{pmatrix} \frac{1}{6}\begin{pmatrix} |u\uparrow d\downarrow u\uparrow\rangle + |u\downarrow d\uparrow u\uparrow\rangle - 2|u\uparrow d\uparrow u\downarrow\rangle + \\ |d\uparrow u\downarrow u\uparrow\rangle + |d\downarrow u\uparrow u\uparrow\rangle - 2|d\uparrow u\uparrow u\downarrow\rangle + \\ -2|u\uparrow u\downarrow d\uparrow\rangle - 2|u\downarrow u\uparrow d\uparrow\rangle + 4|u\uparrow u\uparrow d\downarrow\rangle \end{pmatrix} + \\ \frac{1}{2}\begin{pmatrix} |u\uparrow d\downarrow u\uparrow\rangle - |u\downarrow d\uparrow u\uparrow\rangle - \\ |d\uparrow u\downarrow u\uparrow\rangle + |d\downarrow u\uparrow u\uparrow\rangle \end{pmatrix} \end{pmatrix}$$

$$\sqrt{\frac{1}{2}\frac{1}{6}}\left(1\left(\begin{array}{l} |u\uparrow d\downarrow u\uparrow\rangle+|u\downarrow d\uparrow u\uparrow\rangle-2|u\uparrow d\uparrow u\downarrow\rangle+ \\ \underline{|d\uparrow u\downarrow u\uparrow\rangle}+\underline{|d\downarrow u\uparrow u\uparrow\rangle}-2|d\uparrow u\uparrow u\downarrow\rangle+ \\ -2\underline{|u\uparrow u\downarrow d\uparrow\rangle}-2\underline{|u\downarrow u\uparrow d\uparrow\rangle}+4|u\uparrow u\uparrow d\downarrow\rangle \end{array}\right)+\begin{array}{l} \\ \\ \end{array}\right.$$

$$\left.3\left(\begin{array}{l} |u\uparrow d\downarrow u\uparrow\rangle-|u\downarrow d\uparrow u\uparrow\rangle- \\ \underline{|d\uparrow u\downarrow u\uparrow\rangle}+\underline{|d\downarrow u\uparrow u\uparrow\rangle} \end{array}\right)\right)=$$

$$\sqrt{\frac{1}{2}\frac{1}{6}}\left(\begin{array}{l} 4\underline{|u\uparrow d\downarrow u\uparrow\rangle}-2\underline{|u\downarrow d\uparrow u\uparrow\rangle}-2|u\uparrow d\uparrow u\downarrow\rangle+ \\ 4\underline{|d\downarrow u\uparrow u\uparrow\rangle}-2\underline{|d\uparrow u\downarrow u\uparrow\rangle}-2|d\uparrow u\uparrow u\downarrow\rangle+ \\ -2\underline{|u\uparrow u\downarrow d\uparrow\rangle}-2\underline{|u\downarrow u\uparrow d\uparrow\rangle}+4|u\uparrow u\uparrow d\downarrow\rangle \end{array}\right)=$$

$$\sqrt{\frac{1}{2}\frac{1}{3}}\left(\begin{array}{l} 2|u\uparrow d\downarrow u\uparrow\rangle-|u\downarrow d\uparrow u\uparrow\rangle-|u\uparrow d\uparrow u\downarrow\rangle+ \\ 2|d\downarrow u\uparrow u\uparrow\rangle-|d\uparrow u\downarrow u\uparrow\rangle-|d\uparrow u\uparrow u\downarrow\rangle+ \\ 2|u\uparrow u\uparrow d\downarrow\rangle-|u\downarrow u\uparrow d\uparrow\rangle-|u\uparrow u\downarrow d\uparrow\rangle \end{array}\right)=$$

$$\sqrt{\frac{1}{18}}\left(\begin{array}{l} 2|u\uparrow d\downarrow u\uparrow\rangle-|u\downarrow d\uparrow u\uparrow\rangle-|u\uparrow d\uparrow u\downarrow\rangle+ \\ 2|d\downarrow u\uparrow u\uparrow\rangle-|d\uparrow u\downarrow u\uparrow\rangle-|d\uparrow u\uparrow u\downarrow\rangle+ \\ 2|u\uparrow u\uparrow d\downarrow\rangle-|u\downarrow u\uparrow d\uparrow\rangle-|u\uparrow u\downarrow d\uparrow\rangle \end{array}\right)=|p\uparrow\rangle$$

Anomální magnetický moment protonu a neutronu a dalších baryonů svědčí o tom, že nejsou elementární, ale mají strukturu

Částice mají vlastní magnetický moment, který souvisí s jejich spinem:

$$\vec{\mu} = \frac{e}{m}\vec{S} \Rightarrow S = 1/2 : \mu_z = \frac{e}{m}\frac{\hbar}{2}$$

$$\Delta E = -\vec{\mu}\vec{H}$$

Kdyby proton a neutron byly elementární částice, měly by mít magnetické momenty:

$$\left|\mu_{p_z}\right| = \left|\pm\frac{e}{m_p}\frac{\hbar}{2}\right| = \mu_N$$

$$\mu_{n_z} = 0$$

Experimentální hodnoty ale jsou:

$$\mu_p = 2{,}79 \cdot \mu_N$$

$$\mu_n = -1{,}91 \cdot \mu_N$$

$$\mu_p / \mu_n = -1{,}46$$

To lze objasnit kvarkovou strukturou protonu a neutronu. Jako příklad **(neúplná Vlnová funkce protonu a neutronu):**

$$p = \left|u\uparrow d\downarrow u\uparrow\right\rangle \Rightarrow \mu_p = 2\mu_u - \mu_d$$

$$n = \left|d\uparrow u\downarrow d\uparrow\right\rangle \Rightarrow \mu_p = 2\mu_d - \mu_u$$

$$q_u = +2/3, q_u = -1/3, m_u \cong m_d \Rightarrow \mu_d = -\mu_u/2$$

$$\mu_p = 2\mu_u - \mu_d = 5/2 \cdot \mu_u$$

$$\mu_n = 2\mu_d - \mu_u = -2 \cdot \mu_u$$

$$\mu_p / \mu_n = -1{,}25$$

Výsledek je citlivý na konkrétní tvar vlnové funkce.

Magnetický moment protonu se správnou vlnovou funkcí:

$$\left|p\uparrow\right\rangle = \sqrt{\frac{1}{18}}\begin{pmatrix} \underline{2\left|u\uparrow d\downarrow u\uparrow\right\rangle} - \left|u\downarrow d\uparrow u\uparrow\right\rangle - \left|u\uparrow d\uparrow u\downarrow\right\rangle + \\ 2\left|d\downarrow u\uparrow u\uparrow\right\rangle - \left|d\uparrow u\uparrow u\downarrow\right\rangle - \left|d\uparrow u\downarrow u\uparrow\right\rangle + \\ 2\left|u\uparrow u\uparrow d\downarrow\right\rangle - \left|u\uparrow u\downarrow d\uparrow\right\rangle - \left|u\downarrow u\uparrow d\uparrow\right\rangle \end{pmatrix}$$

$$\boxed{\begin{gathered} \vec{\mu}\left|u\uparrow d\downarrow u\uparrow\right\rangle = (\mu_u - \mu_d + \mu_u)\left|u\uparrow d\downarrow u\uparrow\right\rangle \\ \sqrt{\frac{1}{18}}2\left\langle u\uparrow d\downarrow u\uparrow\right|(\mu_u - \mu_d + \mu_u)\sqrt{\frac{1}{18}}2\left|u\uparrow d\downarrow u\uparrow\right\rangle = \frac{1}{18}2^2(2\mu_u - \mu_d)\ldots \end{gathered}}$$

$$\mu_p = \left\langle p\uparrow\right|\vec{\mu}\left|p\uparrow\right\rangle = \frac{1}{18}3\left(2^2(2\mu_u - \mu_d) + \mu_d + \mu_d\right) = \frac{4\mu_u - \mu_d}{3} \quad ; \quad \mu_n = \left\langle n\uparrow\right|\vec{\mu}\left|n\uparrow\right\rangle = \frac{4\mu_d - \mu_u}{3}$$

$$Q_u = 2/3, Q_d = -1/3, m_u \cong m_d \Rightarrow \mu_d = -\frac{\mu_u}{2}$$

$$\mu_p = \frac{4\mu_u + \mu_u/2}{3} = \frac{3}{2}\mu_u \qquad \mu^{\exp}{}_p = 2{,}79 \cdot \mu_N$$

$$\mu_n = \frac{-2\mu_u - \mu_u}{3} = -\mu_u \qquad \mu^{\exp}{}_n = -1{,}91 \cdot \mu_N$$

$$\frac{\mu_p}{\mu_n} = -1{,}50 \qquad \frac{\mu^{\exp}{}_p}{\mu^{\exp}{}_n} = \frac{2{,}79}{-1{,}91} = 1{,}46$$

Magnetický moment protonu se správnou vlnovou funkcí:

$$\mu_p = \langle p \uparrow | \vec{\mu} | p \uparrow \rangle = \frac{4\mu_u - \mu_d}{3}$$

$$\mu_n = \langle n \uparrow | \vec{\mu} | n \uparrow \rangle = \frac{4\mu_d - \mu_u}{3}$$

$$\mu^{\exp}{}_p = 2{,}79 \cdot \mu_N, \mu^{\exp}{}_n = -1{,}91 \cdot \mu_N \Rightarrow$$

$$\mu_u = 1{,}85\, \mu_N, \mu_u = -0{,}97\, \mu_N$$

$$Q_u = 2/3, Q_d = -1/3, m_u, m_d \Rightarrow$$

$$\mu_u = \frac{\hbar e 2/3}{2m_u} = \frac{2/3}{m_u / m_p} \frac{e\hbar}{2m_p} = \frac{2/3}{m_u / m_p} \mu_N, \quad \mu_d = \frac{-1/3}{m_d / m_p} \mu_N$$

$$\Rightarrow m_u = 338 MeV, m_d = 322 MeV \approx m_p / 3$$

Nejlehčí baryony s orbitálním momentem hybnosti L=0 jsou:
Oktet se spinem 1/2 a Dekuplet se spinem 3/2

Kvantové číslo barva zachraňuje Fermiho statistiku

Kvarky existují ve třech barevných variantách Red, Green a Blue,
Vůňová a spinová část je dohromady symetrická, barevná část vlnové funkce je antisymetrická. Obecně mohou existovat pouze takové vázané stavy kvarků, které jsou celkově bezbarvé, tj. mají barevnou část vlnové funkce antisymetrickou.

$$\Delta^{++} = \left| u\uparrow \cdot u\uparrow \cdot u\uparrow \right\rangle$$

$$\left| u\uparrow \cdot u\uparrow \cdot u\uparrow \right\rangle \frac{1}{\sqrt{6}} \left(\left|RGB\right\rangle - \left|RBG\right\rangle + \left|GBR\right\rangle - \left|GRB\right\rangle + \left|BRG\right\rangle - \left|BGR\right\rangle \right) =$$

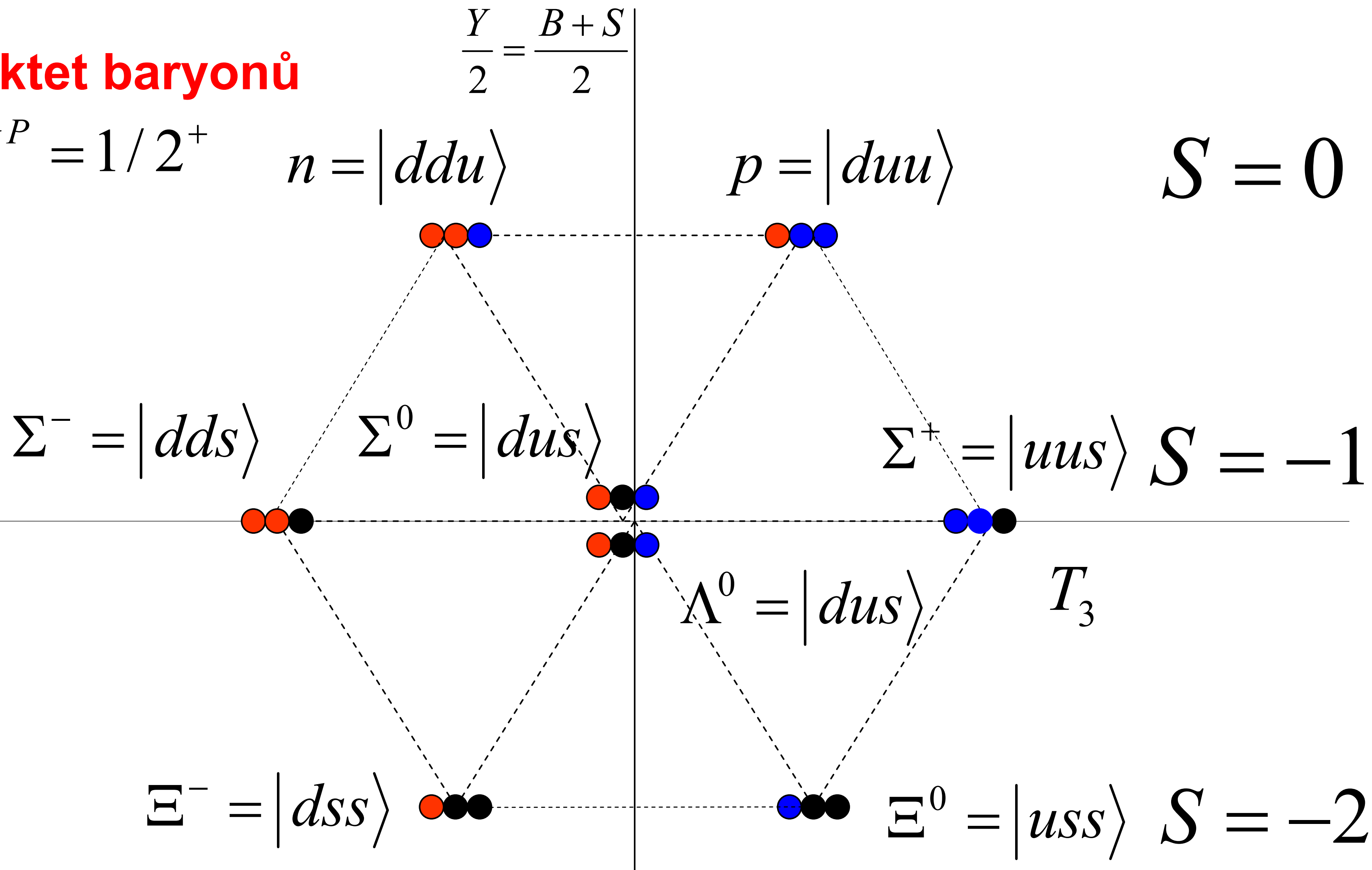
$$\frac{1}{\sqrt{6}} \left(\left| u_R^{\uparrow} u_G^{\uparrow} u_B^{\uparrow} \right\rangle - \left| u_R^{\uparrow} u_B^{\uparrow} u_G^{\uparrow} \right\rangle + \left| u_G^{\uparrow} u_B^{\uparrow} u_R^{\uparrow} \right\rangle - \left| u_G^{\uparrow} u_R^{\uparrow} u_B^{\uparrow} \right\rangle + \left| u_B^{\uparrow} u_R^{\uparrow} u_G^{\uparrow} \right\rangle - \left| u_B^{\uparrow} u_G^{\uparrow} u_R^{\uparrow} \right\rangle \right)$$

$$\left| p\uparrow \right\rangle = \sqrt{\frac{1}{18}} \begin{pmatrix} 2\left|u\uparrow d\downarrow u\uparrow\right\rangle - \left|u\downarrow d\uparrow u\uparrow\right\rangle - \left|u\uparrow d\uparrow u\downarrow\right\rangle + \\ 2\left|d\downarrow u\uparrow u\uparrow\right\rangle - \left|d\uparrow u\uparrow u\downarrow\right\rangle - \left|d\uparrow u\downarrow u\uparrow\right\rangle + \\ 2\left|u\uparrow u\uparrow d\downarrow\right\rangle - \left|u\uparrow u\downarrow d\uparrow\right\rangle - \left|u\downarrow u\uparrow d\uparrow\right\rangle \end{pmatrix}$$

$$\sqrt{\frac{1}{6}} \left(\left|RGB\right\rangle - \left|RBG\right\rangle + \left|GBR\right\rangle - \left|GRB\right\rangle + \left|BRG\right\rangle - \left|BGR\right\rangle \right)$$

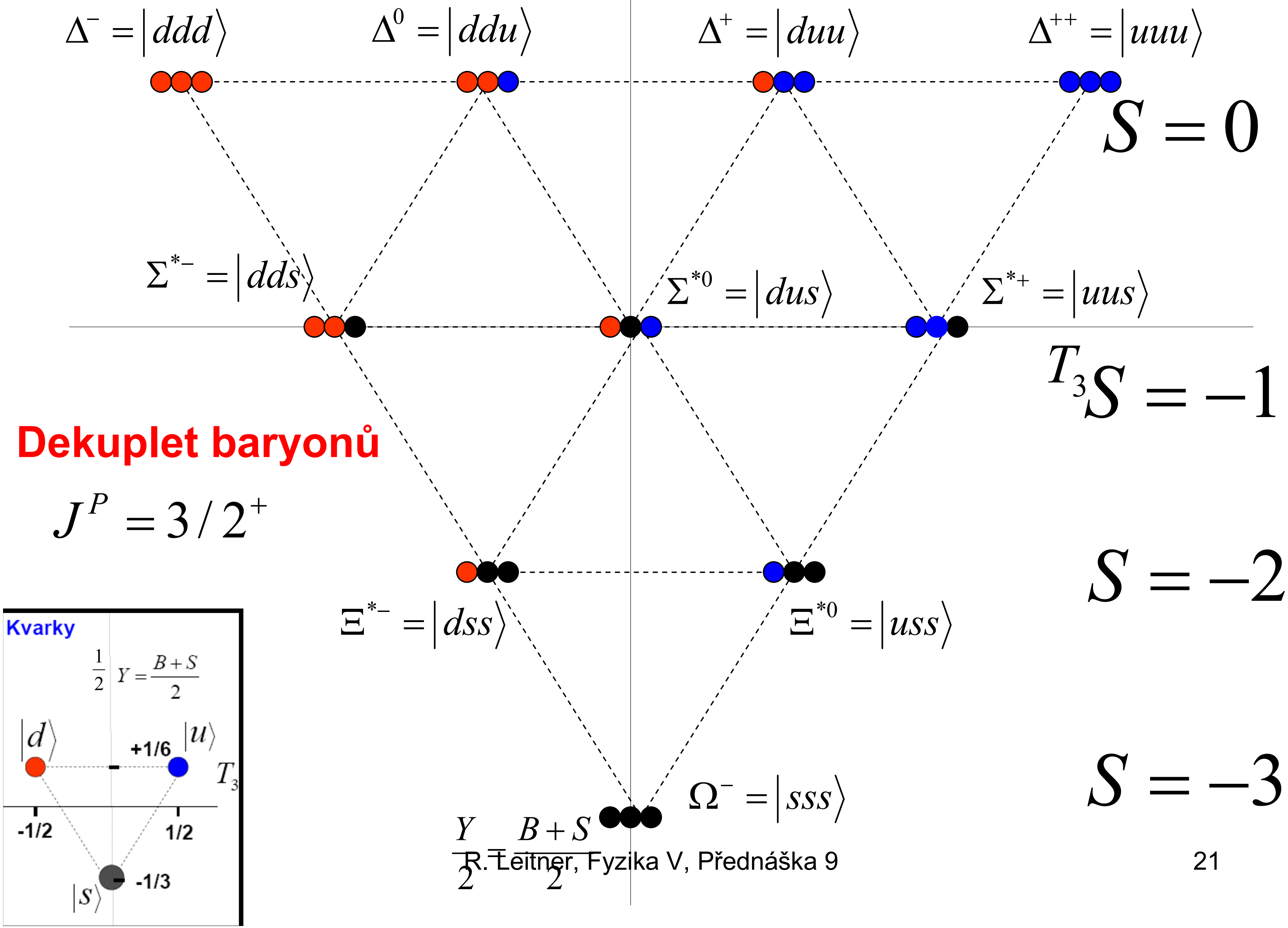
Oktet baryonů

$J^P = 1/2^+$

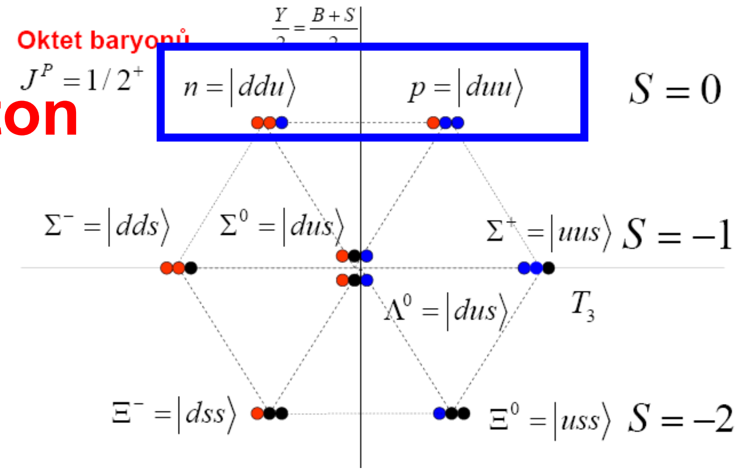


Dekuplet baryonů

$J^P = 3/2^+$



Isotopický dublet nepodivných baryonů v oktetu tvoří neutron a proton



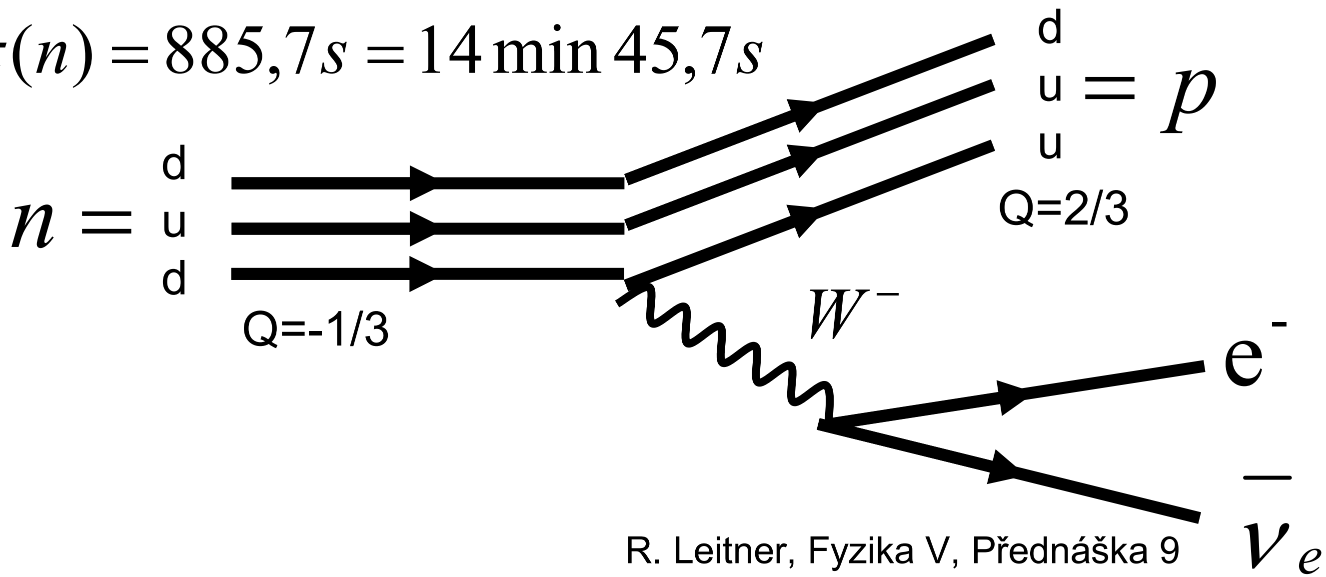
$$M(n) = 939{,}57\,MeV$$

$$M(p) = 938{,}27\,MeV$$

$$\tau(p) > 10^{30}\ years$$

$$n \to p + e^- + \bar{\nu}_e \quad \mathbf{100\%}$$

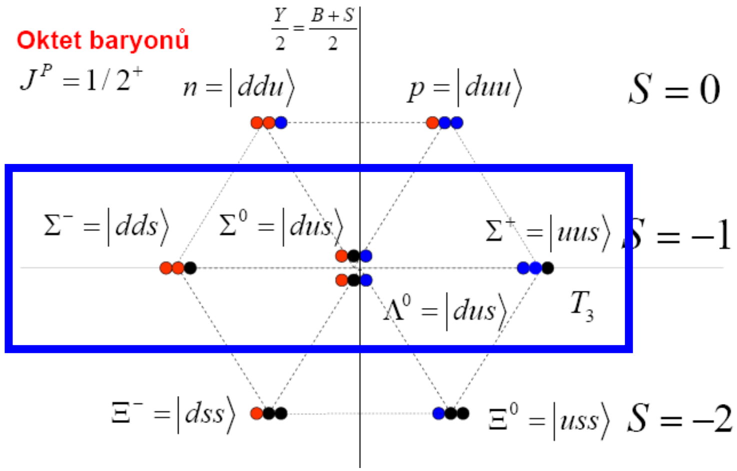
$$\tau(n) = 885{,}7s = 14\min 45{,}7s$$



Baryony s podivností -1

$$\Lambda^0$$

$$\Sigma^-, \Sigma^0, \Sigma^+$$

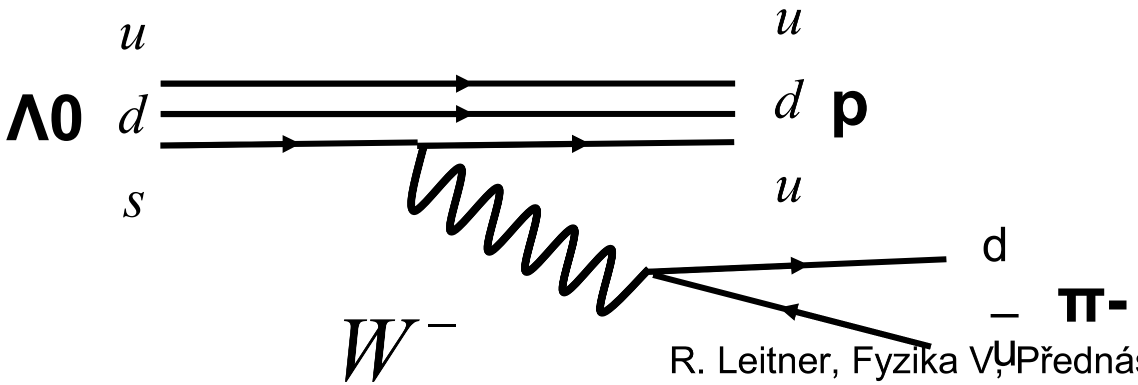


$$M(\Lambda^0) = 1115MeV > M(p/n) + M(\pi) =$$

$$938MeV + 140MeV = 1078MeV$$

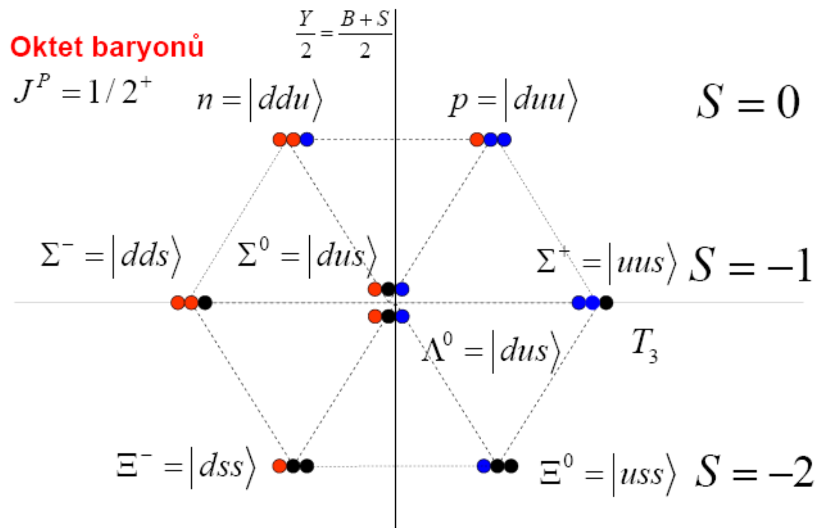
$\Lambda^0 \to p + \pi^-$ **64%** $c\tau(\Lambda^0) = 7{,}9cm \Rightarrow \tau(\Lambda^0) = 0{,}26ns$

$\Lambda^0 \to n + \pi^0$ **36%**



Baryony s podivností -1

$\Sigma^-, \Sigma^0, \Sigma^+$



$M(\Sigma^-) = 1197 MeV$

$M(\Sigma^0) = 1193 MeV$

$M(\Sigma^+) = 1189 MeV$

$M(\Sigma) < M(\Lambda) + M(\pi) = 1115 MeV + 140 MeV = 1255 MeV$

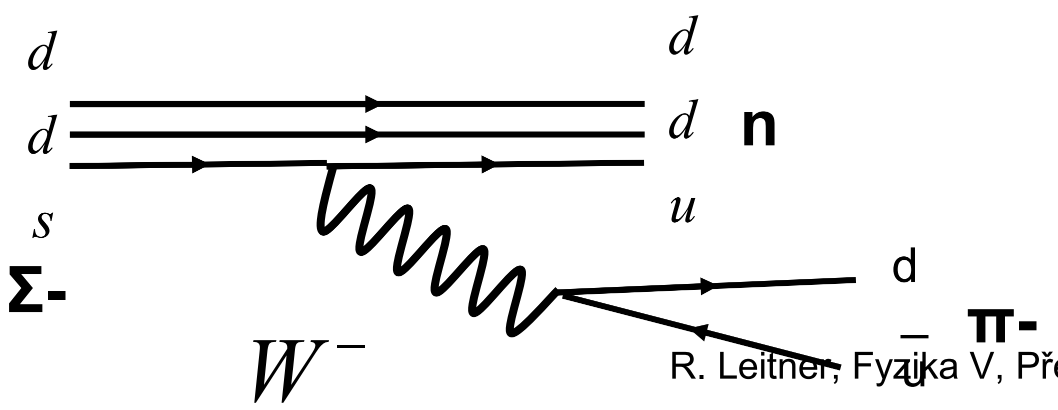
$\Sigma^- \rightarrow n + \pi^-$ **99,8%** $c\tau(\Sigma^-) = 4{,}4 cm \Rightarrow \tau(\Sigma^-) = 0{,}15 ns$

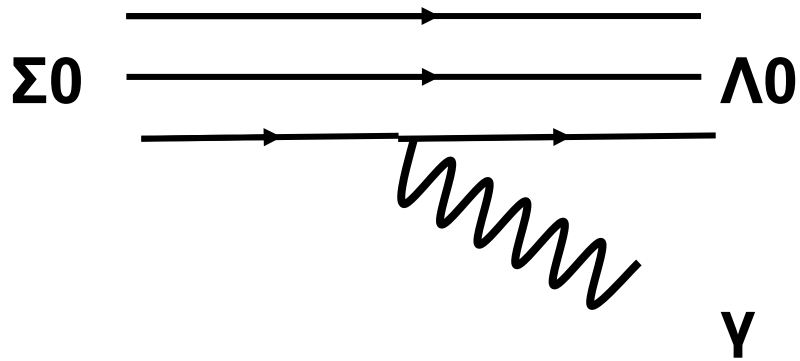
$\Sigma^+ \rightarrow p + \pi^0$ **51,6%** $c\tau(\Sigma^+) = 2{,}4 cm \Rightarrow \tau(\Sigma^-) = 0{,}08 ns$

$\Sigma^+ \rightarrow n + \pi^+$ **48,3%**

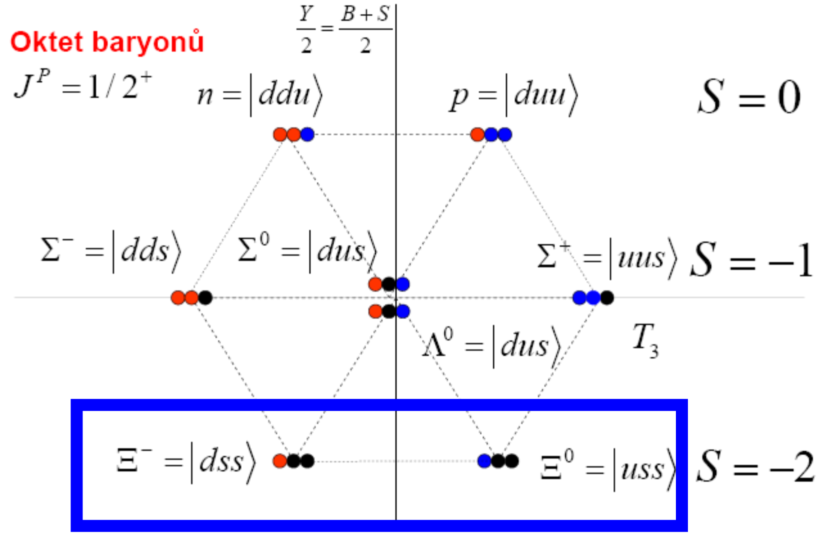
$\Sigma^0 \rightarrow \Lambda^0 + \gamma$ **100%** $c\tau(\Sigma^0) = 2{,}2 \cdot 10^{-11} m \Rightarrow \tau(\Sigma^0) = 7{,}4 \cdot 10^{-20} s$

$c\tau(\Lambda^0) = 7{,}9 cm \Rightarrow \tau(\Lambda^0) = 0{,}26 ns$





Baryony s podivností -2



Ξ^-, Ξ^0

$M(\Xi^-) = 1321 MeV$

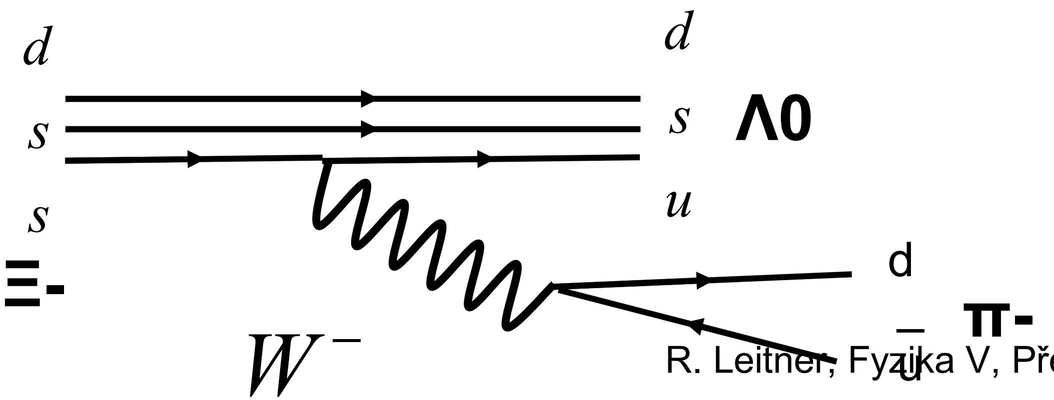
$M(\Xi^0) = 1314 MeV$

$M(\Lambda) + M(\pi) < M(\Xi) < M(\Sigma) + M(\pi)$

$1115 + 140 < 1321 < 1189 + 140$

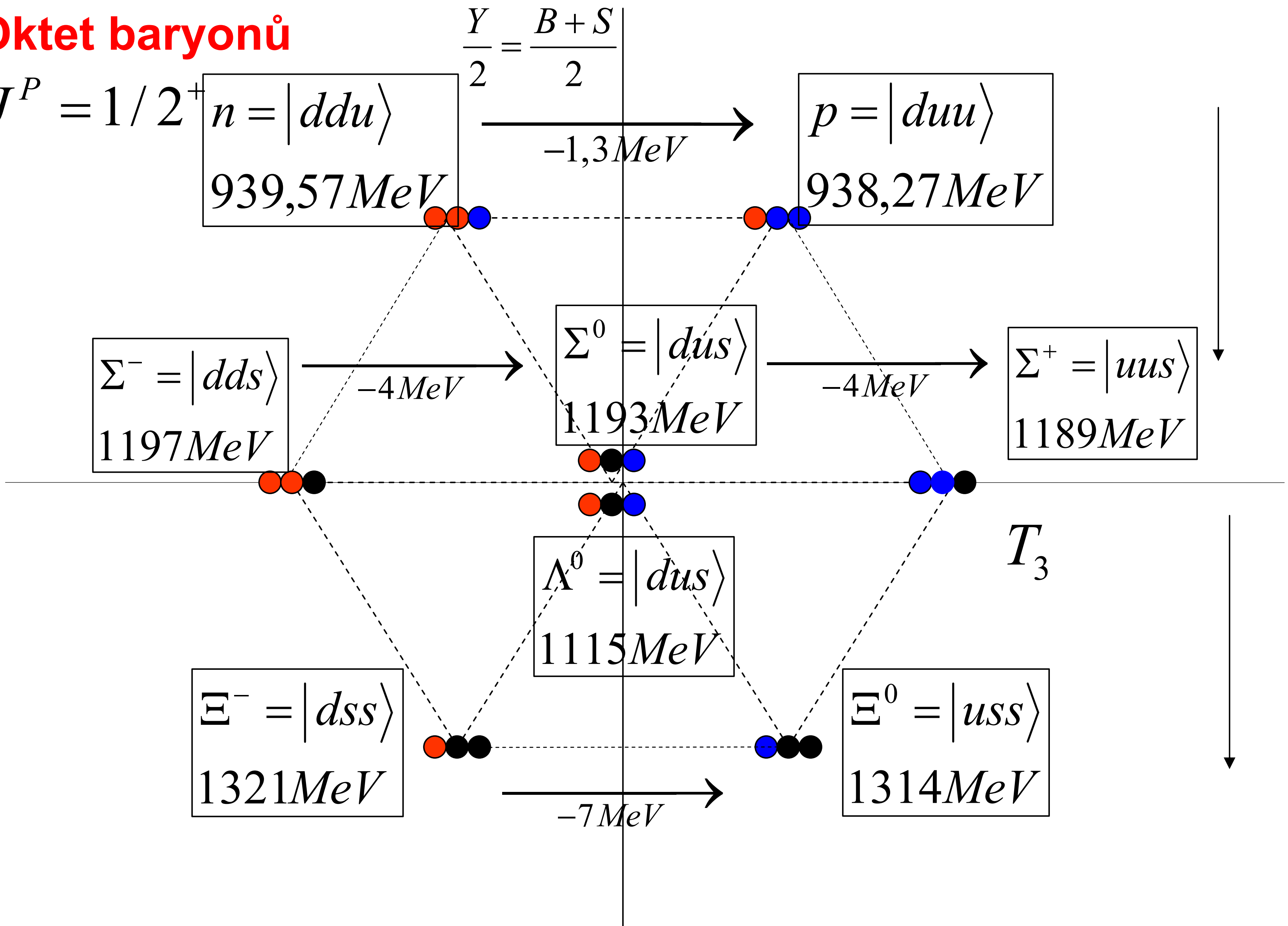
$\Xi^- \to \Lambda^0 + \pi^-$ **99,9%** $c\tau(\Xi^-) = 4{,}9 cm \Rightarrow \tau(\Xi^-) = 0{,}16 ns$

$\Xi^0 \to \Lambda^0 + \pi^0$ **99,5%** $c\tau(\Xi^0) = 8{,}7 cm \Rightarrow \tau(\Xi^0) = 0{,}29 ns$



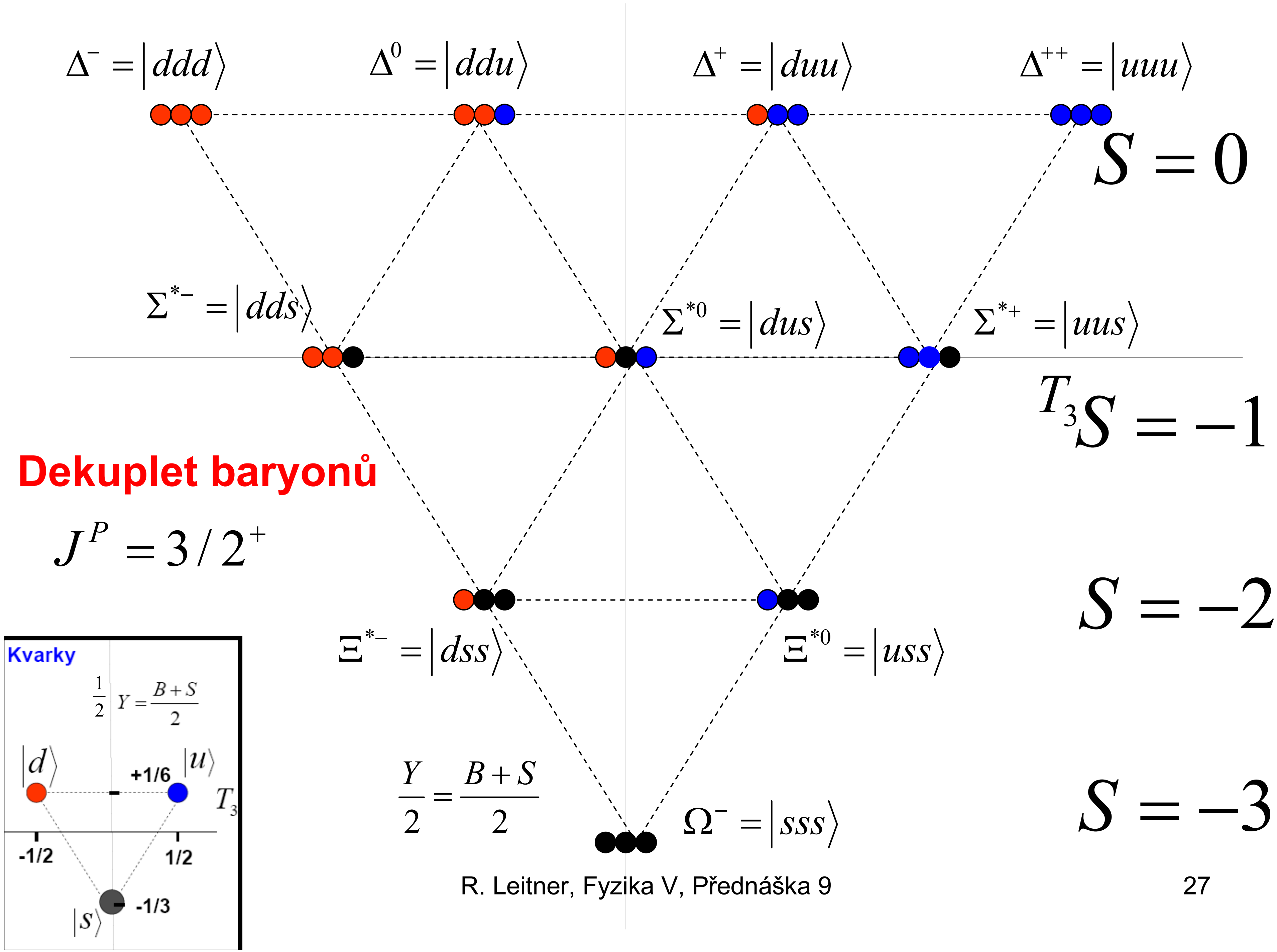
Oktet baryonů

$J^P = 1/2^+$



Dekuplet baryonů

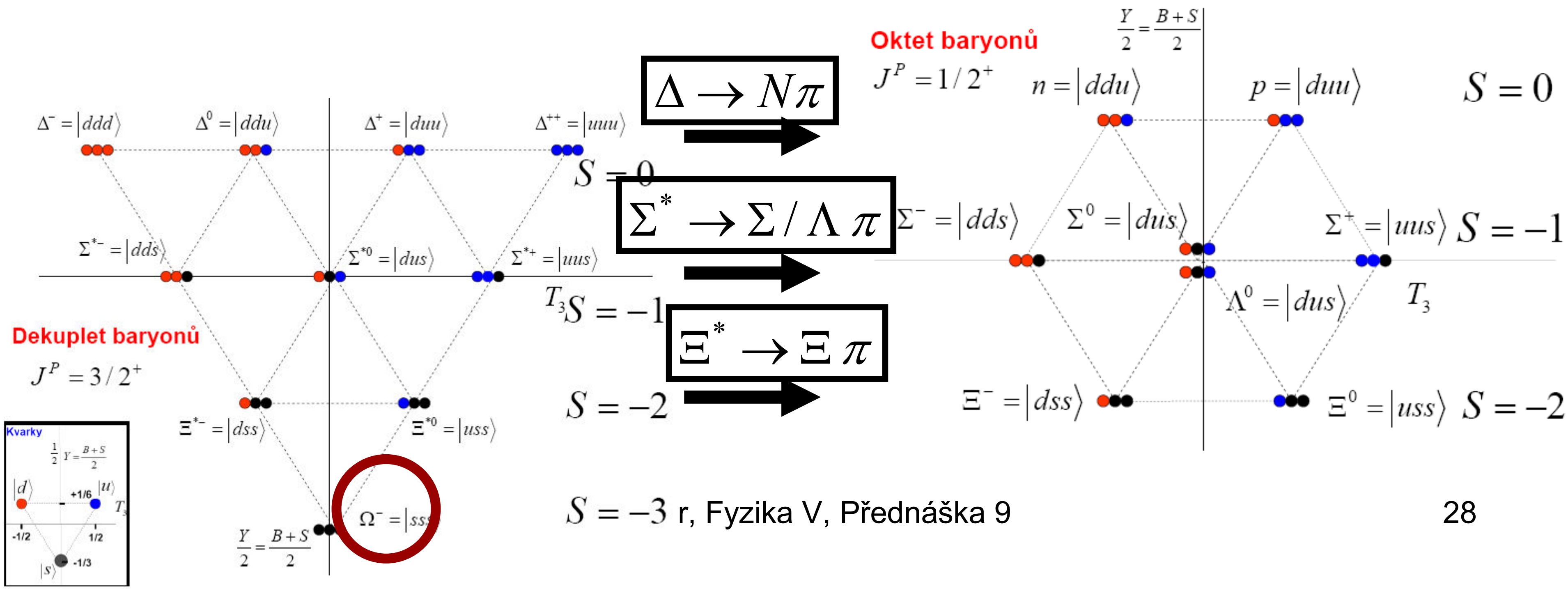
$J^P = 3/2^+$



Dekuplet baryonů $J^P = 3/2^+$

Baryony v dekupletu s podivností 0, -1 a -2 mají lehčí partnery se stejnou podivností v oktetu a rozpadají se na tyto lehčí partnery a pion prostřednictvím silné interakce. Mají tudíž velmi krátkou dobu života, ta se měří jako šířka (10-100 MeV) rezonančního Breit-Wignerova rozdělení. Těmto částicím je zvykem říkat **rezonance.**

Výjimkou je Ω- baryon s podivností -3. Protože do objevu 4. kvarku se mělo za to, že je nejtěžším baryonem stabilním vůči silnému rozpadu, dostal jméno Ω.



Nepodivné rezonance Δ

$\Delta(1232)$

$M(\Delta) = 1232 MeV$

$\Gamma(\Delta) = 118 MeV$

$$\Gamma = \frac{\hbar}{\tau} = \frac{\hbar c}{c\tau} \Rightarrow c\tau = \frac{\hbar c}{\Gamma} = \frac{197 MeV \cdot fm}{118 MeV} = 1{,}7\, fm$$

$\tau = 6 \cdot 10^{-24} s$

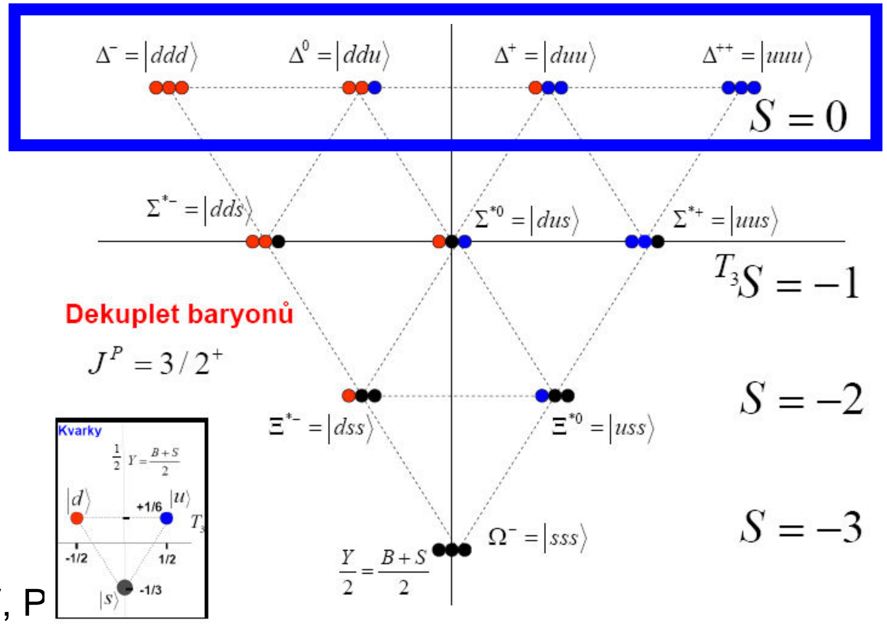
$\Delta \rightarrow N\pi$ **100%**

$\Delta^- \rightarrow n\pi^-$

$\Delta^0 \rightarrow n\pi^0 \quad \Delta^0 \rightarrow p\pi^-$

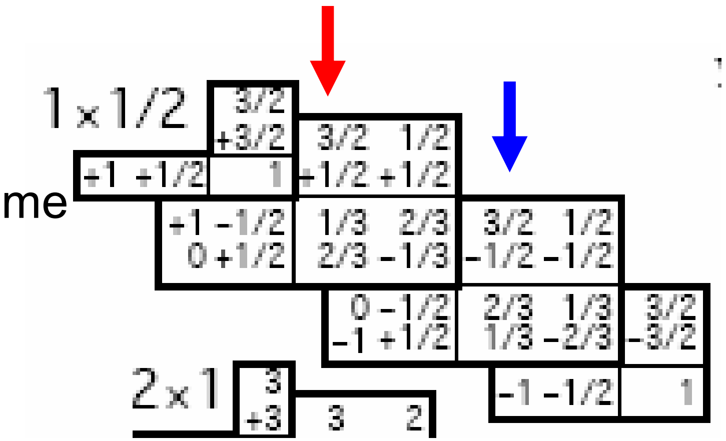
$\Delta^+ \rightarrow n\pi^+ \quad \Delta^+ \rightarrow p\pi^0$

$\Delta^{++} \rightarrow p\pi^+$



R. Leitner, Fyzika V, P

Nepodivné rezonance Δ



Ze zachování izospinu v silných rozpadech dokážeme předpovědět poměry rozpadů na n pi a p pi

$\Delta^0 \to n\pi^0 \quad \Delta^0 \to p\pi^-$

$$\left|\Delta^0 = 3/2,-1/2\right\rangle = \sqrt{\frac{2}{3}}\left|n=1/2,-1/2\right\rangle\left|\pi^0 = 1,0\right\rangle + \sqrt{\frac{1}{3}}\left|p=1/2,+1/2\right\rangle\left|\pi^- = 1,-1\right\rangle$$

$$\frac{\Delta^0 \to n\pi^0}{\Delta^0 \to p\pi^-} = \frac{\left|\left\langle\Delta^0 = 3/2,-1/2\right\|n=1/2,-1/2\right\rangle\left|\pi^0 = 1,0\right\rangle\right|^2}{\left|\left\langle\Delta^0 = 3/2,-1/2\right\|p=1/2,+1/2\right\rangle\left|\pi^- = 1,-1\right\rangle\right|^2} = \frac{\left|\sqrt{\frac{2}{3}}\right|^2}{\left|\sqrt{\frac{1}{3}}\right|^2} = 2$$

$\Delta^+ \to n\pi^+ \quad \Delta^+ \to p\pi^0$

$$\left|\Delta^+ = 3/2,+1/2\right\rangle = \sqrt{\frac{1}{3}}\left|n=1/2,-1/2\right\rangle\left|\pi^+ = 1,+1\right\rangle + \sqrt{\frac{2}{3}}\left|p=1/2,+1/2\right\rangle\left|\pi^0 = 1,-1\right\rangle$$

$$\frac{\Delta^+ \to n\pi^+}{\Delta^+ \to p\pi^0} = \frac{\left|\left\langle\Delta^+ = 3/2,+1/2\right\|n=1/2,-1/2\right\rangle\left|\pi^+ = 1,1\right\rangle\right|^2}{\left|\left\langle\Delta^+ = 3/2,+1/2\right\|p=1/2,+1/2\right\rangle\left|\pi^0 = 1,0\right\rangle\right|^2} = \frac{\left|\sqrt{\frac{1}{3}}\right|^2}{\left|\sqrt{\frac{2}{3}}\right|^2} = \frac{1}{2}$$

Rezonance s podivností -1

$\Sigma(1385)$

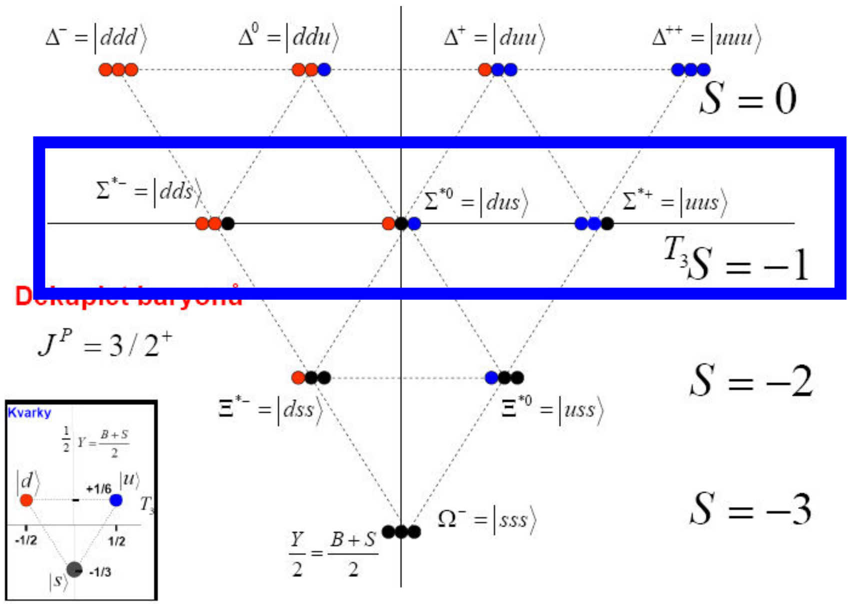
$$M(\Sigma^{*-}) = 1387 MeV \quad \Gamma(\Sigma^{*-}) = 39 MeV$$

$$M(\Sigma^{*0}) = 1384 MeV \quad \Gamma(\Sigma^{*-}) = 36 MeV$$

$$M(\Sigma^{*+}) = 1383 MeV \quad \Gamma(\Sigma^{*-}) = 36 MeV$$

$\Sigma^{*} \rightarrow \Lambda\pi$ **87%**

$\Sigma^{*} \rightarrow \Sigma\pi$ **12%**



R. Leitner, Fyzika V

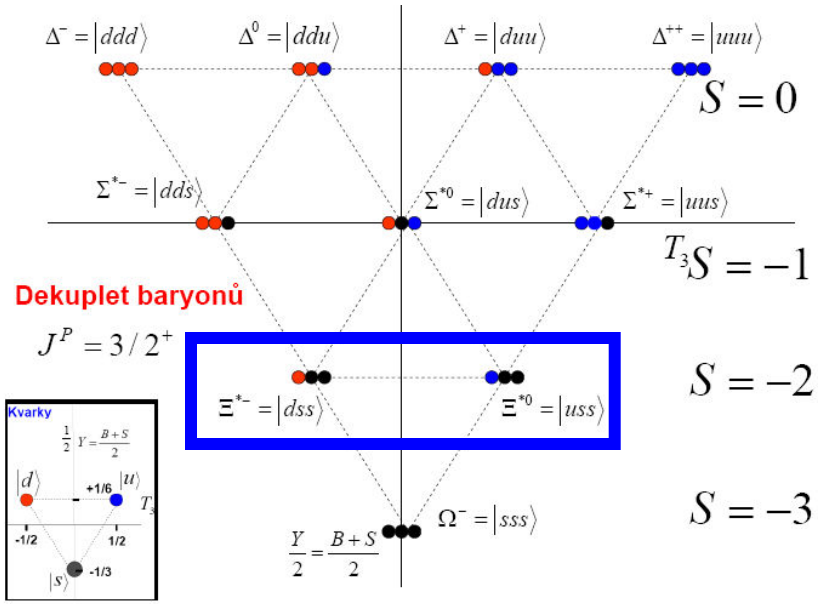
Rezonance s podivností -2

$\Xi(1530)$

$M(\Xi^{*-}) = 1535 MeV \quad \Gamma(\Xi^{*-}) = 9 MeV$

$M(\Xi^{*0}) = 1531 MeV \quad \Gamma(\Xi^{*-}) = 10 MeV$

$\Xi^{*} \to \Xi\pi \quad$ **100%**



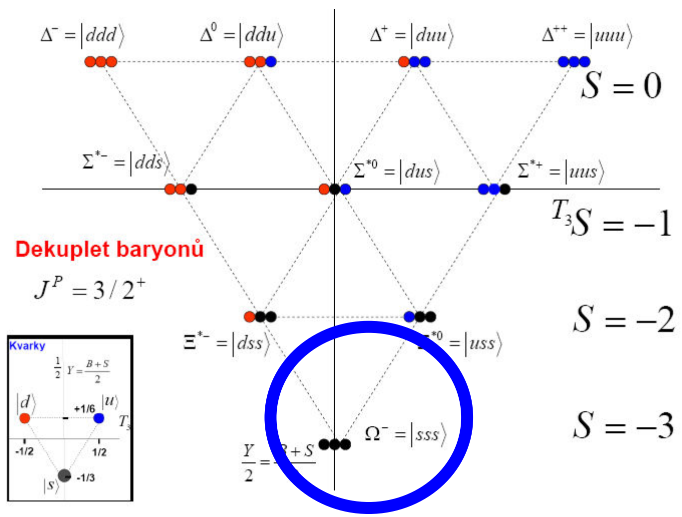
Ω baryon s podivností -3

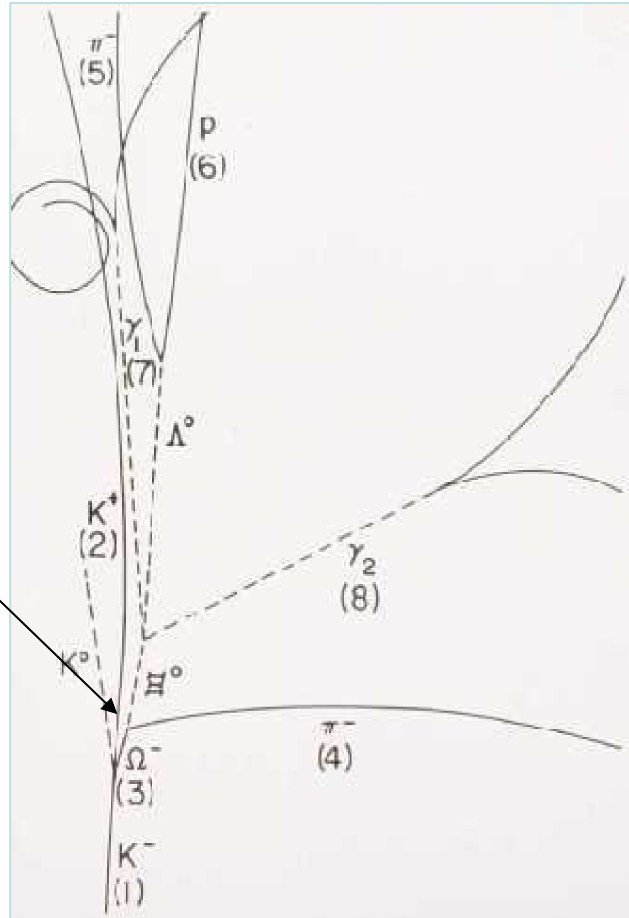
$$M(\Omega^-) = 1672 MeV \quad c\tau = 2{,}5 cm$$

$\Omega^- \to \Lambda^0 K^-$ **67,8%**

$\Omega^- \to \Xi^0 \pi^-$ **23,6%**

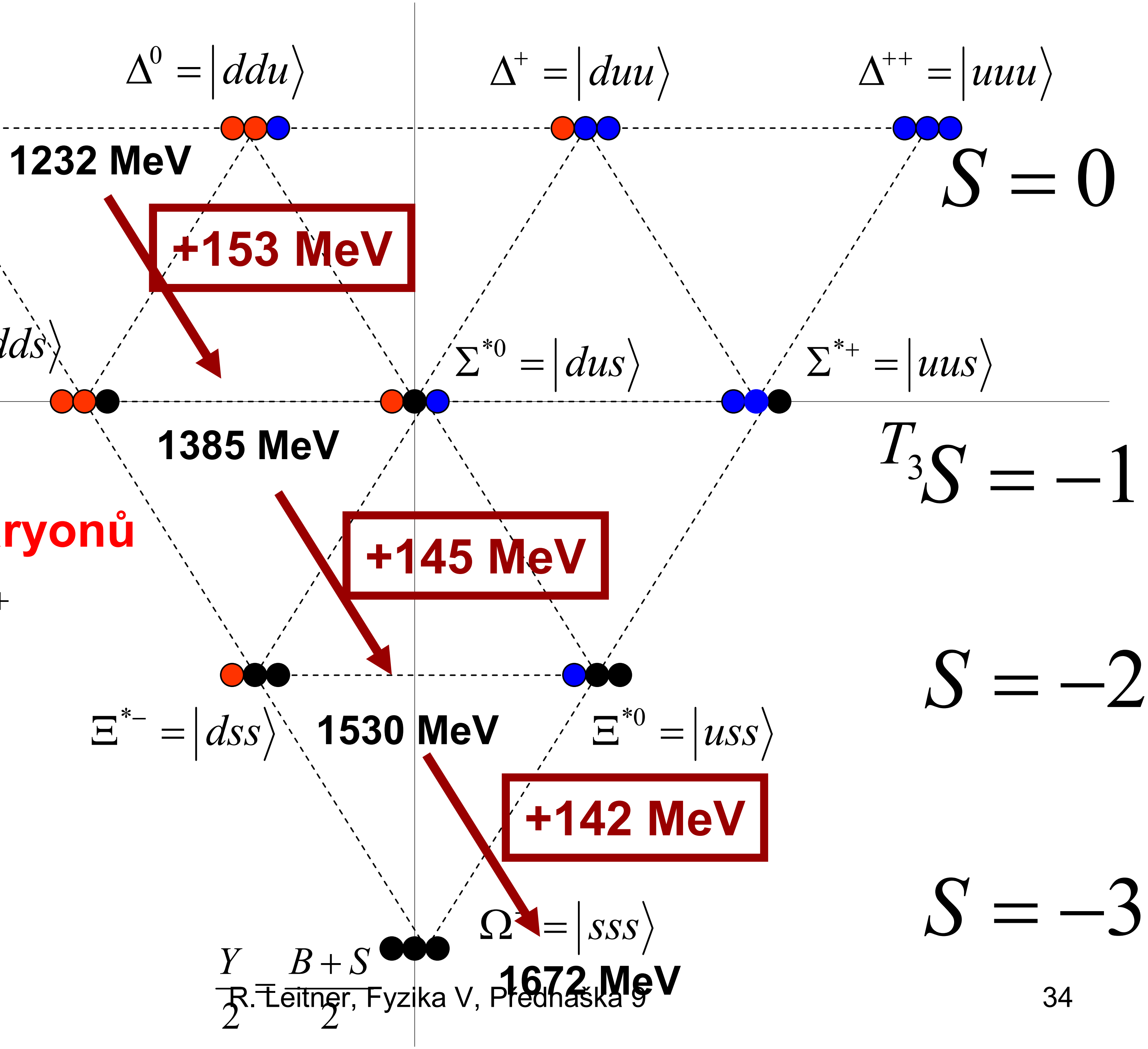
$\Omega^- \to \Xi^- \pi^0$ **8,6%**

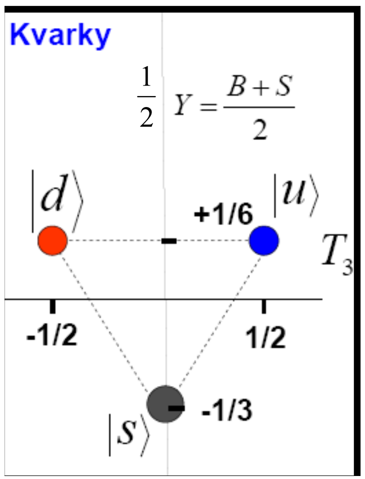




Dekuplet baryonů

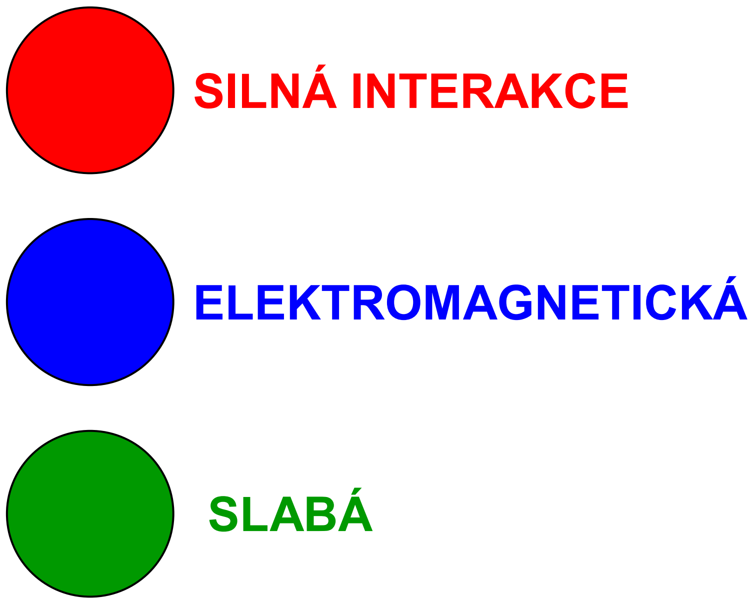
$J^P = 3/2^+$

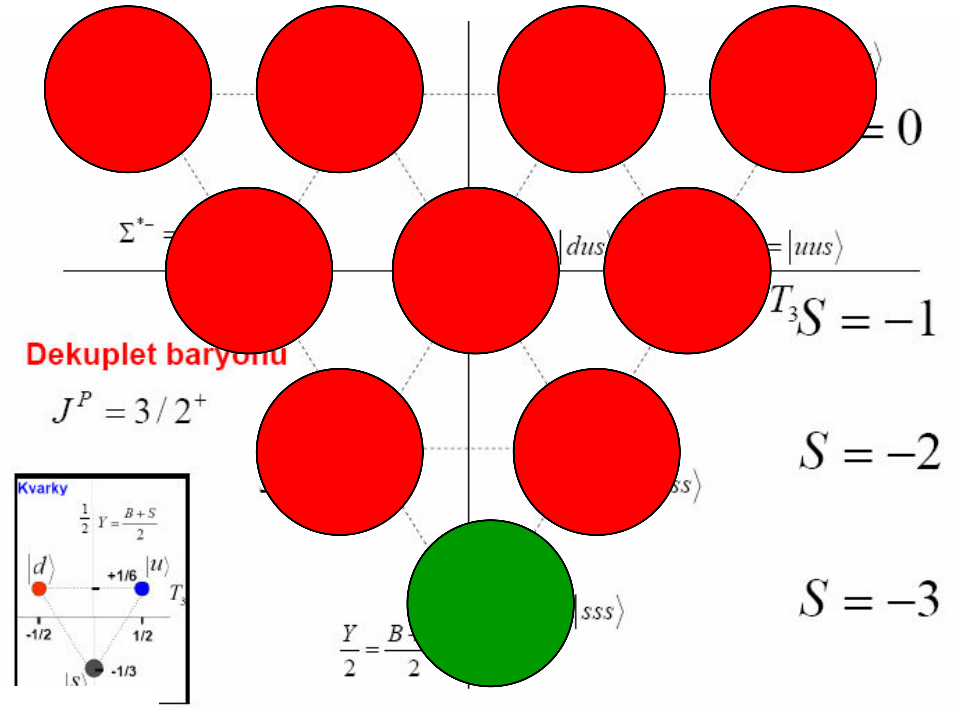


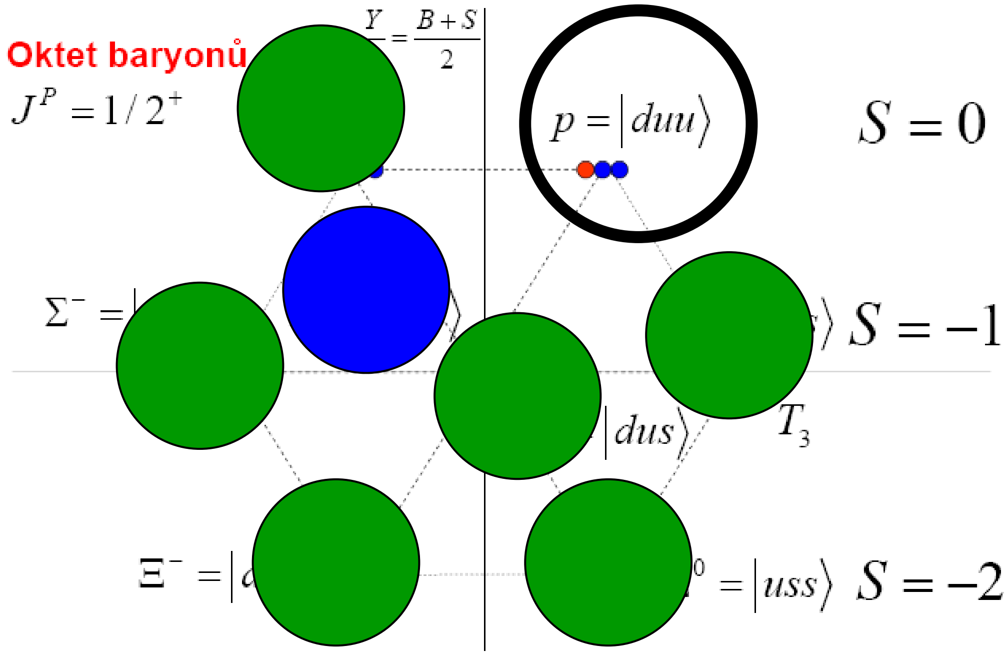


Některé zákonitosti v rozpadech rezonancí:

	$Q[MeV]$		$\Gamma[MeV]$
$\Delta \rightarrow N\pi$	153		118
$\Sigma^* \rightarrow \Lambda\pi$	130	87%	36
$\Sigma^* \rightarrow \Sigma\pi$	52	12%	
$\Xi^* \rightarrow \Xi\pi$	75		10


SILNÁ INTERAKCE
ELEKTROMAGNETICKÁ
SLABÁ


Dekuplet baryonů
$J^P = 3/2^+$
Kvarky
$S = -1$
$S = -2$
$S = -3$

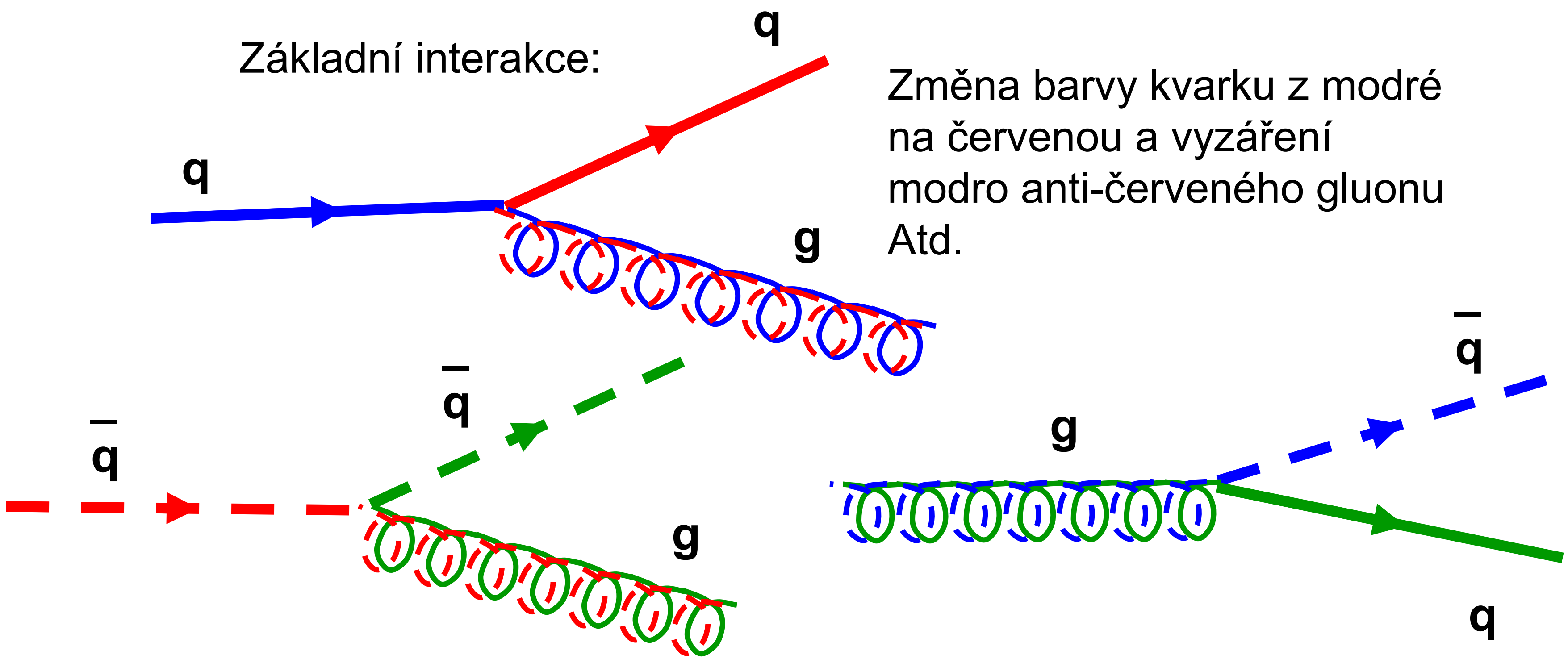

Oktet baryonů
$J^P = 1/2^+$
$\frac{Y}{2} = \frac{B+S}{2}$
$p = |duu\rangle$
$S = 0$
$\Sigma^- =$
$S = -1$
$|dus\rangle$
T_3
$\Xi^- =$
$= |uss\rangle$
$S = -2$

Silná interakce

Silná interakce je spojena s kvantovým číslem barva.
Je zprostředkována výměnou gluonů, což jsou bosony se spinem 1.

Je celkem 9 kombinací barva anti-barva. Jedna z nich je totálně symetrická
A nepřenáší proto barvu, ostatní tvoří **8 gluonů.**
Gluony mají nulovou hmotu, spin jedna.

Základní interakce:

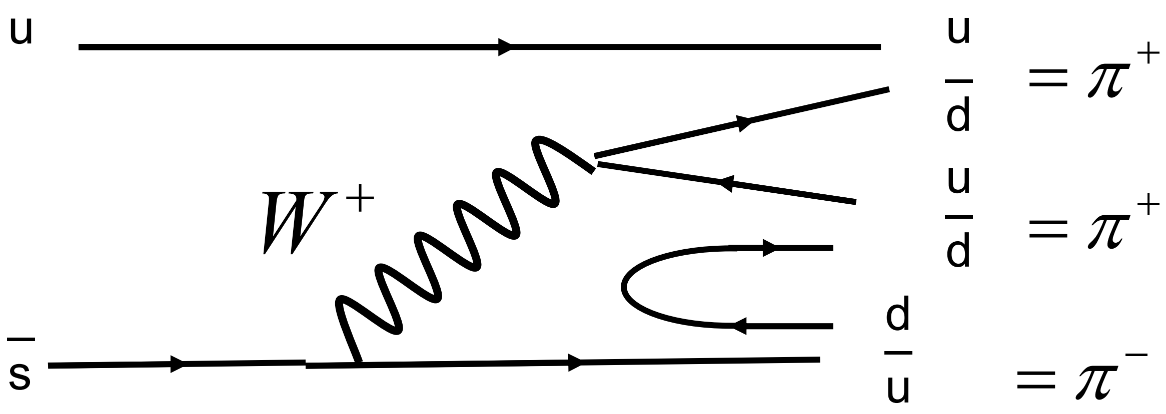


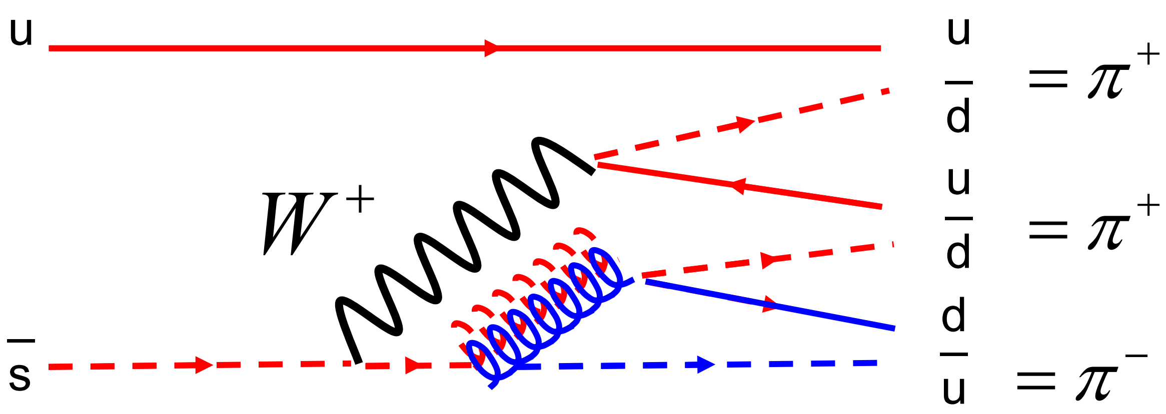
Změna barvy kvarku z modré
na červenou a vyzáření
modro anti-červeného gluonu
Atd.

Baryony = qqq s úplně antisymetrickou kombinací barev tří kvarků

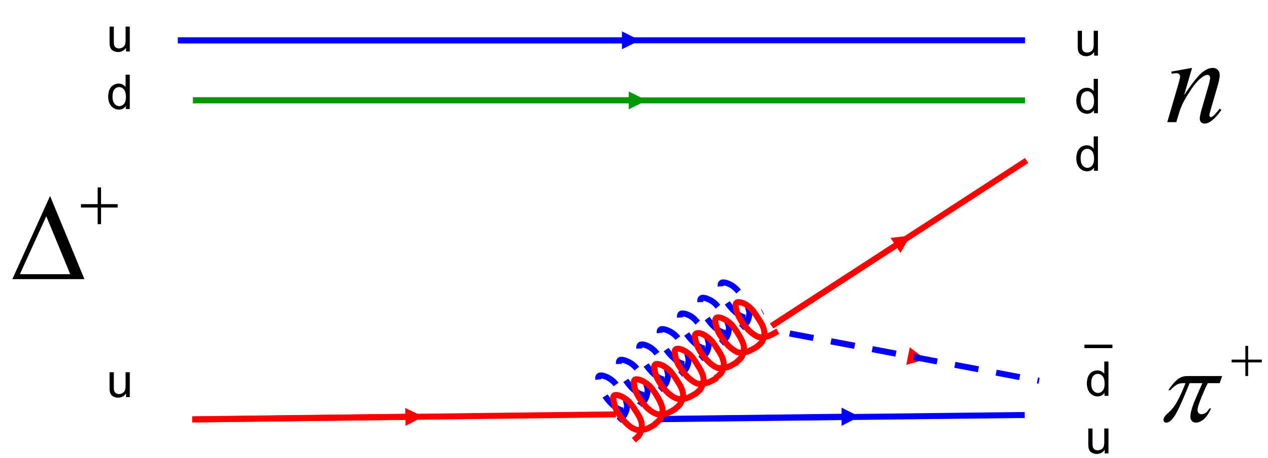
Mezony = q anti-q Kvark má barvu, antikvark opačnou antibarvu.

$$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$$

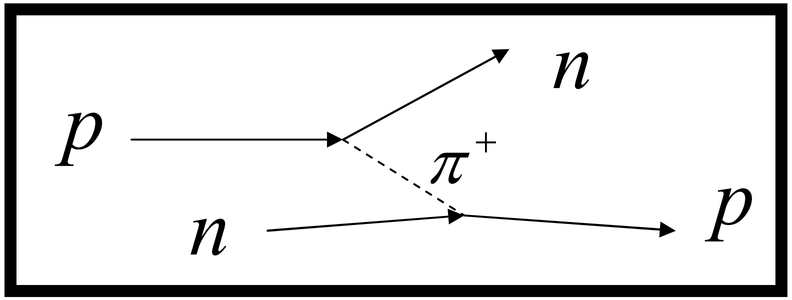


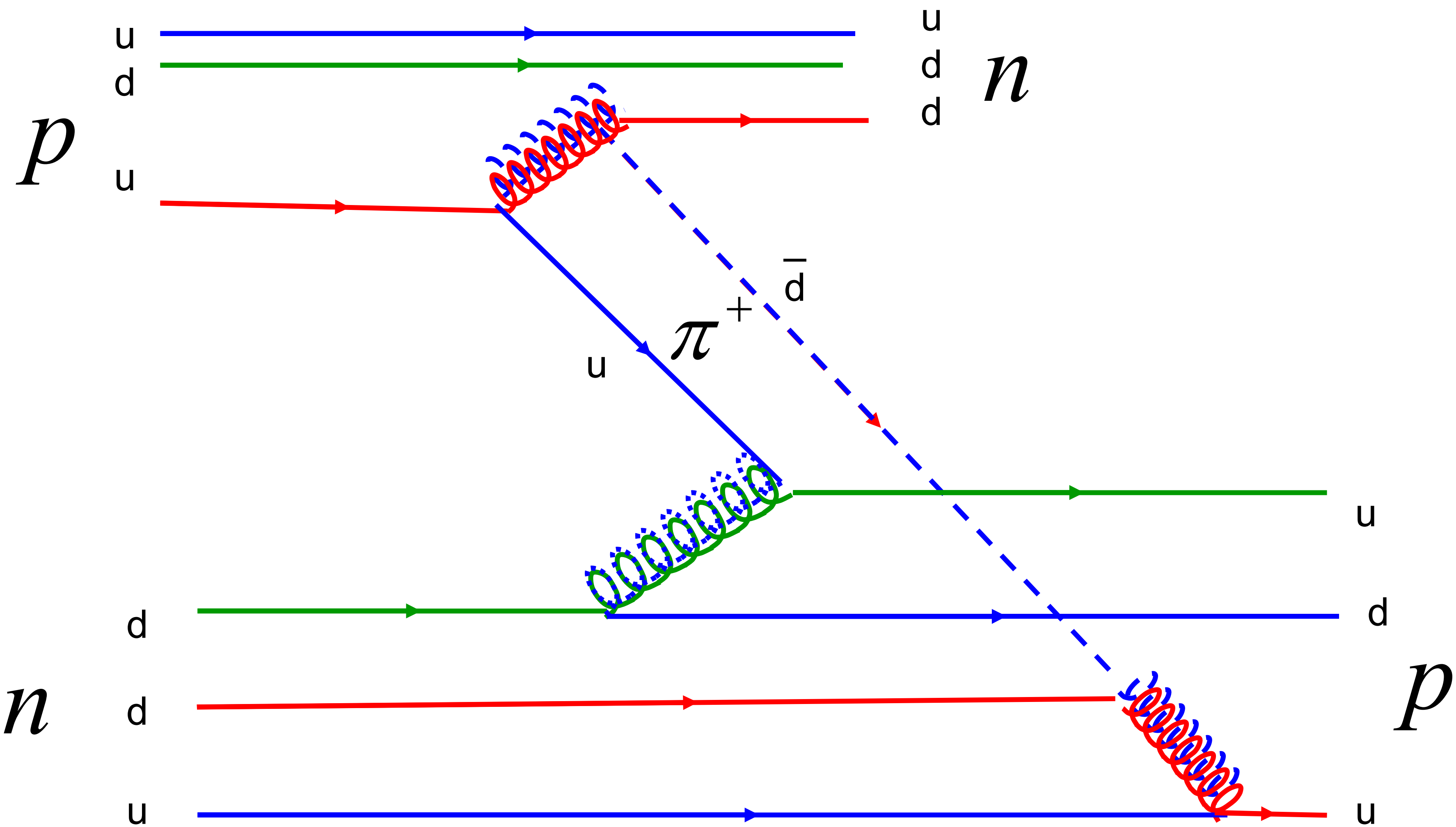


$$\boxed{\Delta^+ \rightarrow n + \pi^+}$$



Jaderná interakce mezi nukleony v jádře probíhá jako výměna pi mezonů takto:





Mezonové rezonance

Spin a parita

$$J^P = 1^-$$

$$L_{q\bar{q}} = 0 \;,\; S_{q\bar{q}} = 1 \Rightarrow J = 1$$

$$P = P_q \cdot P_{\bar{q}} \cdot (-1)^L = -1$$

$$J^P = 1^+$$

$$L_{q\bar{q}} = 1 \;,\; S_{q\bar{q}} = 0 \Rightarrow J = 1$$

$$P = P_q \cdot P_{\bar{q}} \cdot (-1)^L = -1 \cdot (-1)^L = +1$$

$$J^P = 2^+$$

$$L_{q\bar{q}} = 1 \;,\; S_{q\bar{q}} = 1 \Rightarrow J = 0,1,2$$

$$P = P_q \cdot P_{\bar{q}} \cdot (-1)^L = -1 \cdot (-1)^L = +1$$

ATD.

Oktet a singlet = Nonet vektorových mezonů

$$J^P = 1^-$$

$$\frac{1}{2}Y = \frac{B+S}{2}$$

$K^{*0} = |d\bar{s}\rangle$ $\quad$ +1/2 $\quad$ $K^{*+} = |u\bar{s}\rangle$

$$\rho^- = |d\bar{u}\rangle \qquad \rho^0 = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle - |d\bar{d}\rangle\right) \qquad \rho^+ = -|u\bar{d}\rangle$$

-1 $\quad$ +1 $\quad$ T_3

$$\omega^0 = \frac{1}{\sqrt{2}}\left(|d\bar{d}\rangle + |u\bar{u}\rangle\right)$$

$$\phi^0 = \left(|s\bar{s}\rangle\right)$$

-1/2

$K^{*-} = |s\bar{u}\rangle$ $\quad$ $\overline{K}^{*0} = |-s\bar{d}\rangle$

Vektorové mezonové rezonance s podivností:

$$K(892)$$

$$m(K^{*\pm}) = 892MeV \quad \Gamma = 50MeV$$

$$m(K^{*0}) = 896MeV$$

$$K^{*} \to K\pi \approx \mathbf{100\%}$$

Nepodivné vektorové mezonové rezonance:

ρ^-, ρ^0, ρ^+

$m(\rho) = 770 MeV \quad \Gamma = 149 MeV$

$\rho \to \pi\pi \approx \mathbf{100\%}$

ω^0

$m(\omega) = 783 MeV \quad \Gamma = 8{,}5 MeV$

$\omega \to \pi\pi\pi \approx \mathbf{89\%}$

$\omega \to \pi\pi \approx \mathbf{2\%}$

$\omega \to \pi\gamma \approx \mathbf{9\%}$

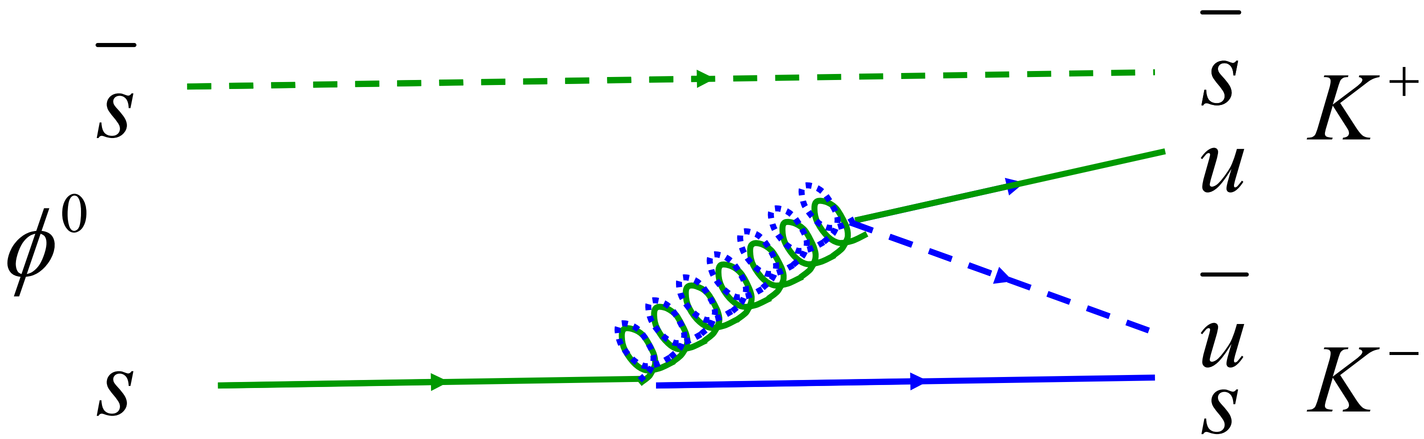
ϕ^0

$m(\phi^0) = 1019 MeV \quad \Gamma = 4{,}3 MeV$

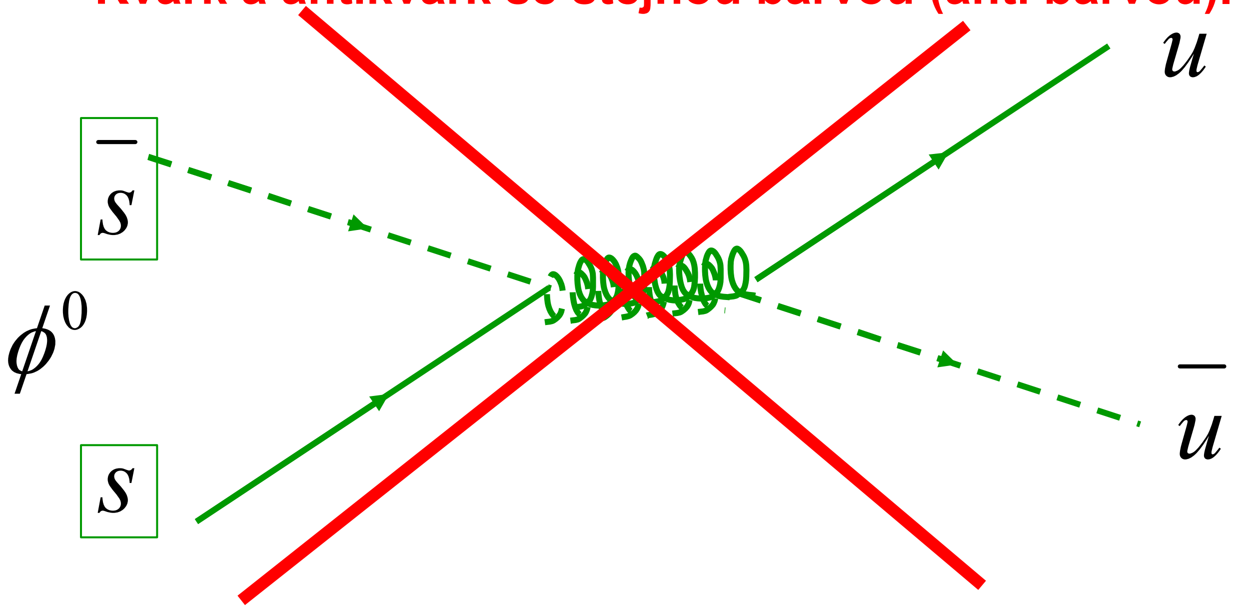
$\phi^0 \to K\overline{K} \approx \mathbf{83\%}$

$\phi^0 \to \pi\pi\pi \approx \mathbf{15\%}$

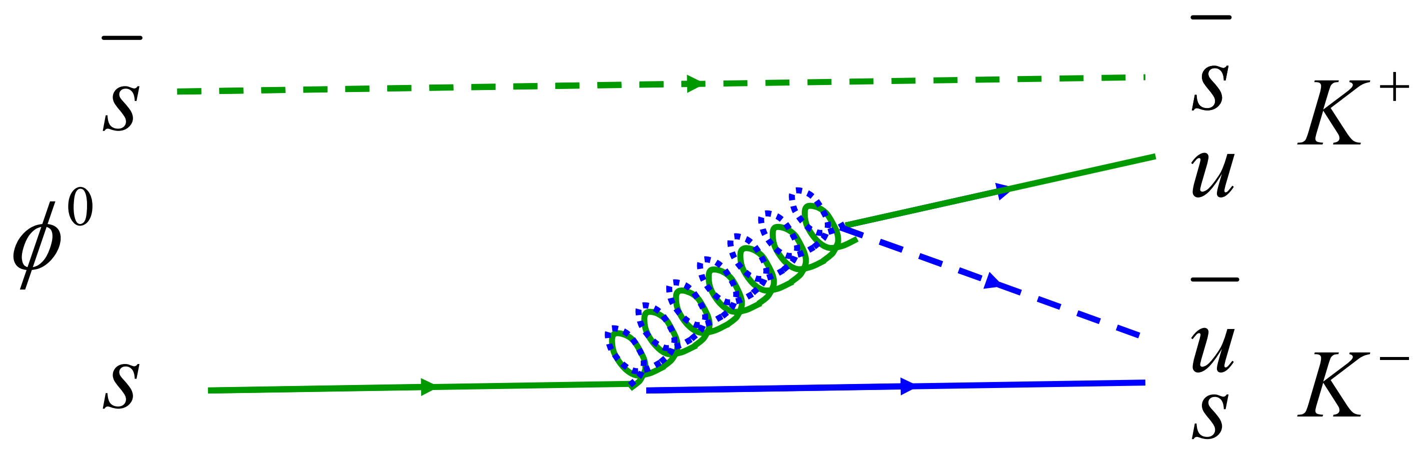
Toto je preferovaný způsob rozpadu – na dva podivné mezony.



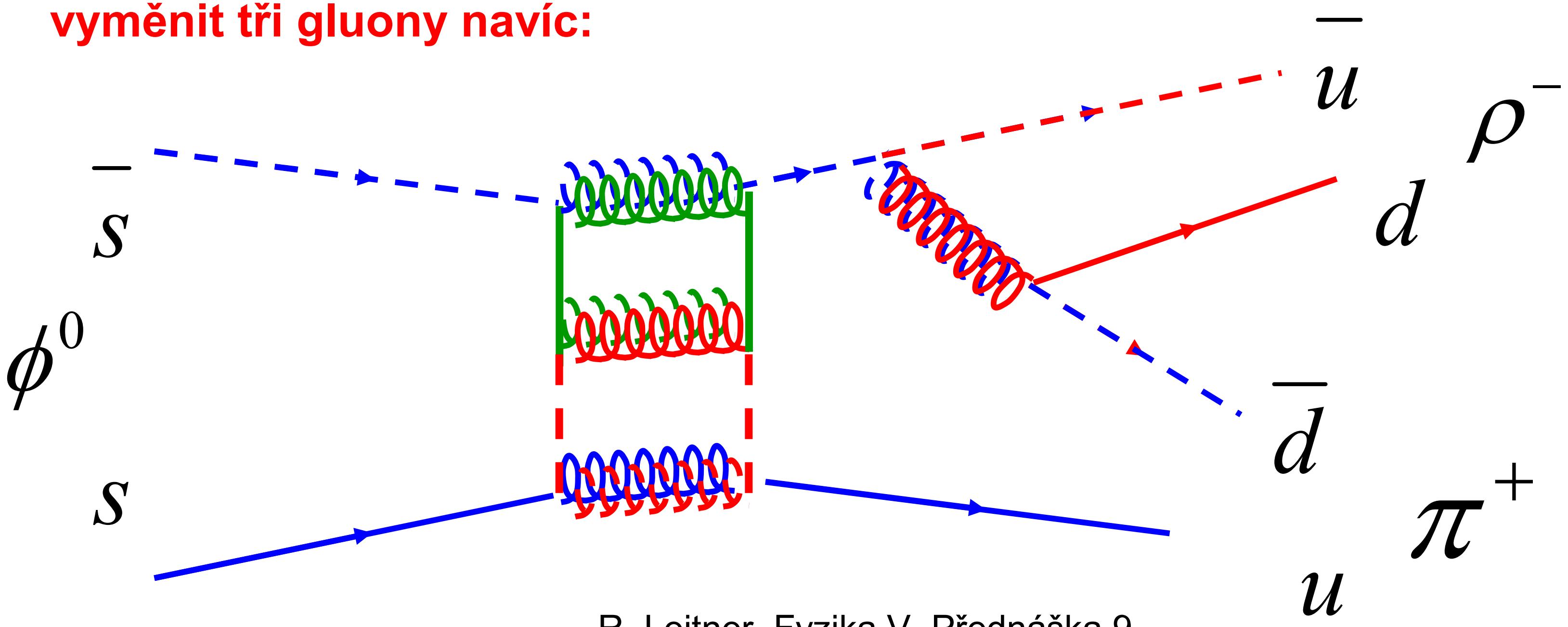
Takováto přeměna nejde, protože gluony musí nést barvu, tj. musí se potkat Kvark a antikvark se stejnou barvou (anti barvou).



Toto je preferovaný způsob rozpadu – na dva podivné mezony.

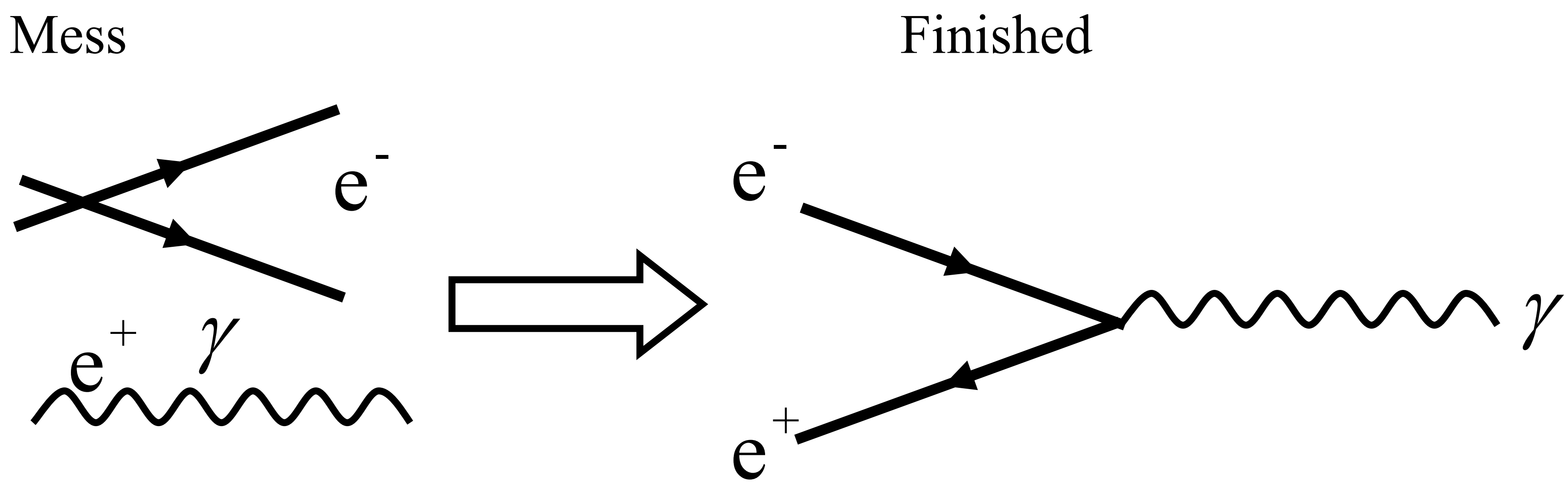


Rozpad φ0 na nepodivné částice je silně potlačen, protože se musí vyměnit tři gluony navíc:



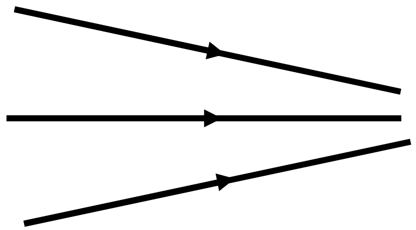
What to do...

- The idea will be to take the pre-made objects and arrange them in a diagram

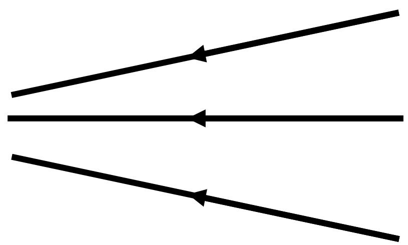


Your tool kit:

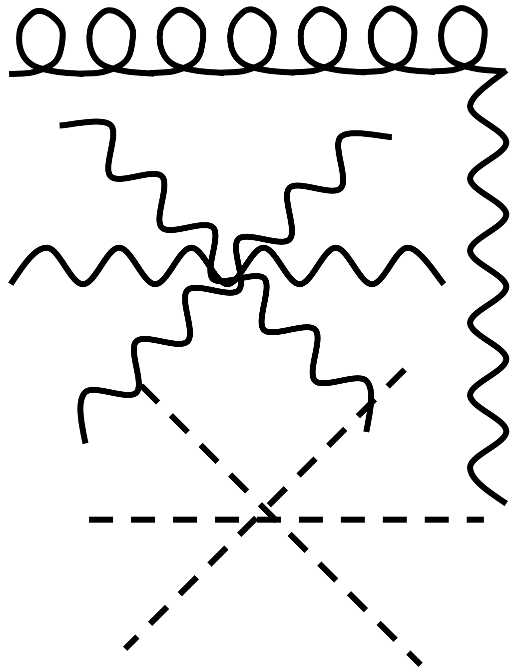
Real Particles



Anti Particles



Bosons



Particles

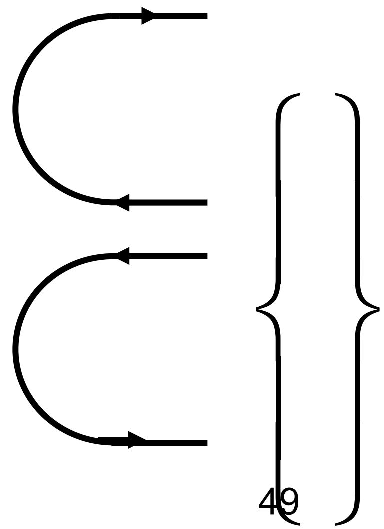
e^- e^+ γ

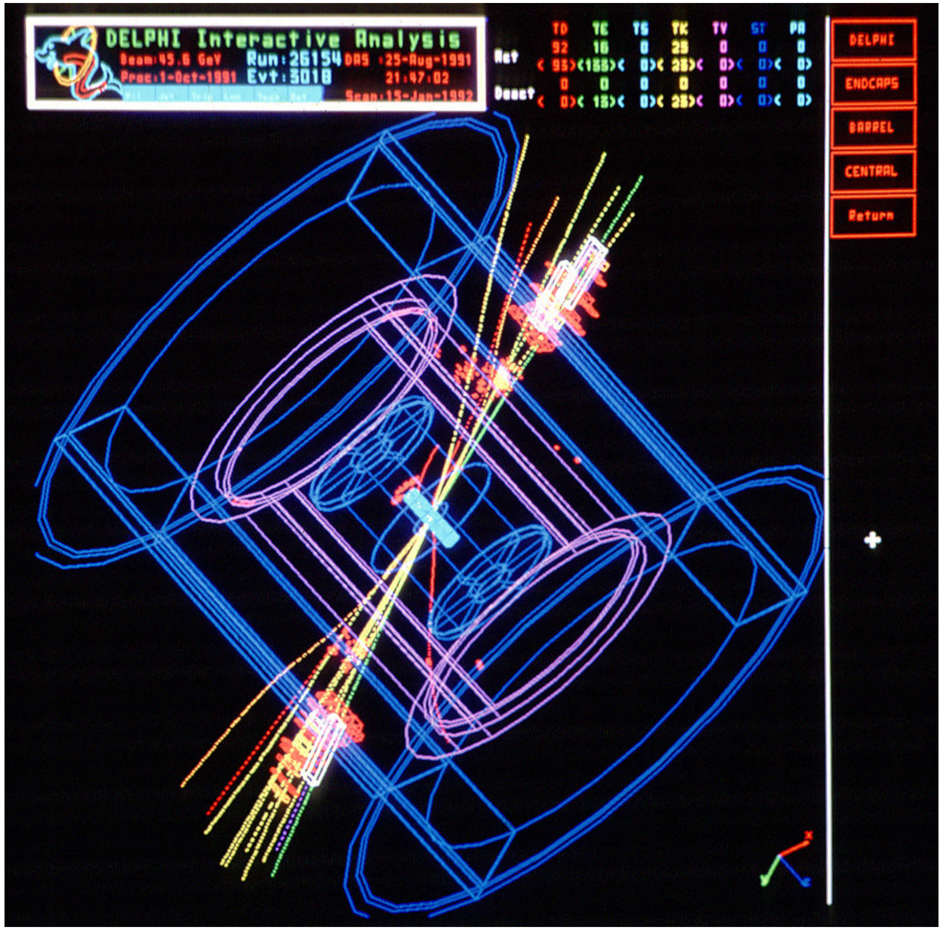
p^- p^+ n^0

π^- π^+ π^0

$\bar{\nu}_e$ $\bar{\nu}_\tau$ $\bar{\nu}_\pi$

W^- W^+




DELPHI Interactive Analysis
Beam:45.6 GeV
Run:26154
Evt:3018
DELPHI
ENDCAPS
BARREL
CENTRAL
Return

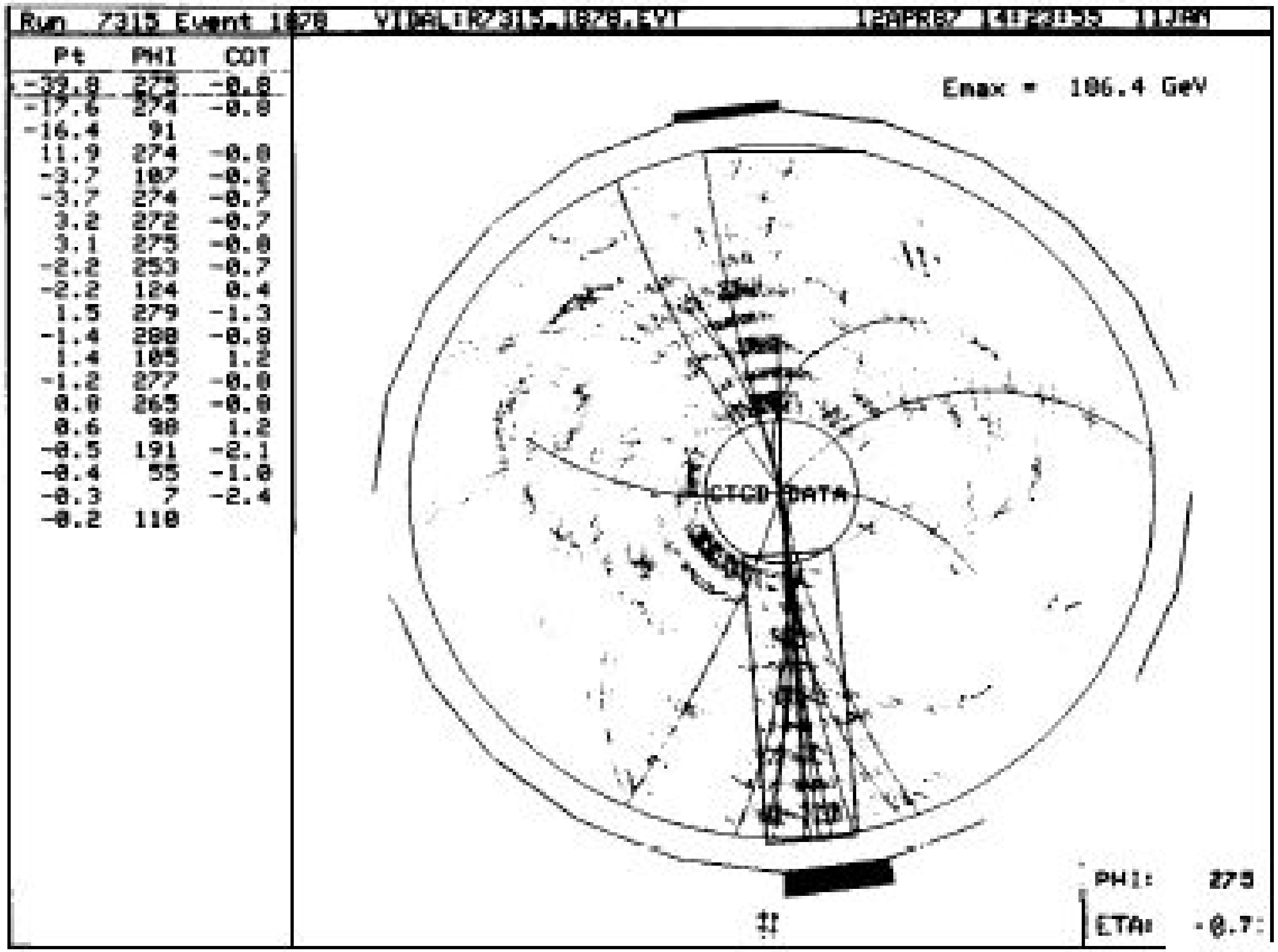
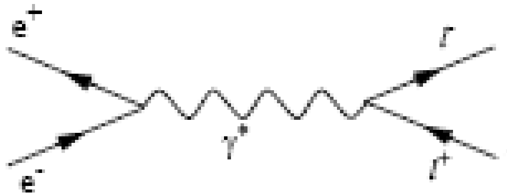
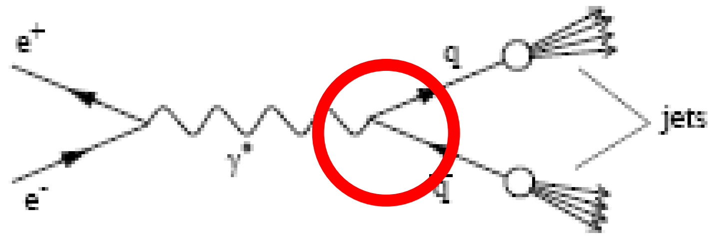


Figure 10. CDF Fermilab dijet at 1.8 TeV.

ELECTRON-POSITRON INTERACTIONS



$$\frac{d\sigma}{d\cos\theta}(e^+e^- \to l^+l^-) = \frac{\pi\alpha^2}{2Q^2}(1+\cos^2\theta)$$

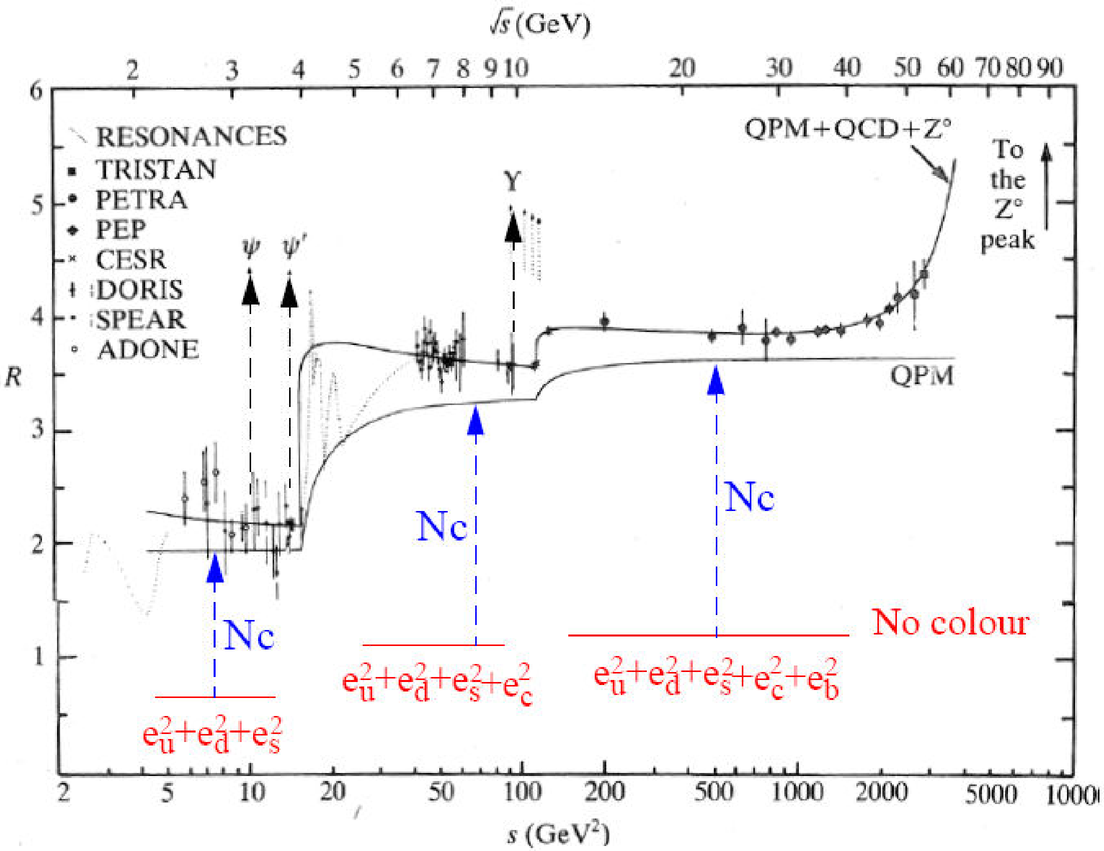


$$\frac{d\sigma}{d\cos\theta}(e^+e^- \to q\bar{q}) = N_c e_q^2 \frac{\pi\alpha^2}{2Q^2}(1+\cos^2\theta)$$

Nc=počet barev

$$R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c\left(Q_u^2 + Q_d^2 + Q_s^2 + \ldots\right) = N_c\left(\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2\right) = \frac{2}{3}N_c$$

$$R = 2 \Rightarrow N_c = 3$$



Objev kvarku c (charm)

The Nobel Prize in Physics 1976

"for their pioneering work in the discovery of a heavy elementary particle of a new kind"


Burton Richter	Samuel Chao Chung Ting
1/2 of the prize	1/2 of the prize
USA	USA
Stanford Linear Accelerator Center Stanford, CA, USA	Massachusetts Institute of Technology (MIT) Cambridge, MA, USA
b. 1931	b. 1936

FROM THE PSI TO CHARM - THE EXPERIMENTS OF 1975 AND 1976

Nobel Lecture, December 11, 1976

by
BURTON RICHTER
Stanford University, Stanford, California, USA

1. INTRODUCTION

Exactly 25 months ago the announcement of the ψ/J particle by Professor Ting's and my groups [1, 2] burst on the community of particle physicists. Nothing so strange and completely unexpected had happened in particle physics for many years. Ten days later my group found the second of the ψ's, [3] and the sense of excitement in the community intensified, The long

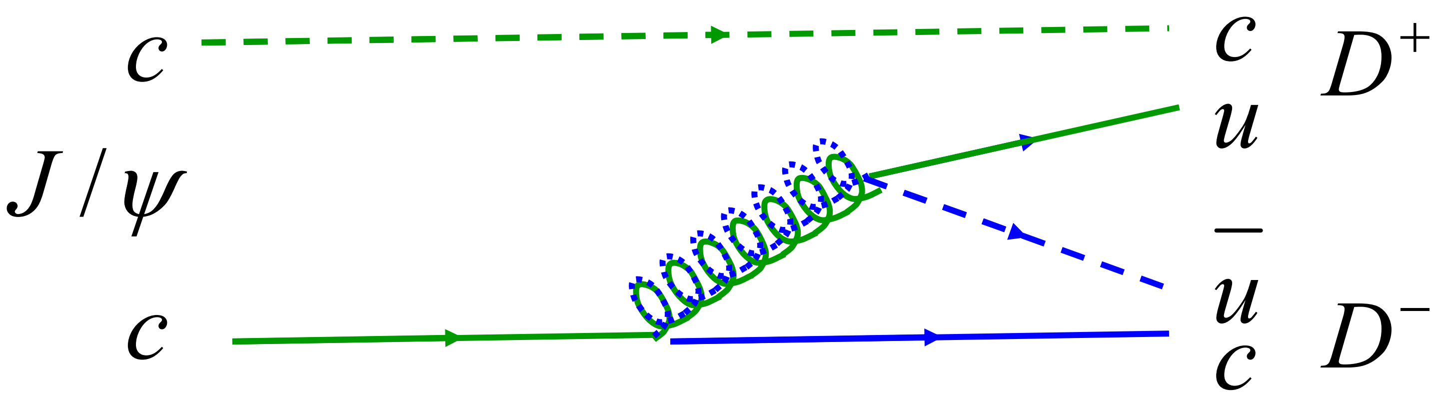
THE DISCOVERY OF THE J PARTICLE:

A personal recollection

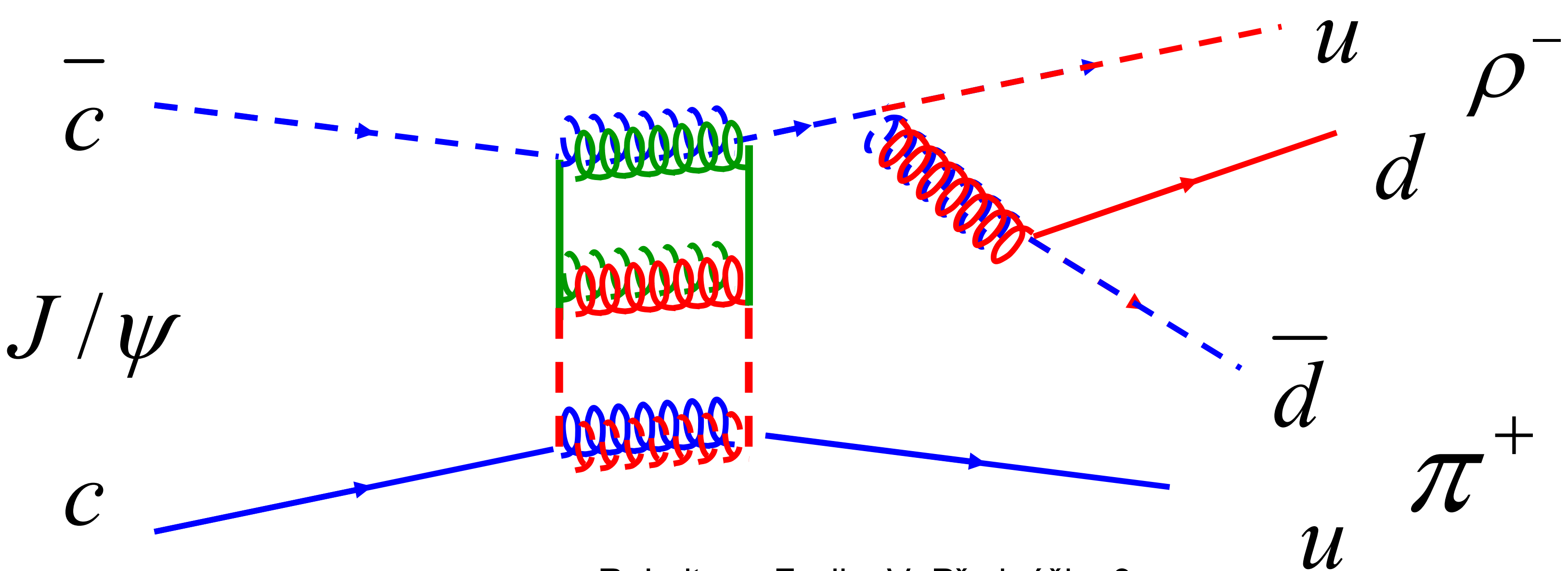
Nobel Lecture, 11 December, 1976

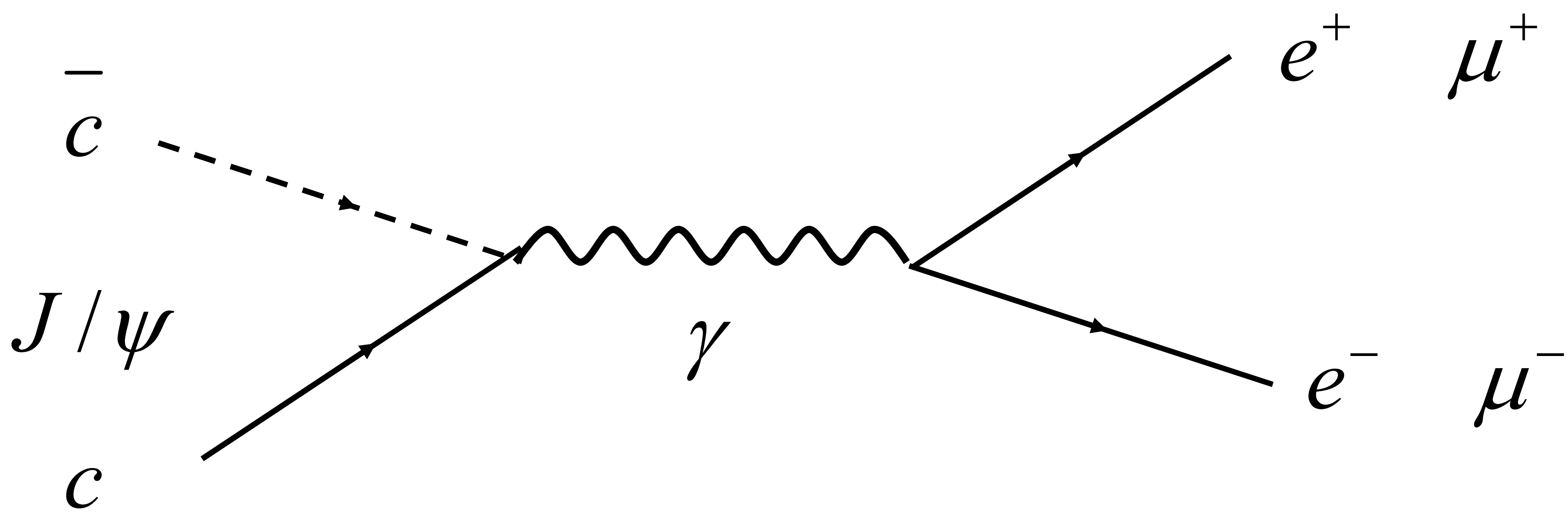
by
SAMUEL C. C. TING
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
and
CERN, European Organization for Nuclear Research, Geneva, Switzerland

Charmonium J-psi. Toto by byl preferovaný způsob rozpadu – na dva půvabné mezony. Ale dva D mezony jsou ~~těžší~~ než J/psi

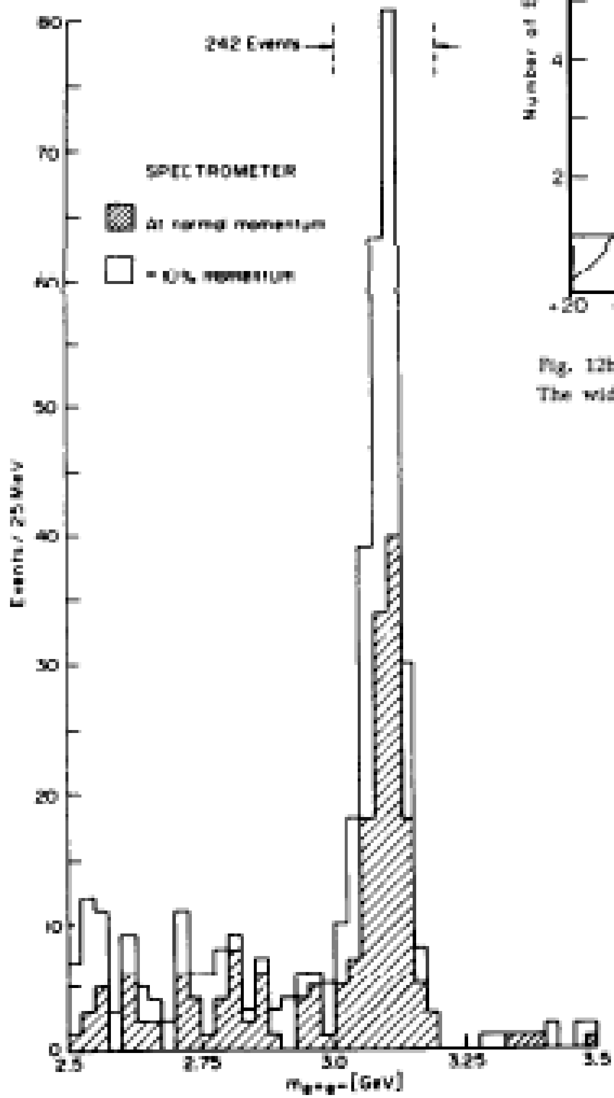


Rozpad J-psi na nepůvabné částice je silně potlačen, protože se musí vyměnit tři gluony navíc:





Proto je možný i poměrně častý rozpad pomocí elektromagnetické
Interakce na elektron pozitron anebo na kladný a záporný mion.
Přibližně v 6% případů se J/psi rozpadá na ee a v 6% případů na miony.



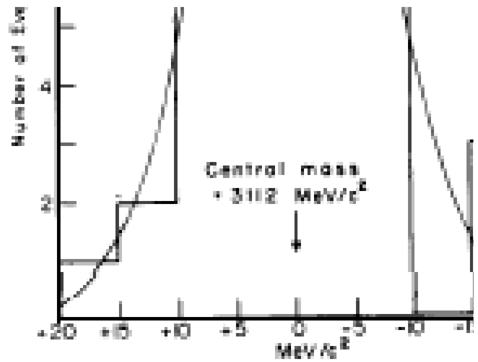
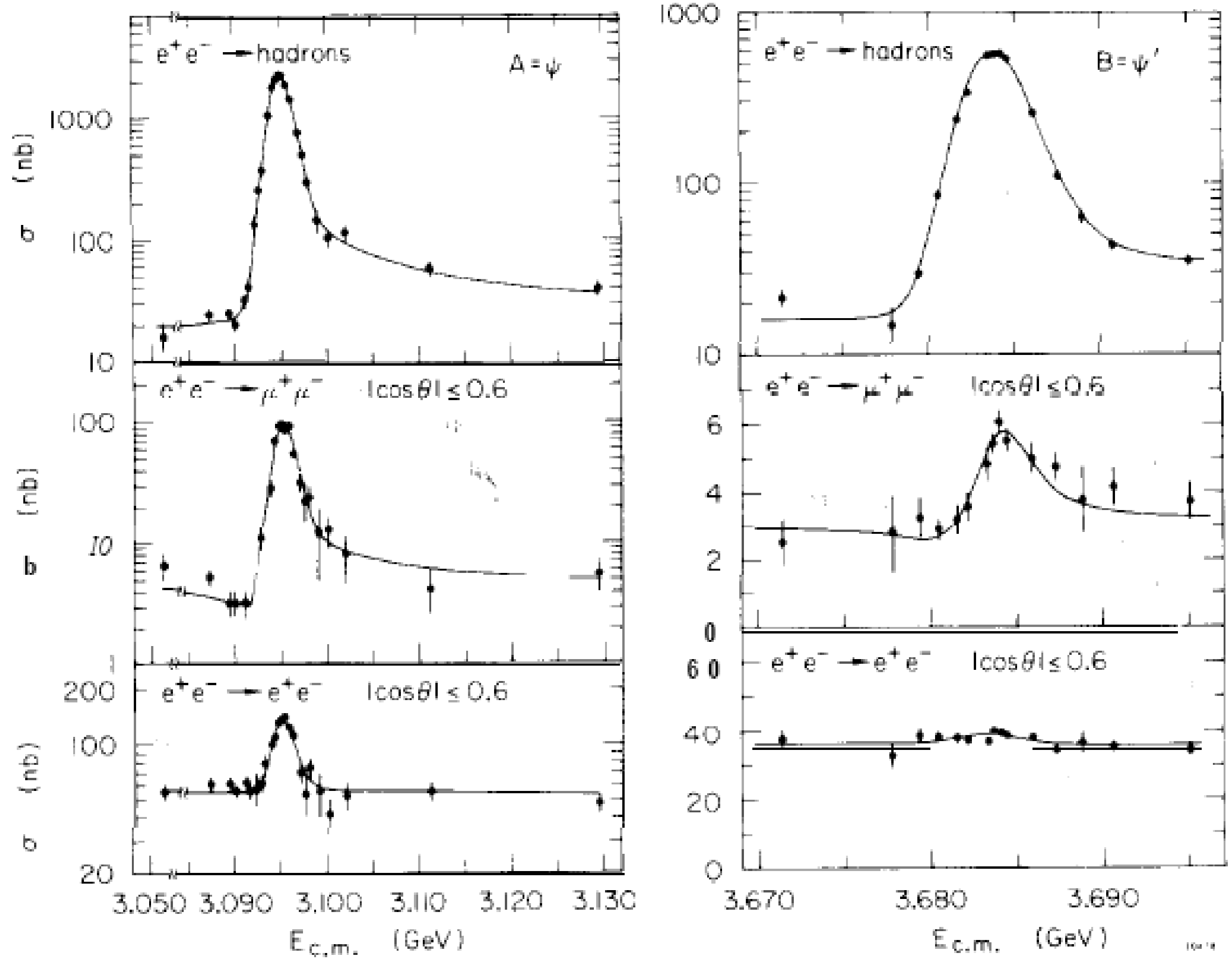


Fig. 12b. The measurement of the width of
The width is shown to be less than 5 MeV.

Fig. 12a Mass spectrum for events in the mass range $2.5 < m_{ee} < 3.5$ GeV/c. The shaded events correspond to those taken at the normal magnet setting, while the unshaded ones correspond to the spectrometer magnet setting at - 10% lower than normal value.



5. Hadron. $\mu^+\mu^-$ and e^+e^- pair production cross section in the regions of the ψ and ψ'. The curves arc fits to the data using the energy spread in the colliding beams as the determinant of the widths.

Objev botomonia

L. Lederman – ještě před
Tingem a Richterem
viděl náznak J/ψ v rozdělení
Invariantní hmoty mionů

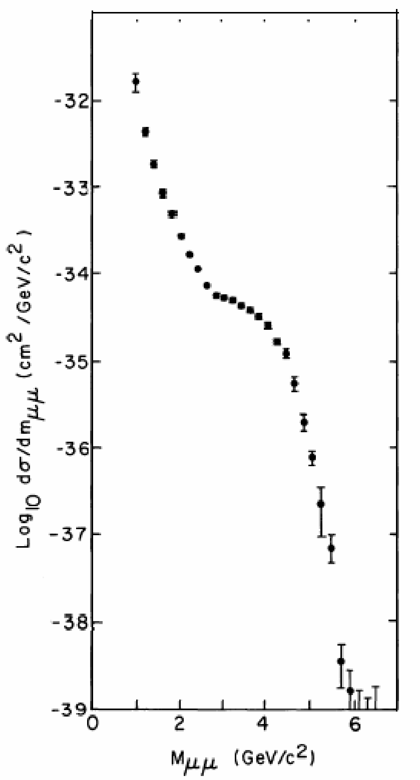


Figure 7a. Data on yield of dimuons vs. mass at 30 GeV.

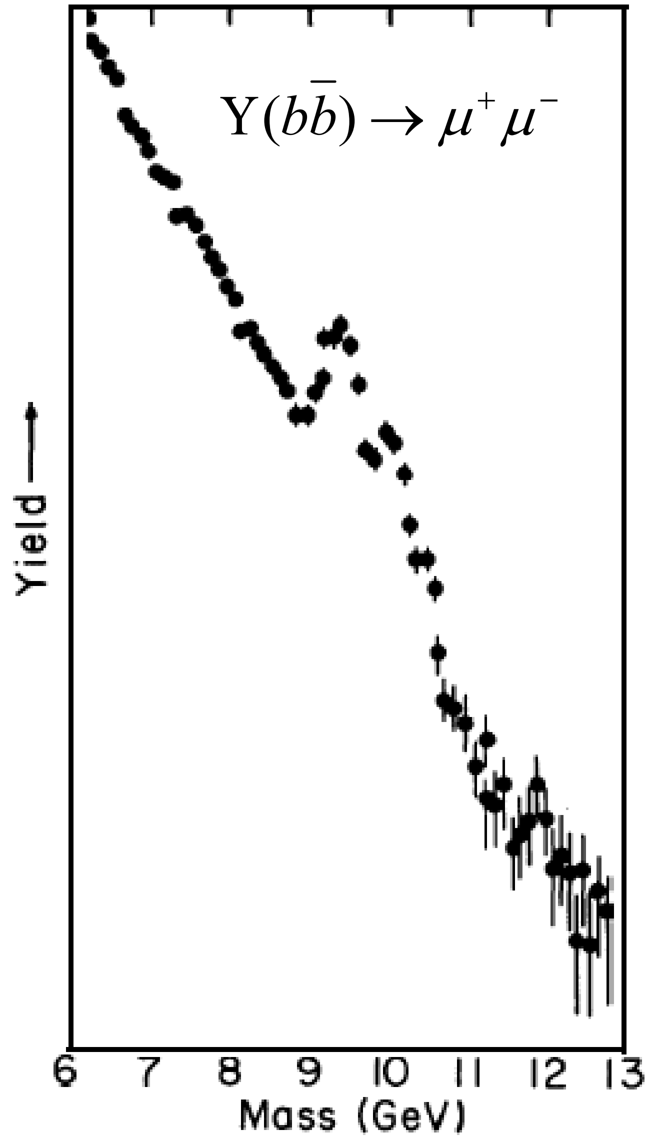


Figure 12a. Peaks on Drell-Yan continuum.

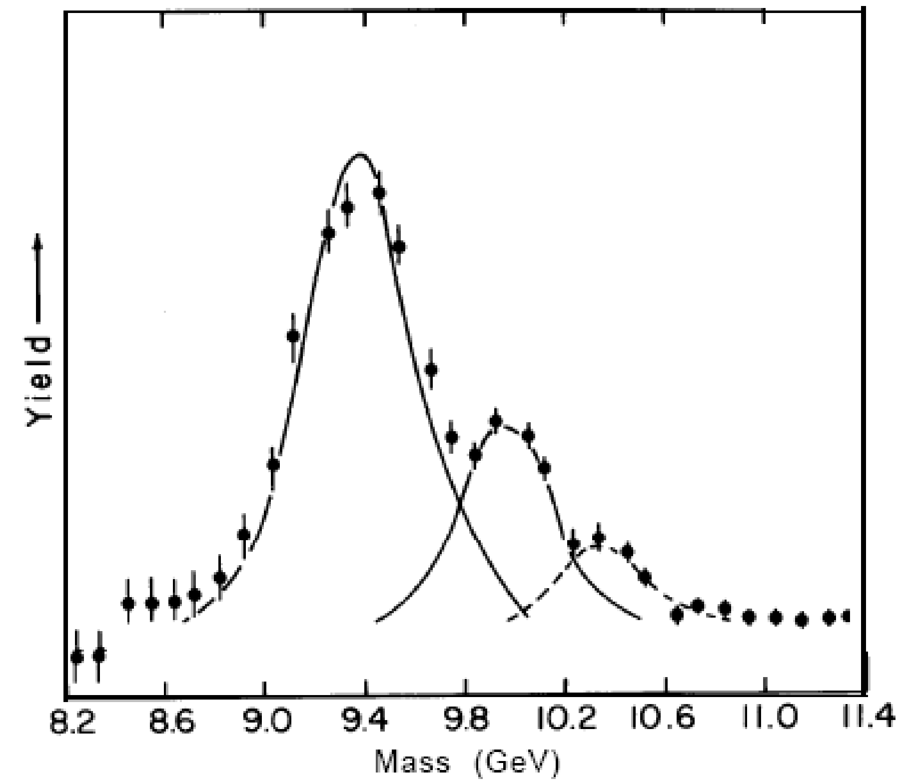


Figure 12*b*. Peaks with continuum subracted.

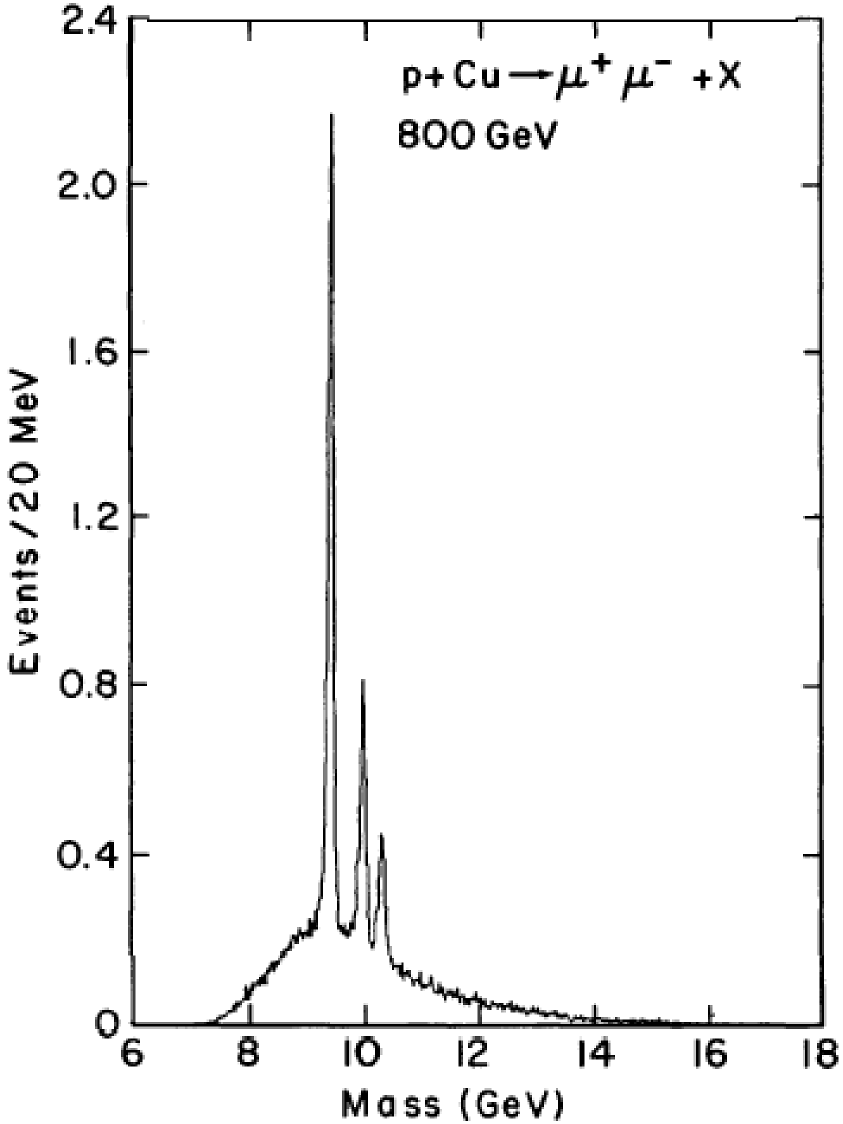
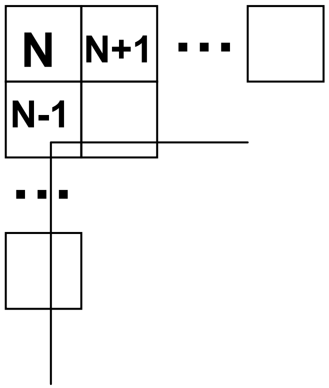


Figure 13. Fermilab E-605 data.

Table 14.1: Additive quantum numbers of the quarks.

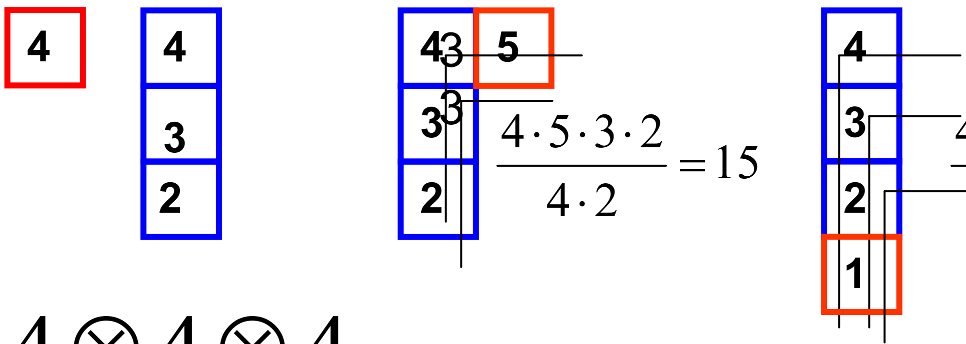
Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	$+1$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

SU(4) – 4 kvarky – jaké multiplety mohou vzniknout?



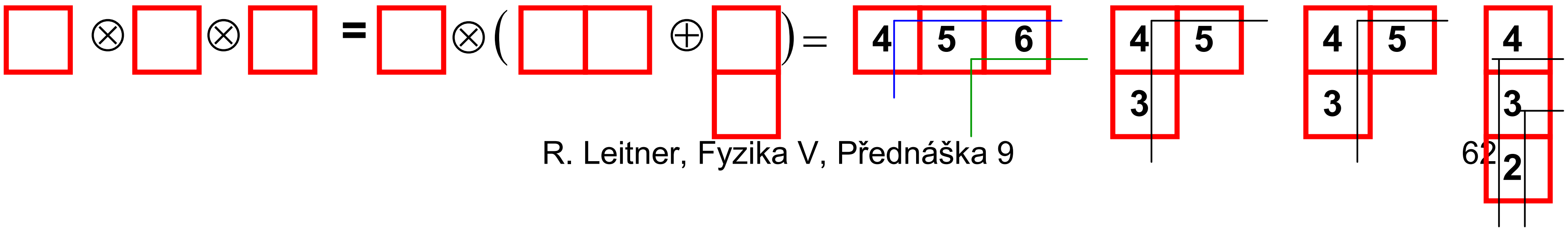
$$MULT = \frac{\left(N \cdot (N+1) \cdot \ldots\right) \cdot \left((N-1) \cdot \ldots\right) \cdot \ldots}{NH_1 \cdot \ldots \cdot NH_n}$$

$4 \otimes \bar{4}$ $\qquad$ 15 $\qquad$ 1



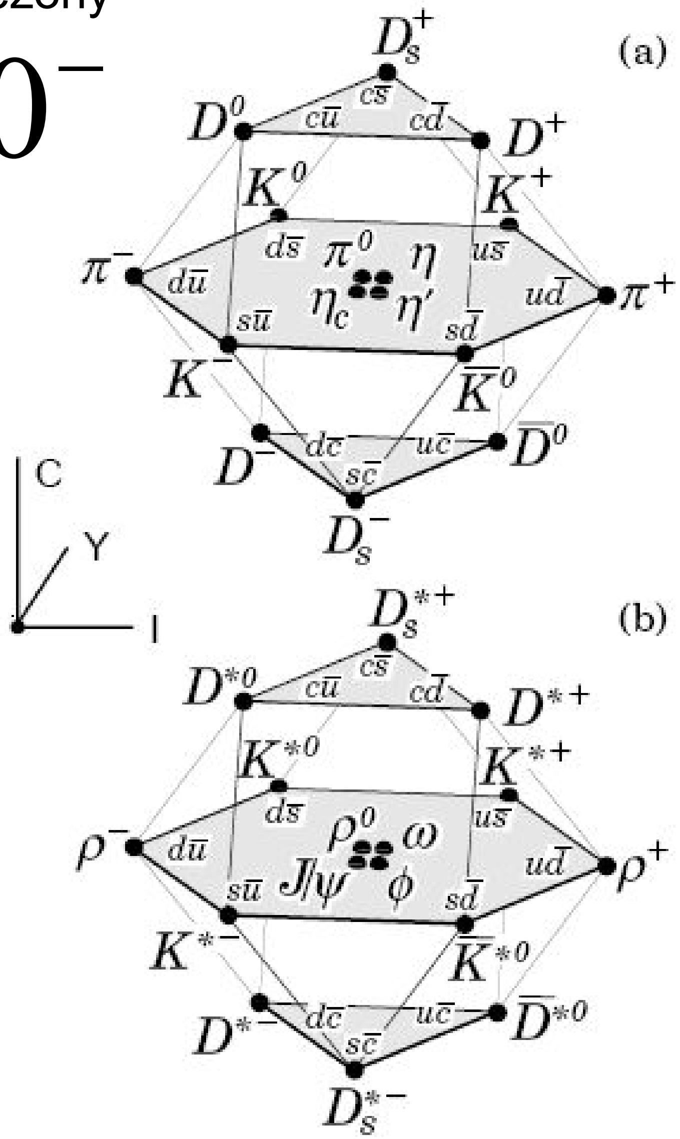
$$\frac{4 \cdot 5 \cdot 3 \cdot 2}{4 \cdot 2} = 15 \qquad \frac{4 \cdot 3 \cdot 2 \cdot 1}{2 \cdot 3 \cdot 4} = 1$$

$4 \otimes 4 \otimes 4$ $\qquad$ 20 $\frac{4 \cdot 5 \cdot 6}{3 \cdot 2} = 20$ $\quad$ 20 $\frac{4 \cdot 5 \cdot 3}{3} = 20$ $\quad$ 20 $\quad$ 4



Pseudoskalární mezony

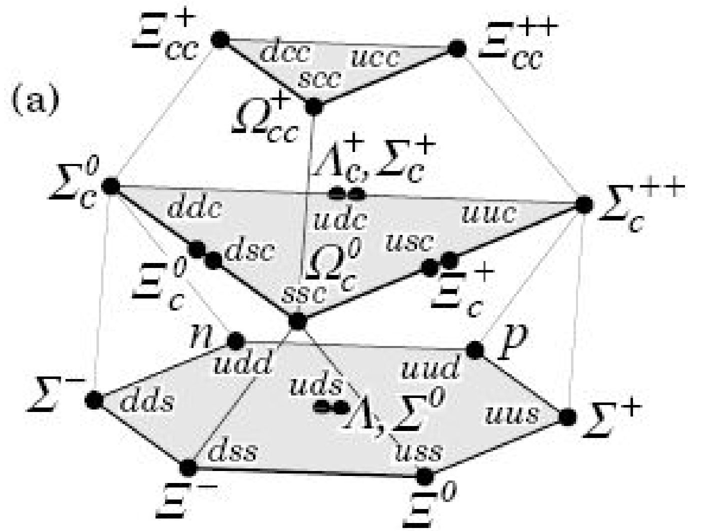
0^-



Vektorové mezony

1^-

Baryony $1/2^+$



Baryony $3/2^+$