

# Přednáška 7. (12.11.2007)

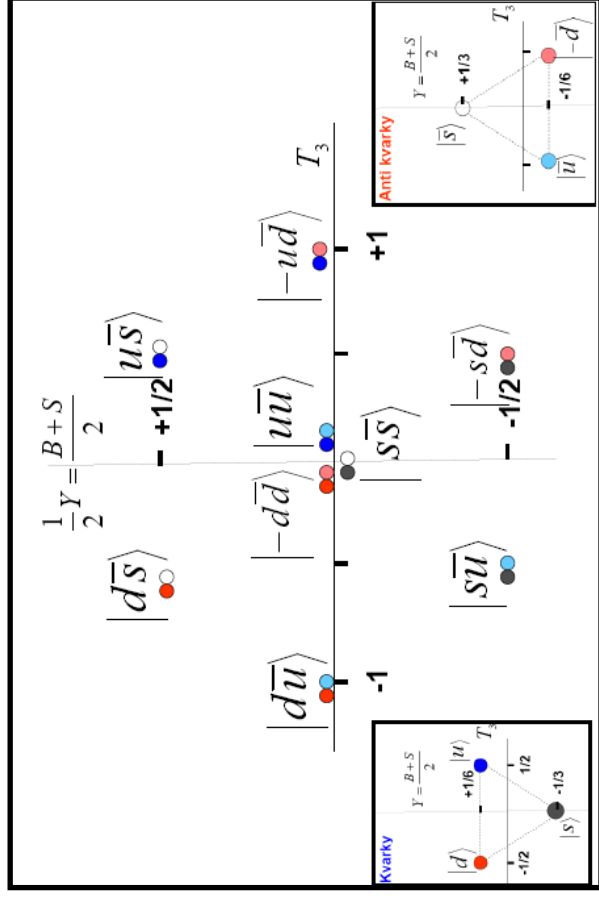
Mezony (kvark anti-kvark) a baryony (tři kvarky)

Interakce elementárních částic

Feynmanovy diagramy

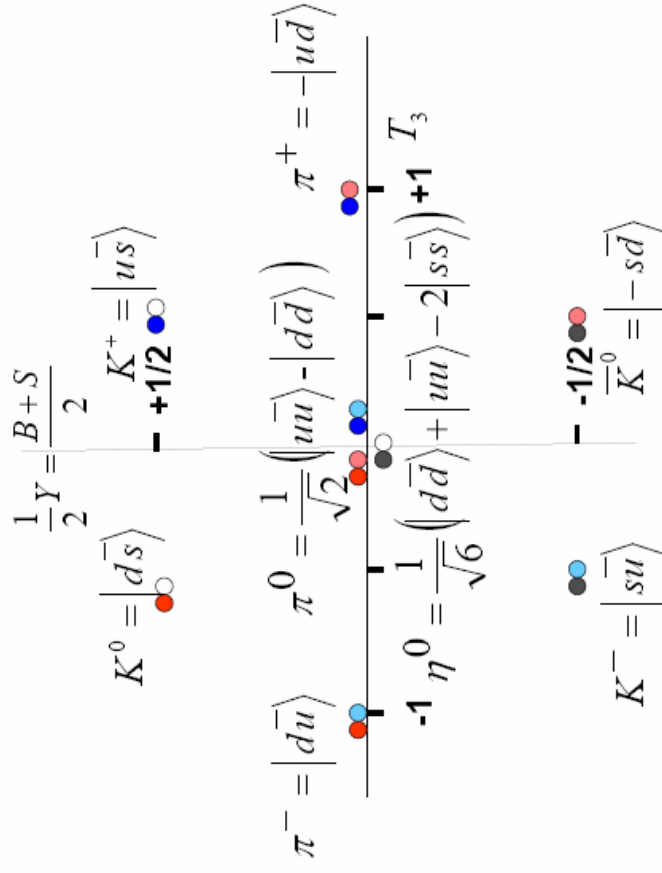
Slabé interakce, intermediální bosony  $W$  a  $Z$

Oktet pseudoskalárních mezonů –  $\pi$  a  $K$  mezony

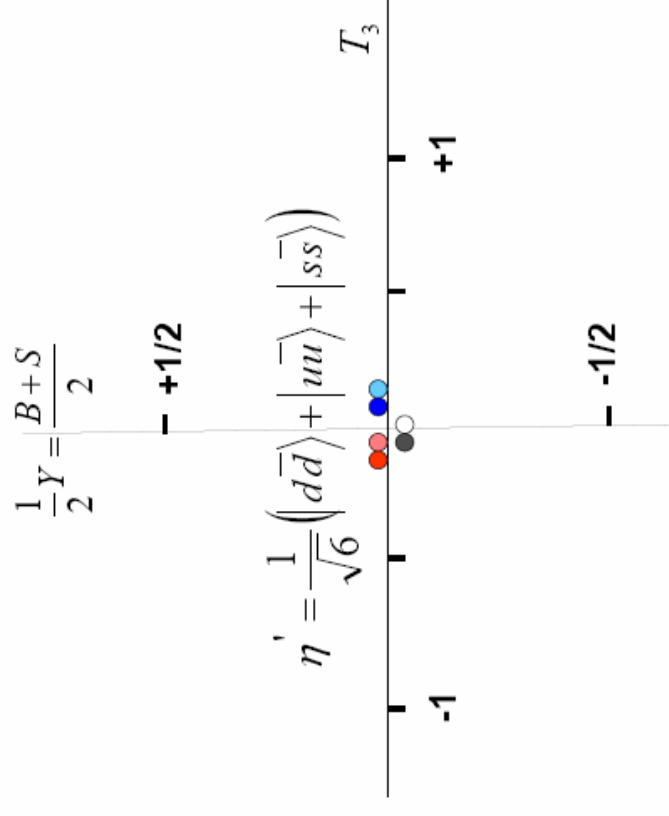


$$3 \otimes \bar{3} = 8 \oplus 1$$

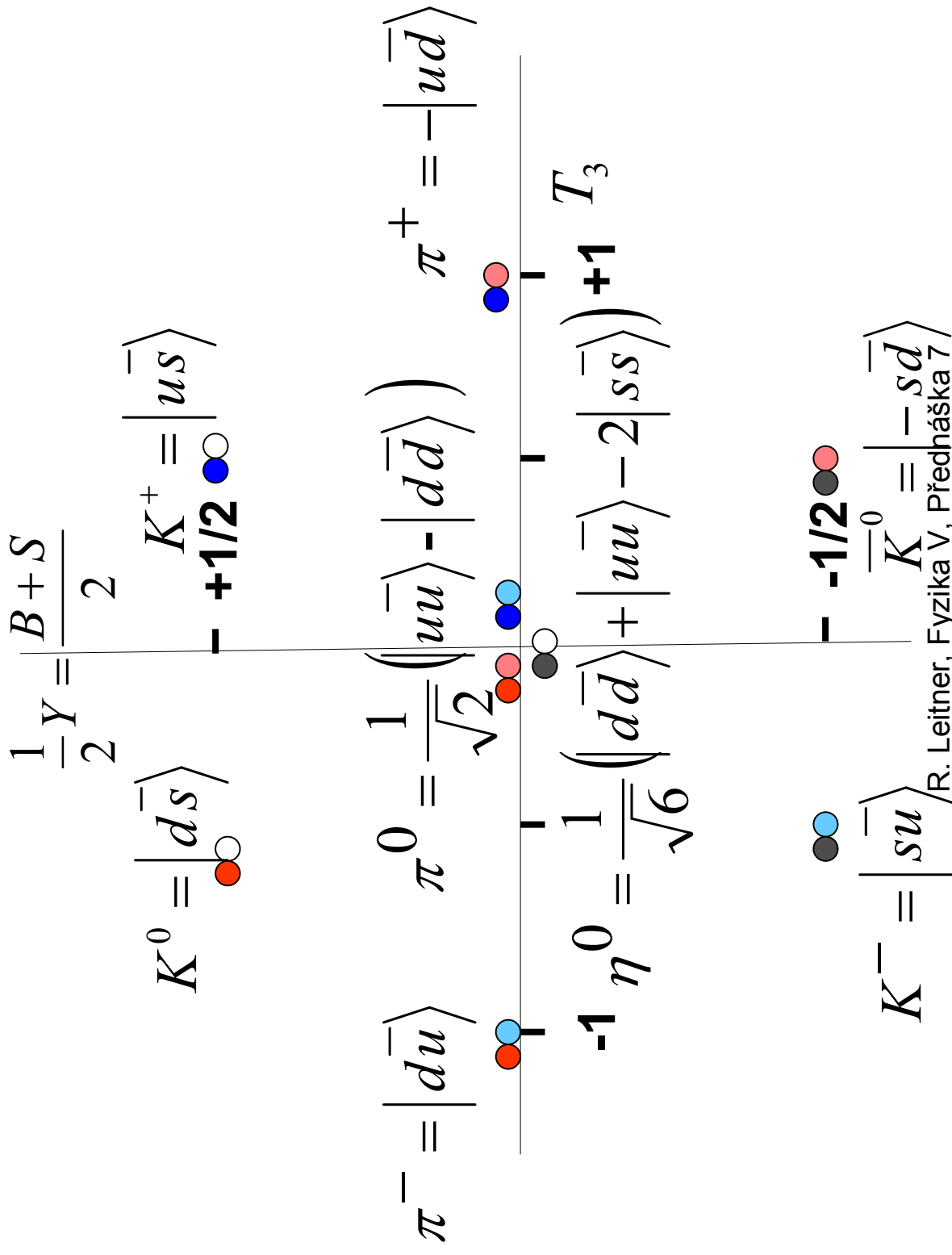
### Oktet pseudoskalárních mezonů



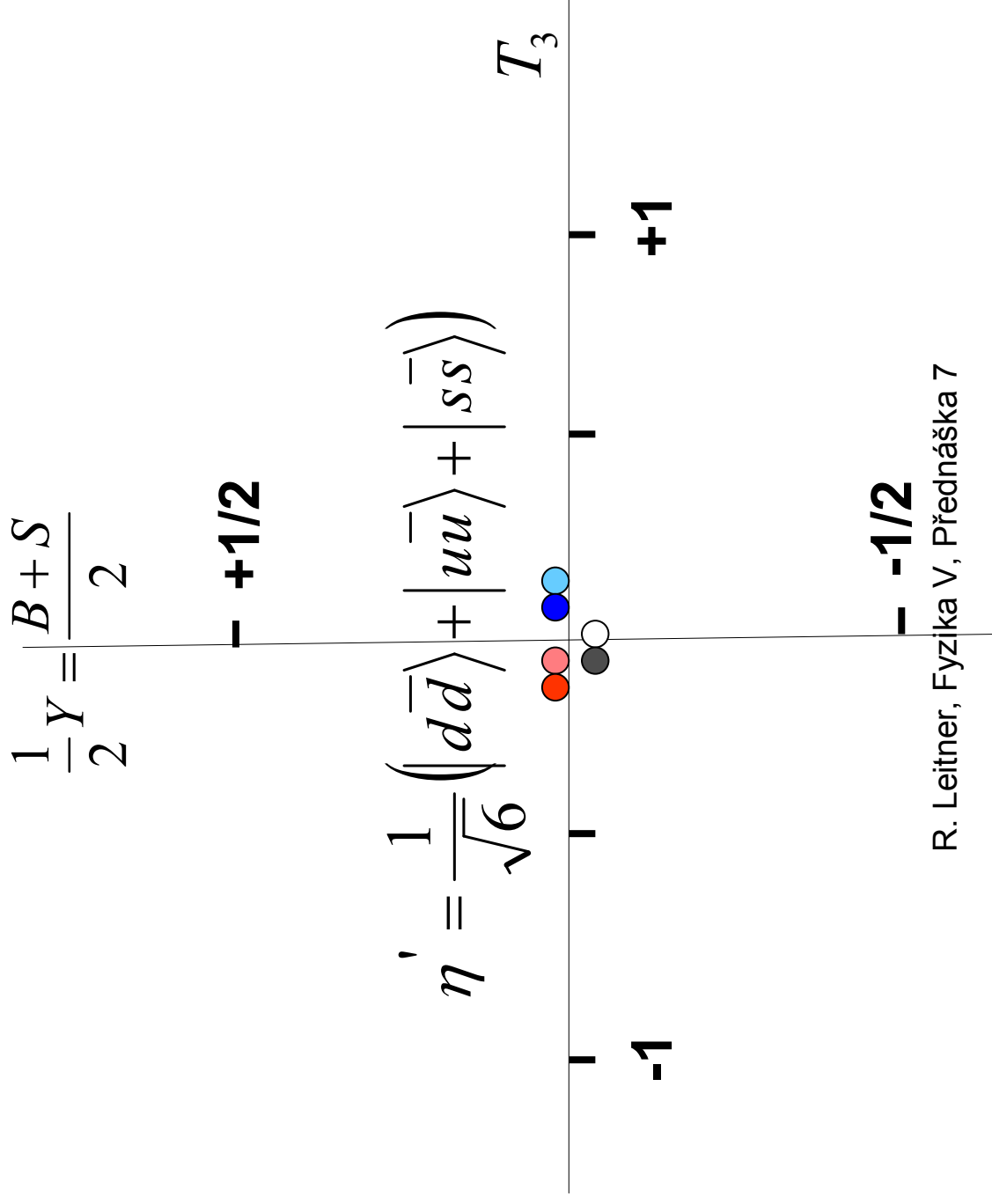
### Singlet pseudoskalárních mezonů

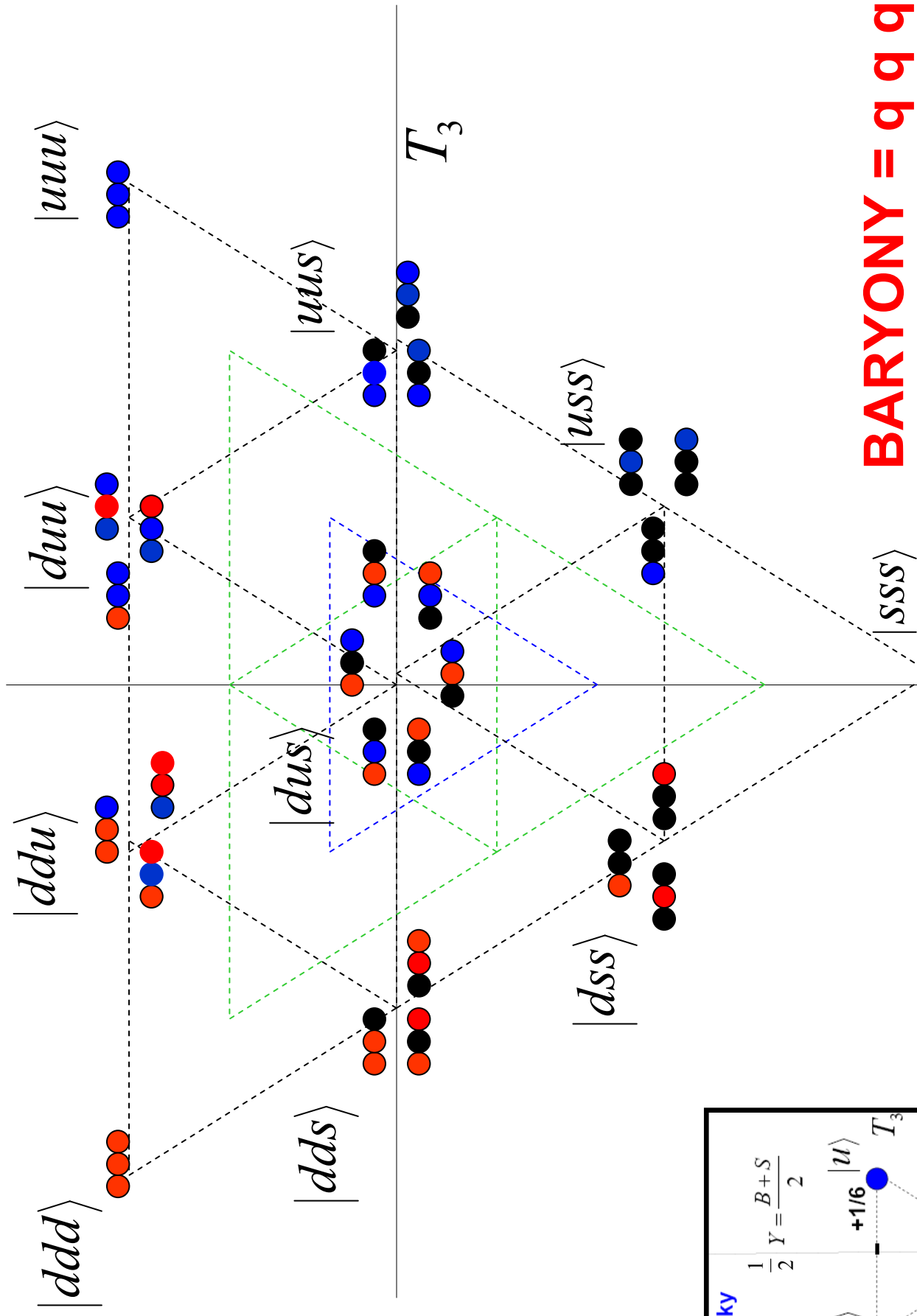
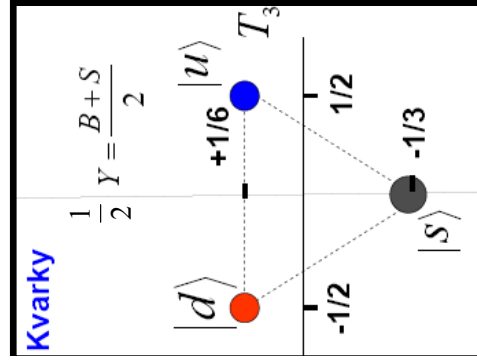


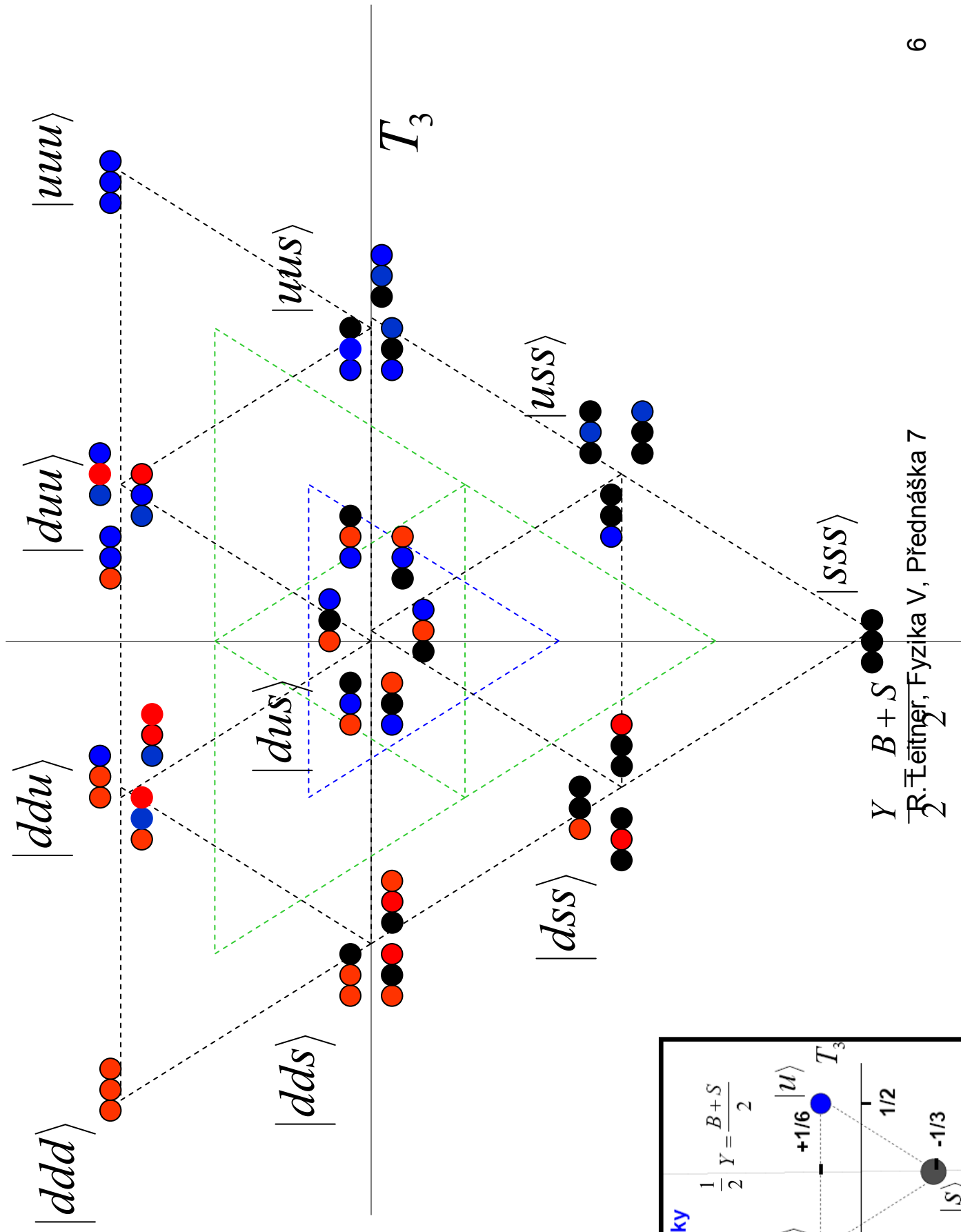
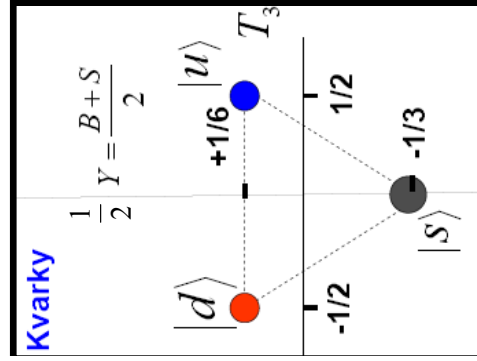
# Oktet pseudoskalárních mezonů



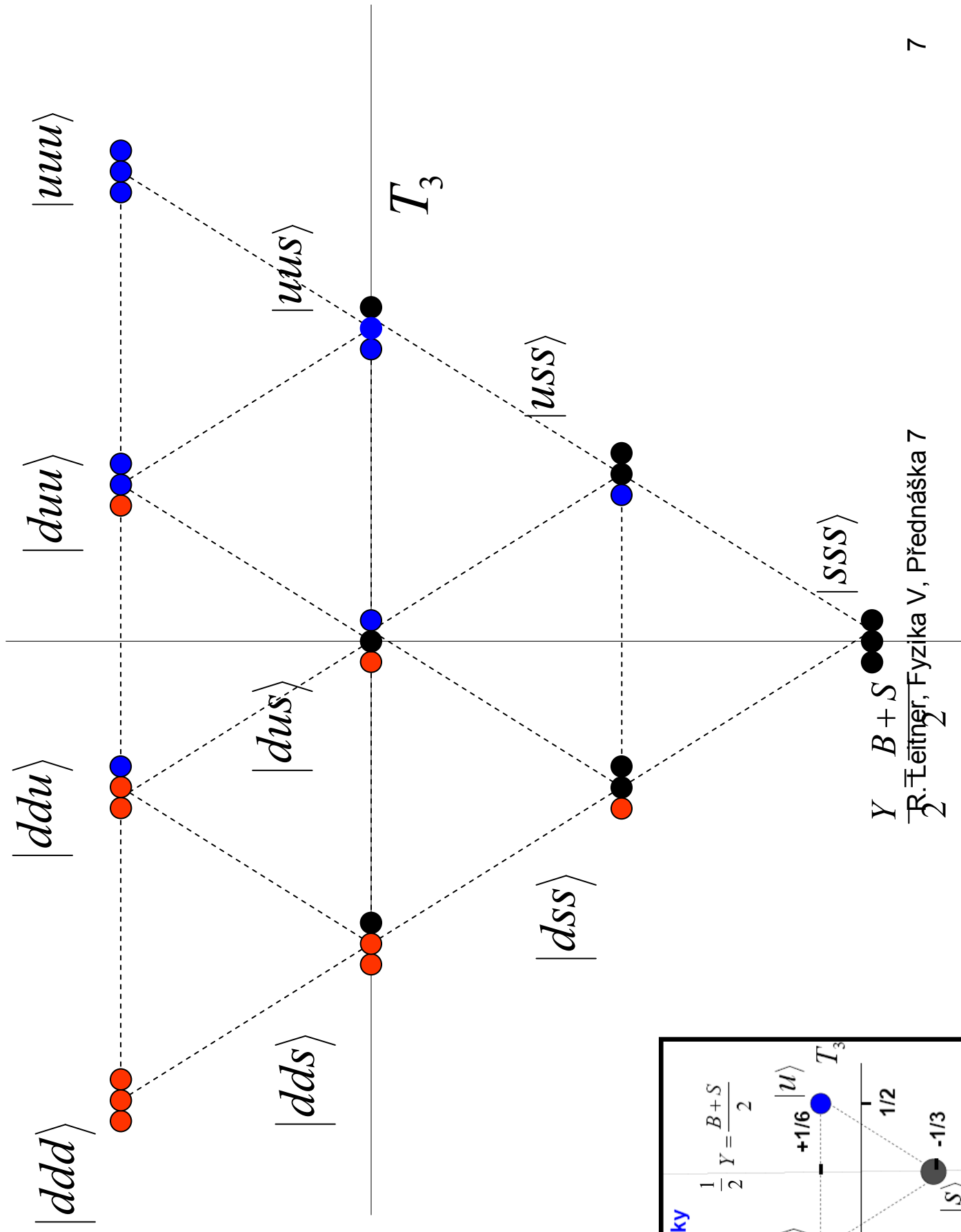
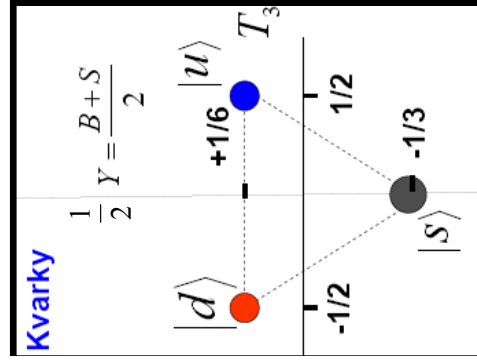
# Singlet pseudoskalárních mezonů

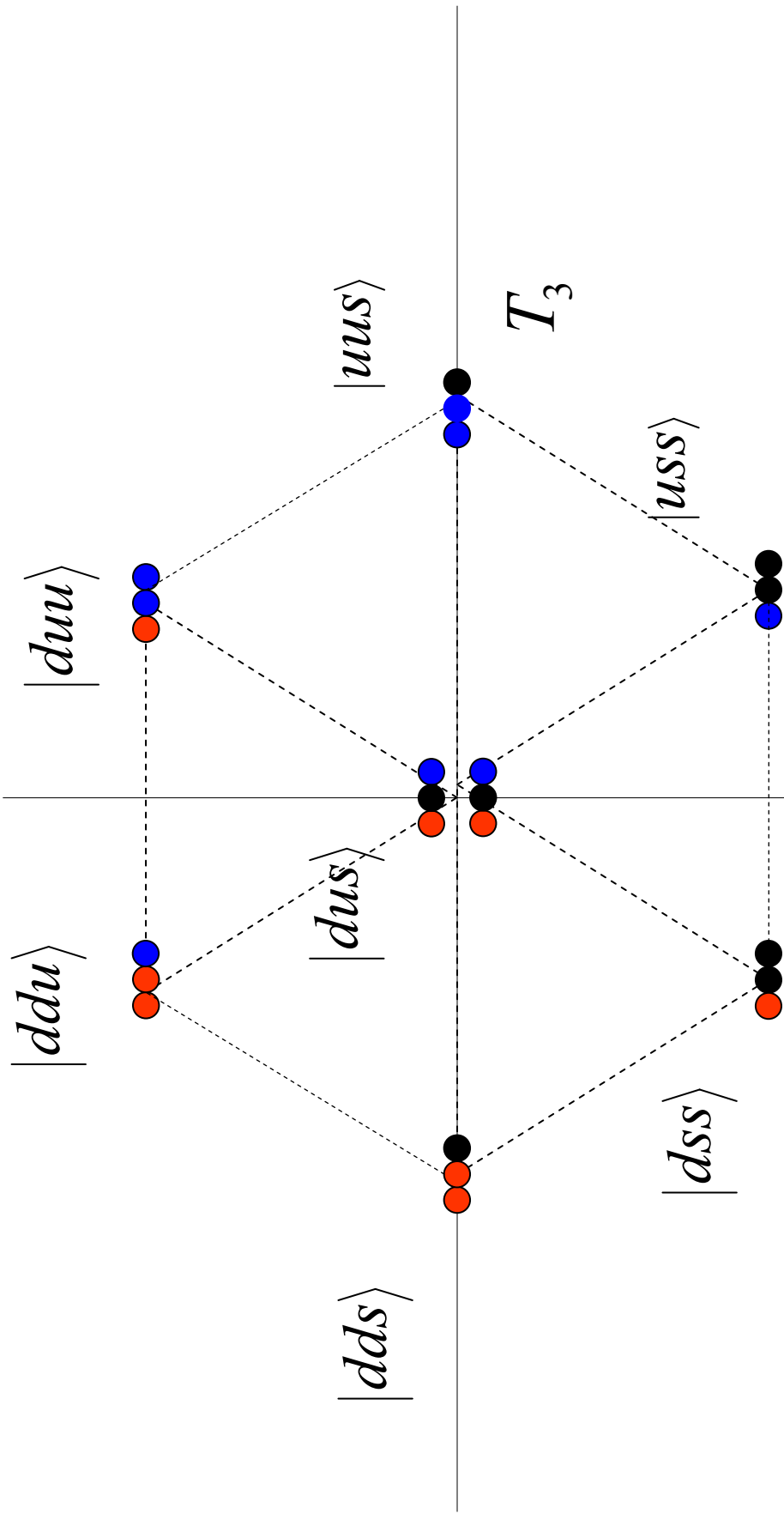
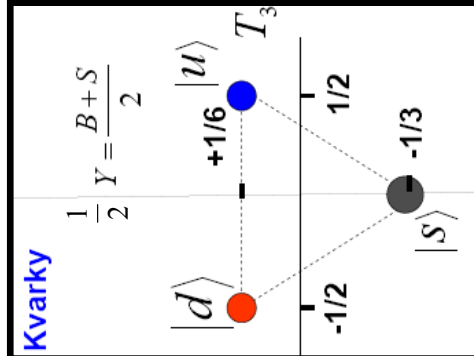




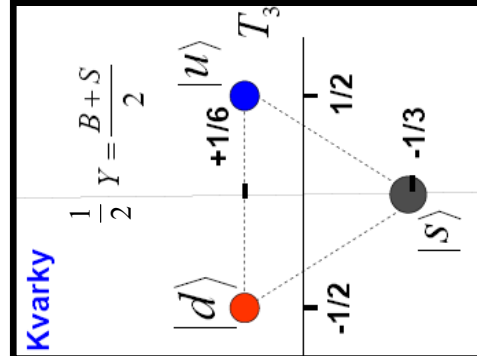


Y  $B + S$   
 R. Leitner, Fyzika V, Přednáška 7





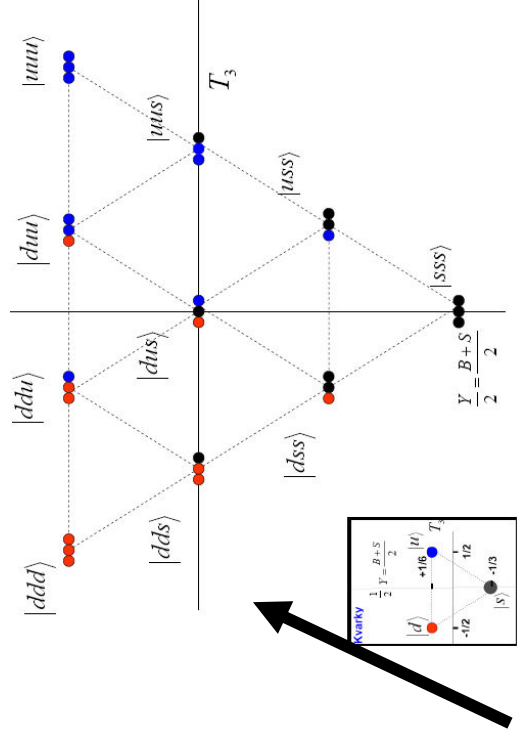
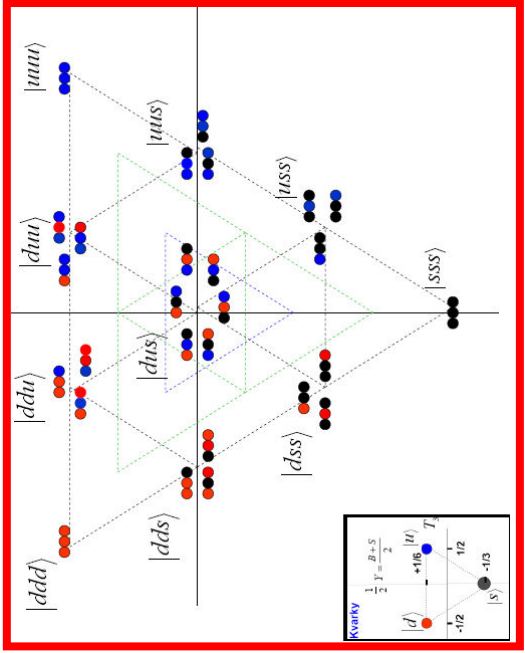




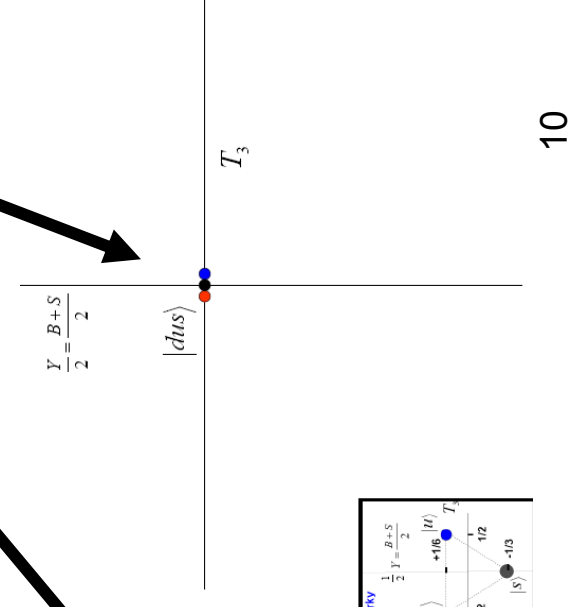
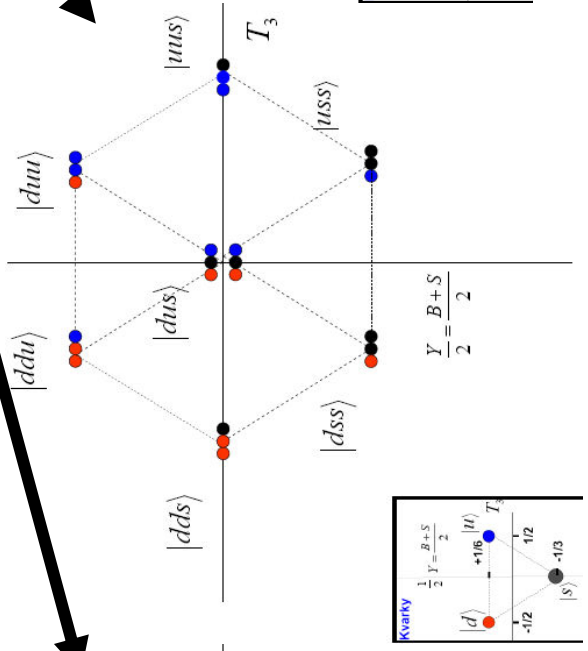
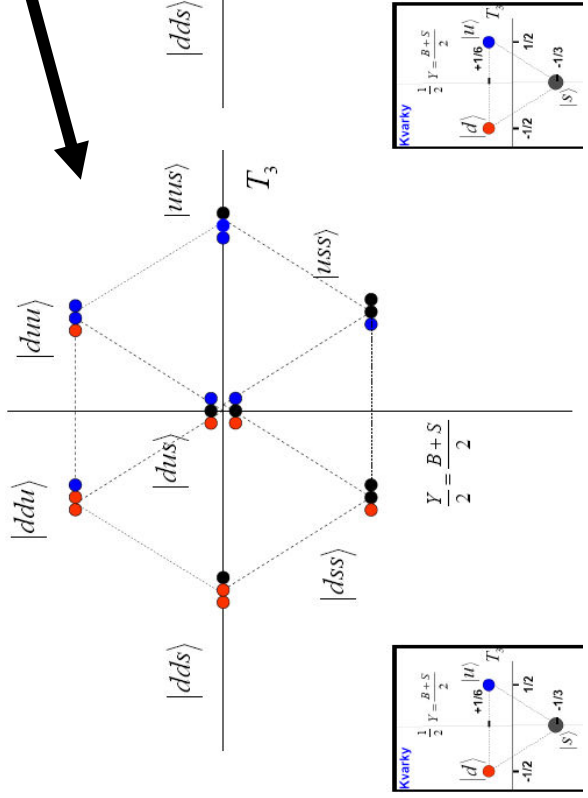
$$\frac{Y}{2} = \frac{B+S}{2}$$

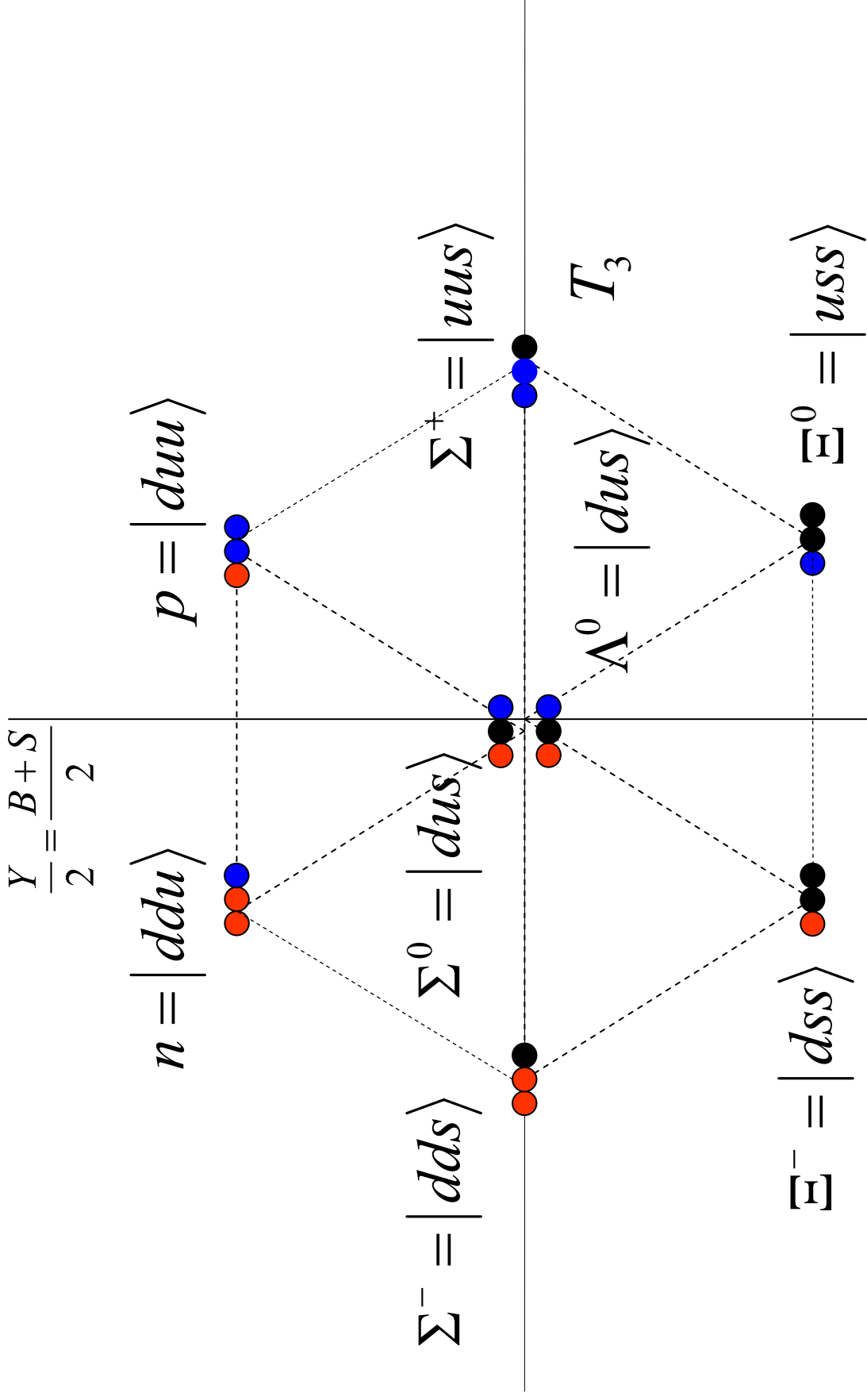
$|dus\rangle$

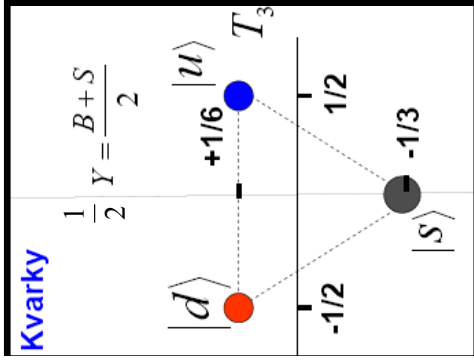
$T_3$



$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$







## Leptony

### Leptony

$$e^{-}, \nu_e^{-}$$

$$m_e = 0,511 MeV$$

$$\mu^{-}, \nu_{\mu}^{-}$$

$$m_{\mu} = 106 MeV$$

$$\tau^{-}, \nu_{\tau}^{-}$$

$$m_{\tau} = 1777 MeV$$

$$m_{\nu} < \sim eV$$

Mají stejně jako kvarky spin=1/2, dle současných znalostí nemají další vnitřní strukturu, jsou elementární.

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## Interakce mezi částicemi a rozpady částic a jejich grafické znázornění pomocí Feynmanových diagramů

### 1.5. Rozptyl v kvantové mechanice

$$\frac{d\sigma}{d\Omega} = \frac{M^2}{4\pi^2(\hbar c)^4} \left| \int e^{-i\frac{\vec{q}r}{\hbar c}} \cdot V(r') \cdot d^3r' \right|^2$$

Elektromagnetická - Intermediálním bosonem je  $\gamma$

$$V(r) = \alpha z_1 z_2 \frac{\hbar c}{r} e^{-\frac{mr}{\hbar c}}$$

$$V(q) = \int d^3 \vec{r} \cdot e^{i \frac{\vec{q} \vec{r}}{\hbar c}} V(r)$$

$$V(q) = \alpha z_1 z_2 \hbar c \int_0^\infty r^2 dr \frac{1}{r} e^{-\frac{mr}{\hbar c}} \cdot \int_{-1}^{+1} e^{i \frac{qr \cos(\theta)}{\hbar c}} d \cos(\theta) \cdot \int_0^{2\pi} d\phi$$

$$V(q) = 2\pi \alpha z_1 z_2 \hbar c \int_0^\infty r^2 dr \frac{1}{r} e^{-\frac{mr}{\hbar c}} \cdot \frac{2\hbar c \sin(qr / \hbar c)}{qr}$$

$$V(q) = \frac{4\pi \alpha z_1 z_2 (\hbar c)^3}{q} \int_0^\infty dr \frac{1}{\hbar c} \sin(qr / \hbar c) e^{-\frac{mr}{\hbar c}} =$$

$$\frac{4\pi \alpha z_1 z_2 (\hbar c)^3}{q} \int_0^\infty d\rho \sin(q\rho) e^{-m\rho} =$$

$$\frac{4\pi \alpha z_1 z_2 (\hbar c)^3}{q} \cdot \left( \frac{-e^{-m\rho} (q \cos(q\rho) + m \sin(q\rho))}{q^2 + m^2} \right) \Bigg|_0^\infty =$$

$$\frac{4\pi \alpha z_1 z_2 (\hbar c)^3}{q} \frac{q}{q^2 + m^2} = V(q)$$

$$V(r) = \alpha z_1 z_2 \frac{\hbar c}{r} e^{-\frac{mr}{\hbar c}}$$

• **A, z<sub>1</sub>**

• **B, z<sub>2</sub>**

## Feynmanův diagram

A+B → A+B

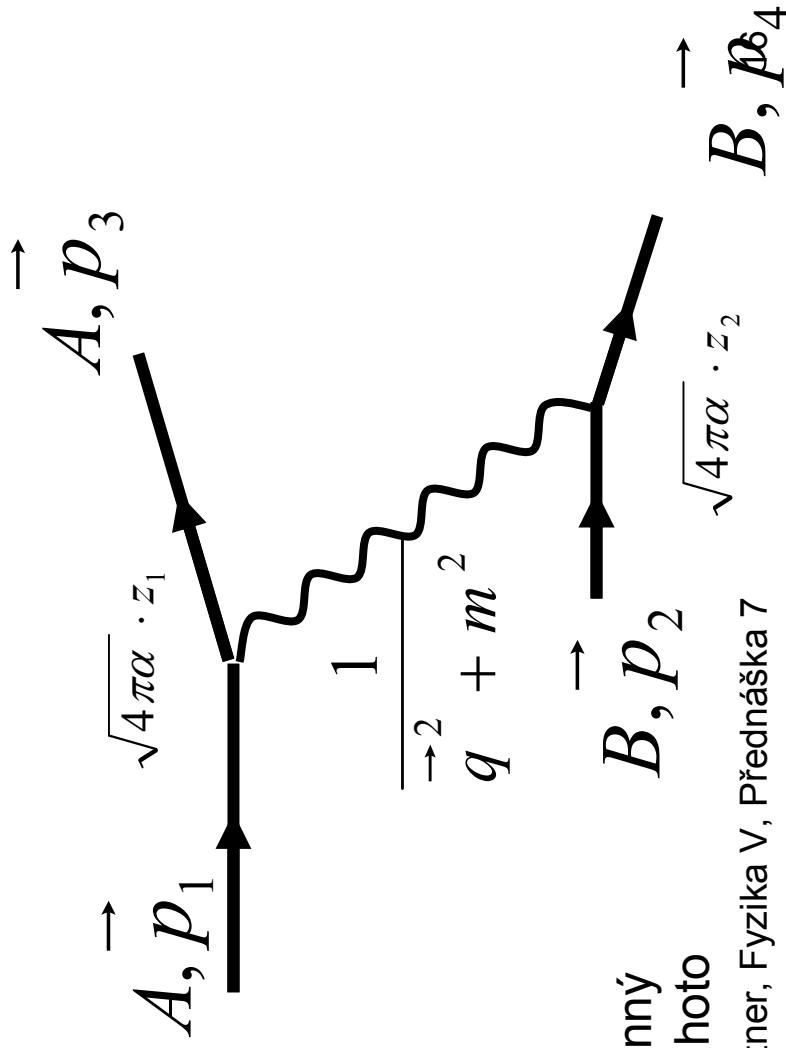
Feynmanovu diagramu odpovídá výraz pro maticový element a účinný průřez je pak úměrný kvadrátu tohoto maticového elementu

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$$V(q) = (\hbar c)^3 \frac{4\pi\alpha z_1 z_2}{q^2 + m^2} =$$

$$(\hbar c)^3 \sqrt{4\pi\alpha} \cdot z_1 \frac{1}{q^2 + m^2} \sqrt{4\pi\alpha} \cdot z_2$$

$$q = p_3 - p_1 = p_2 - p_4$$





# Elektromagnetická interakce

Feynmanův diagram

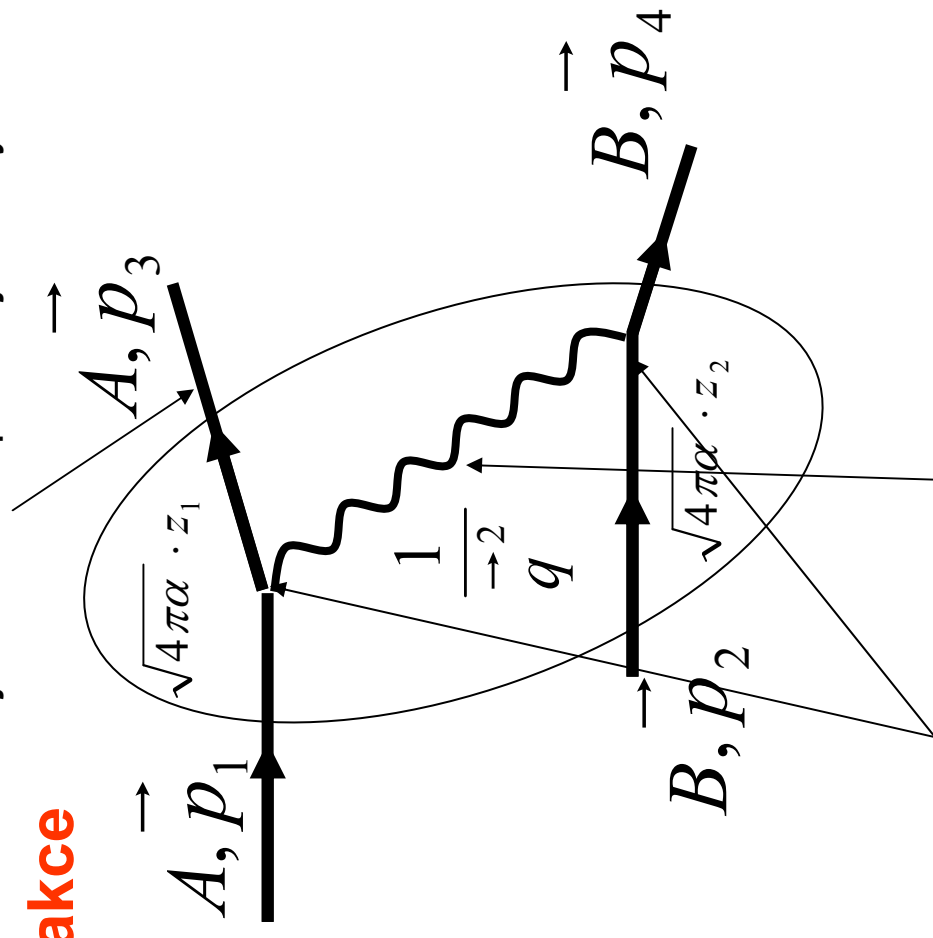
$$A+B \rightarrow A+B$$

Feynmanovu diagramu odpovídá výraz pro maticový element a účinný průřez je pak úměrný kvadrátu tohoto maticového elementu

$$M \approx \sqrt{4\pi\alpha} z_1 \frac{1}{2} \frac{1}{q} \sqrt{4\pi\alpha} z_2$$

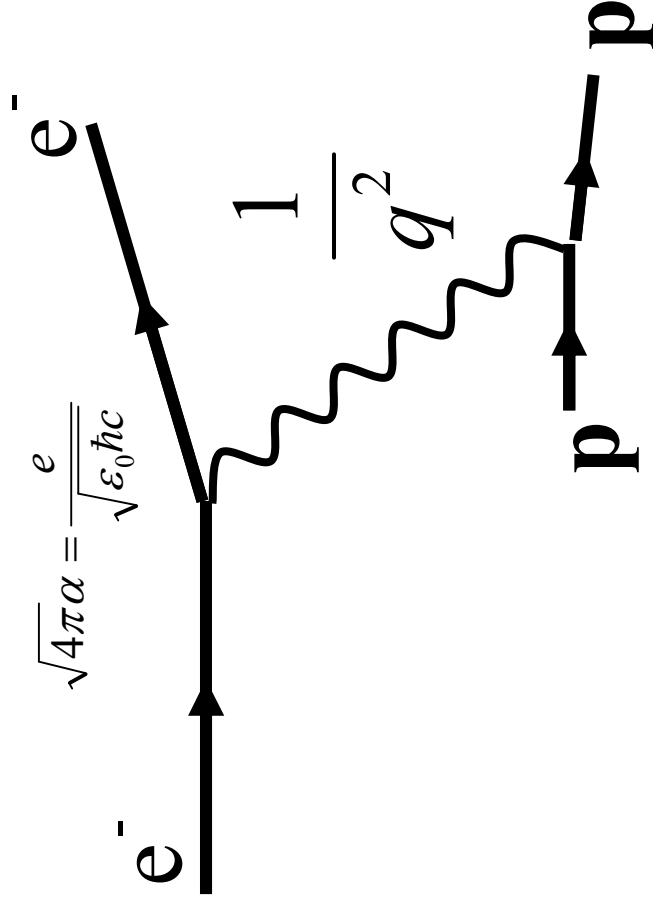
$$\sigma \approx |M|^2 \approx \alpha^2 z_1^2 z_2^2 \frac{1}{q^4}$$

Vnější linie – odpovídají reálným částicím



Vrcholy a propagátor:  
odpovídají interakci mezi částicemi  
Vrcholy = určují sílu interakce  
Propagátor = tvar interakce (1/r)

$$e^- + p \rightarrow e^- + p$$



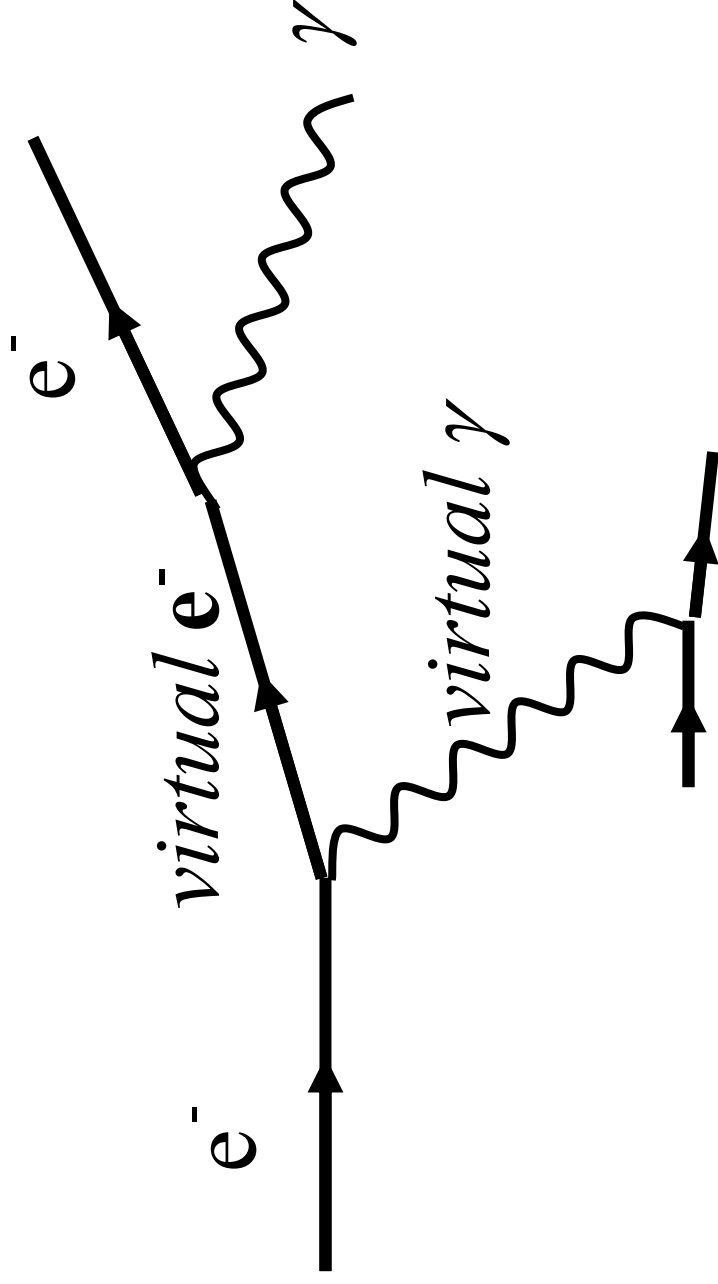
$$\sqrt{4\pi\alpha} = \frac{e}{\sqrt{\epsilon_0 \hbar c}}$$

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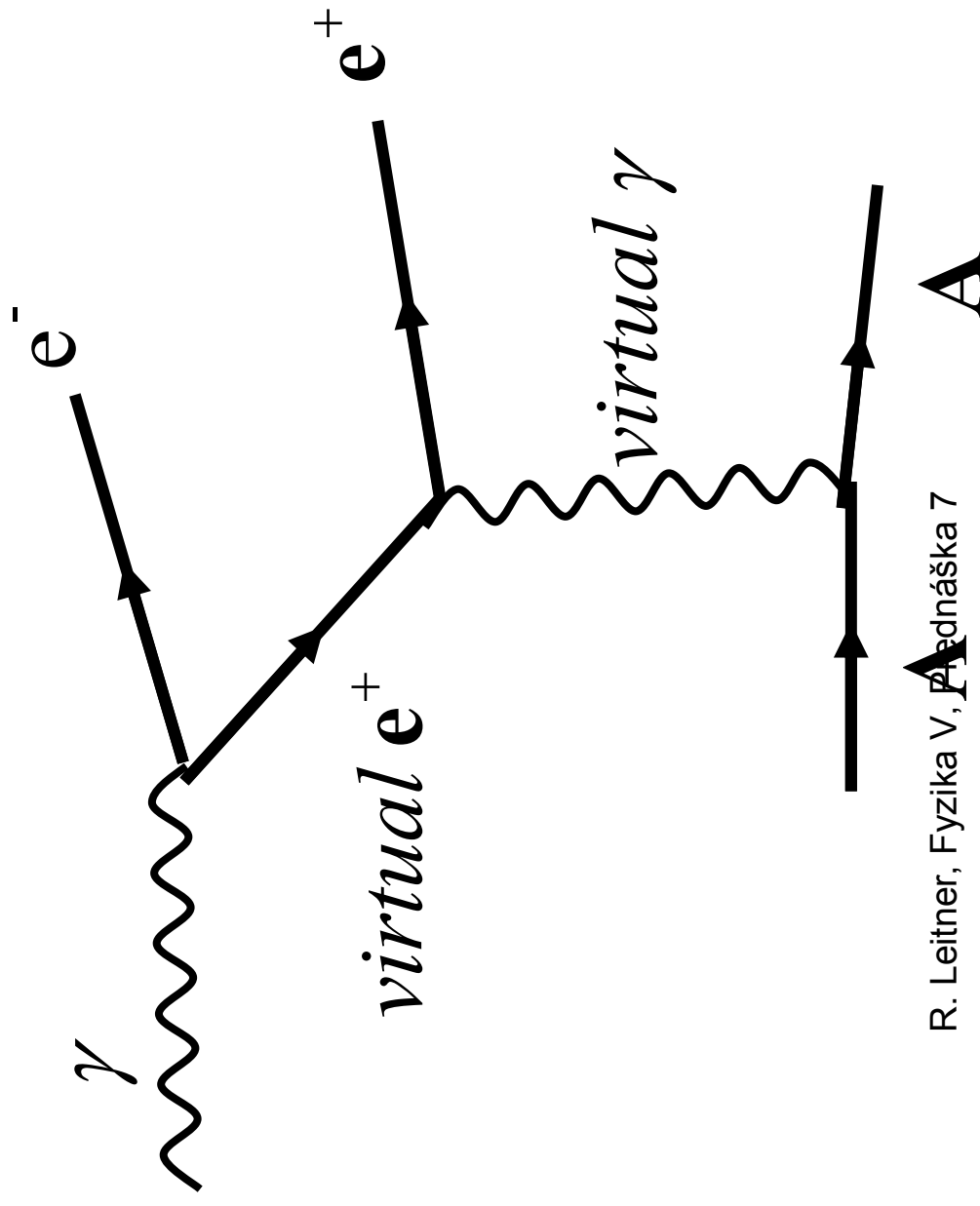
$$q = p_3 - p_1 = p_2 - p_4$$

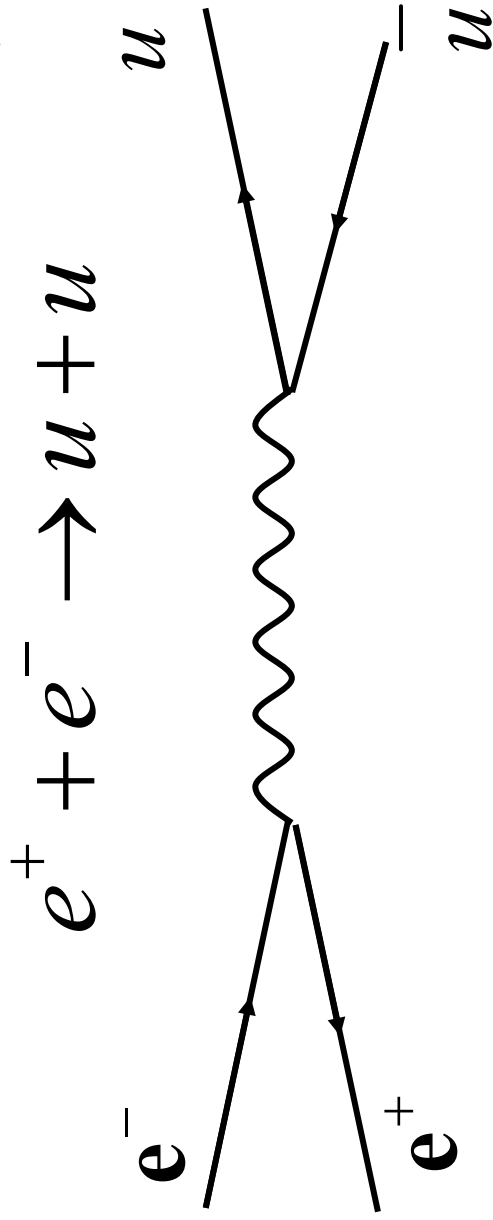
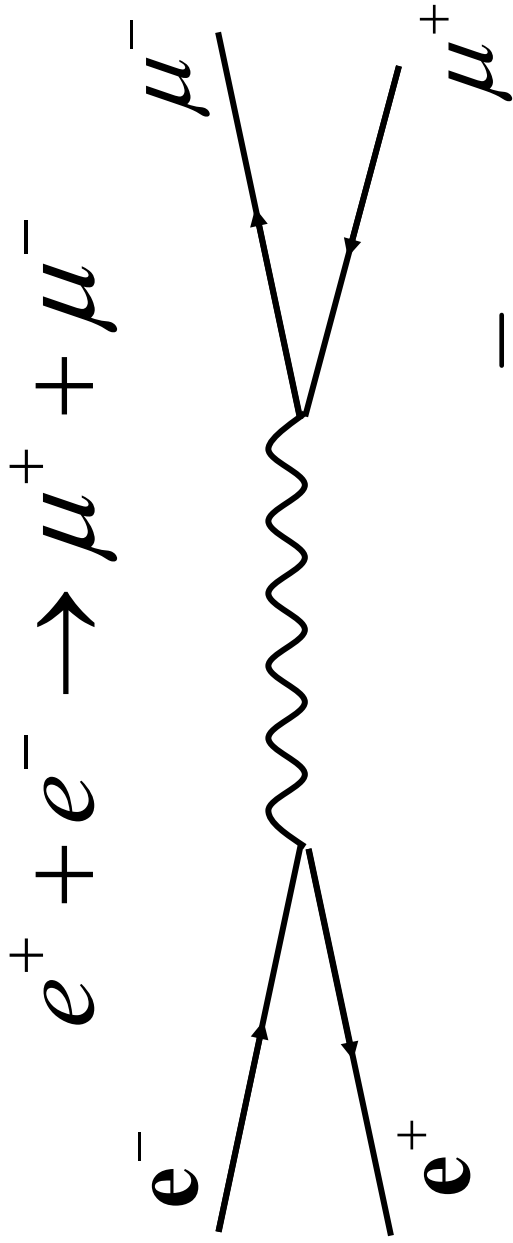
$$\frac{1}{4\pi\alpha} \frac{1}{q^2}$$

$$e^- + A \rightarrow e^- + A + \gamma$$



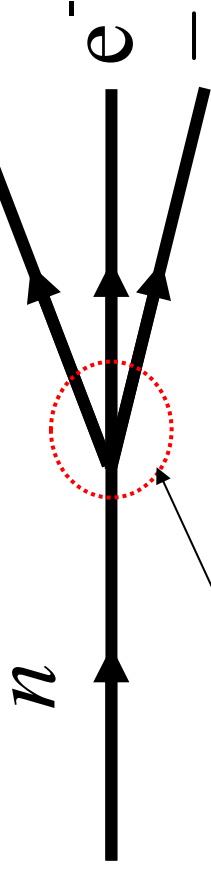
$$\gamma + A \rightarrow A + e^- + e^+$$



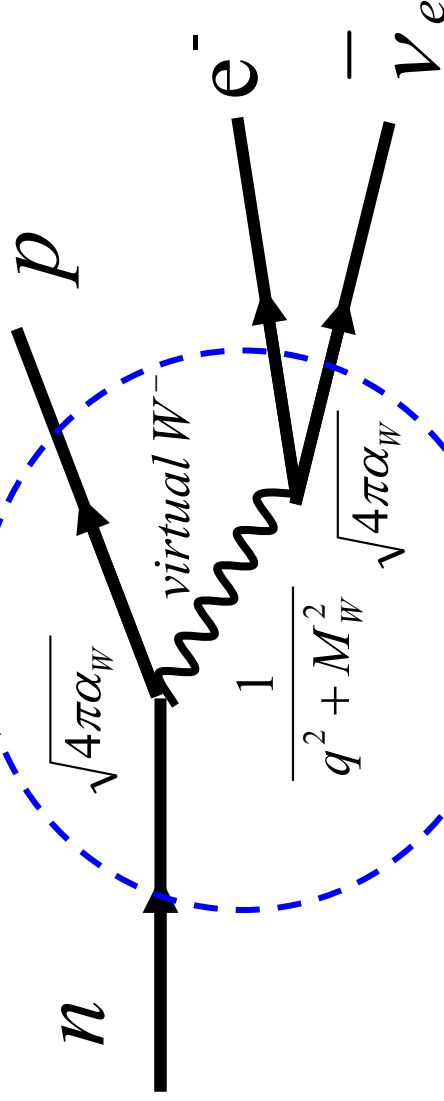


# Slabá interakce

$n \rightarrow p + e^- + \nu_e$  Fermiho teorie



$$4\sqrt{2}G_F; G_F = 1,16 \cdot 10^{-5} \text{ GeV}^{-2}$$



Teorie Glashow,  
Weinberg, Salam

$$4\sqrt{2}G_F = \frac{4\pi\alpha_W}{q^2 + M_W^2} \xrightarrow{q^2 \ll M_W^2} G_F = \frac{4\pi\alpha_W}{4\sqrt{2}M_W^2}$$

$$\alpha_W \approx \alpha = 1/137 \Rightarrow M_W \approx \sqrt{\frac{4\pi/137}{4\sqrt{2} \cdot 1,16 \cdot 10^{-5} \text{ GeV}^{-2}}} \approx 37 \text{ GeV}$$



## The Nobel Prize in Physics 1979

"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"



**Sheldon Lee Glashow**

🏆 1/3 of the prize

USA

Harvard University,  
Lyman Laboratory  
Cambridge, MA, USA

b. 1932



**Abdus Salam**

🏆 1/3 of the prize

Pakistan

International Centre for  
Theoretical Physics  
Trieste, Italy; Imperial  
College  
London, United Kingdom

b. 1926  
d. 1996



**Steven Weinberg**

🏆 1/3 of the prize

USA

Harvard University  
Cambridge, MA, USA

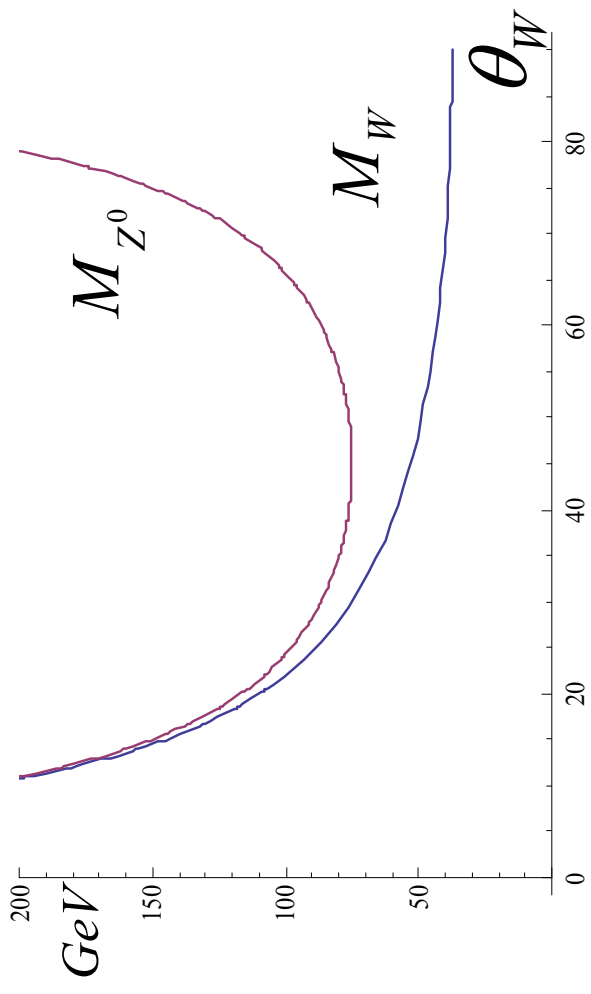
b. 1933

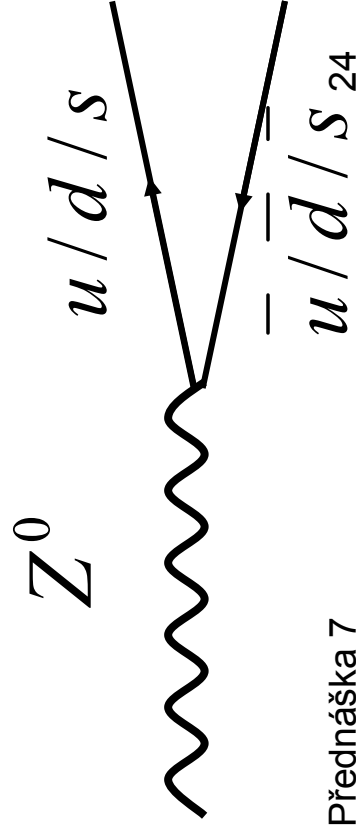
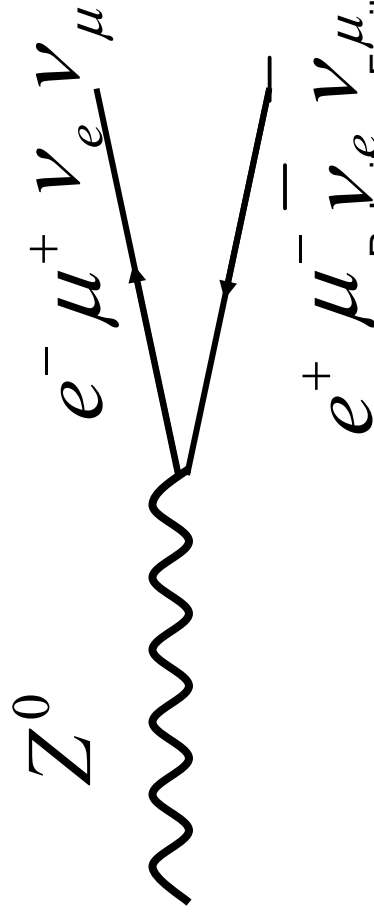
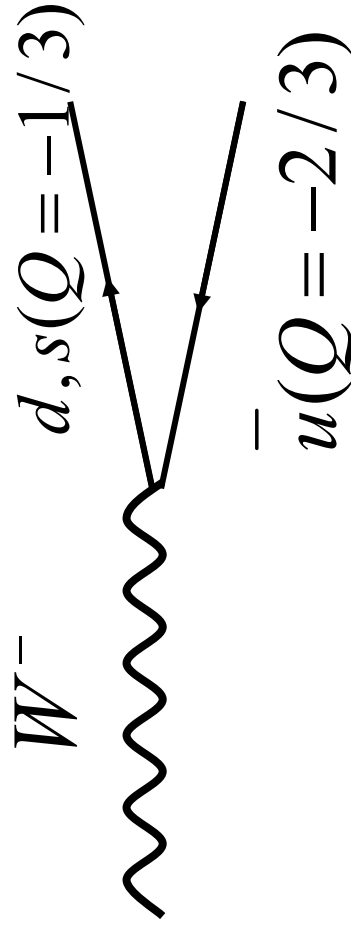
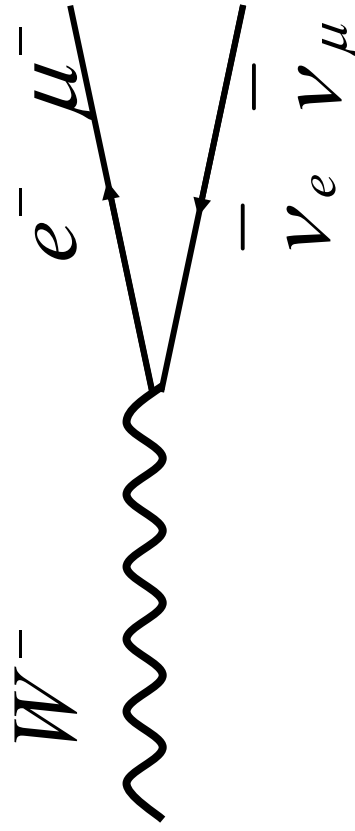
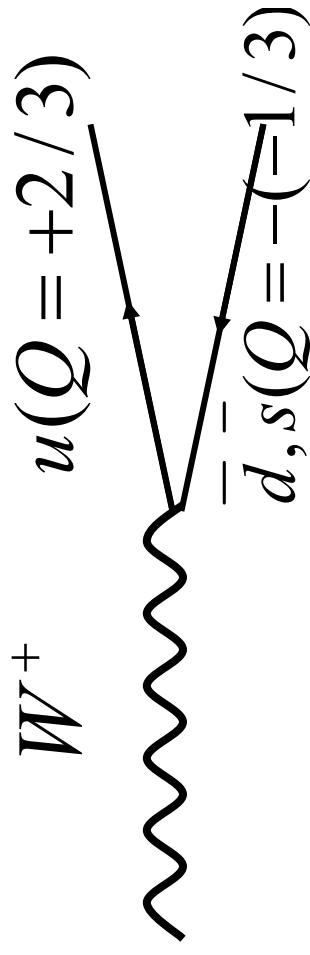
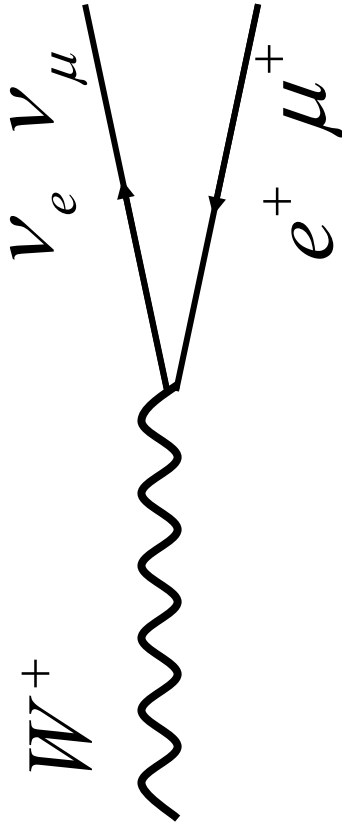
$$4\sqrt{2}G_F = \frac{4\pi\alpha_W}{q^2 + M_W^2} \xrightarrow{q^2 \ll M_W^2} G_F = \frac{4\pi\alpha_W}{4\sqrt{2}M_W^2}$$

$$\alpha_W = \alpha / \sin^2(\theta_W) = 1/(137 \sin^2(\theta_W)) \Rightarrow$$

$$M_W = \frac{1}{\sin(\theta_W)} \sqrt{\frac{4\pi/137}{4\sqrt{2} \cdot 1,16 \cdot 10^{-5} \text{GeV}^{-2}}} \cong \frac{37 \text{GeV}}{\sin(\theta_W)} \Rightarrow M_W \geq 37 \text{GeV}$$

$$\cos(\theta_W) = \frac{M_W}{M_{Z^0}}$$



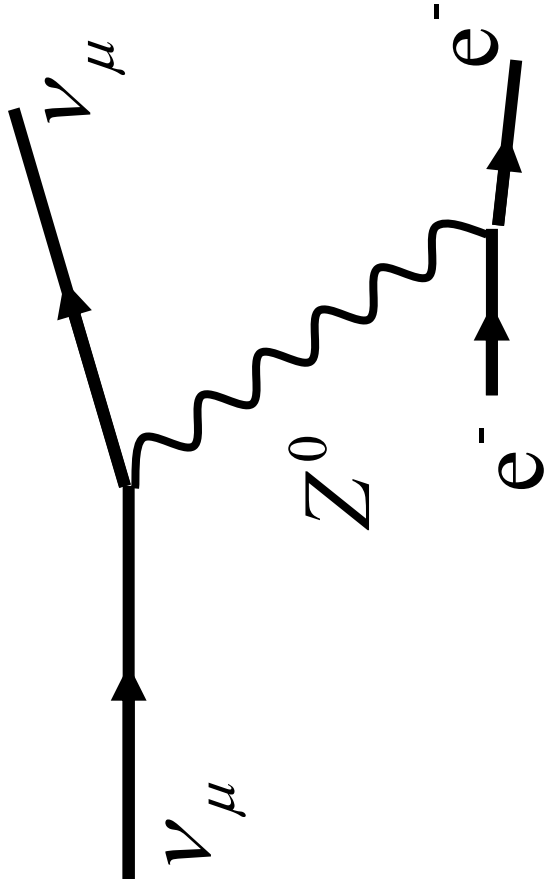




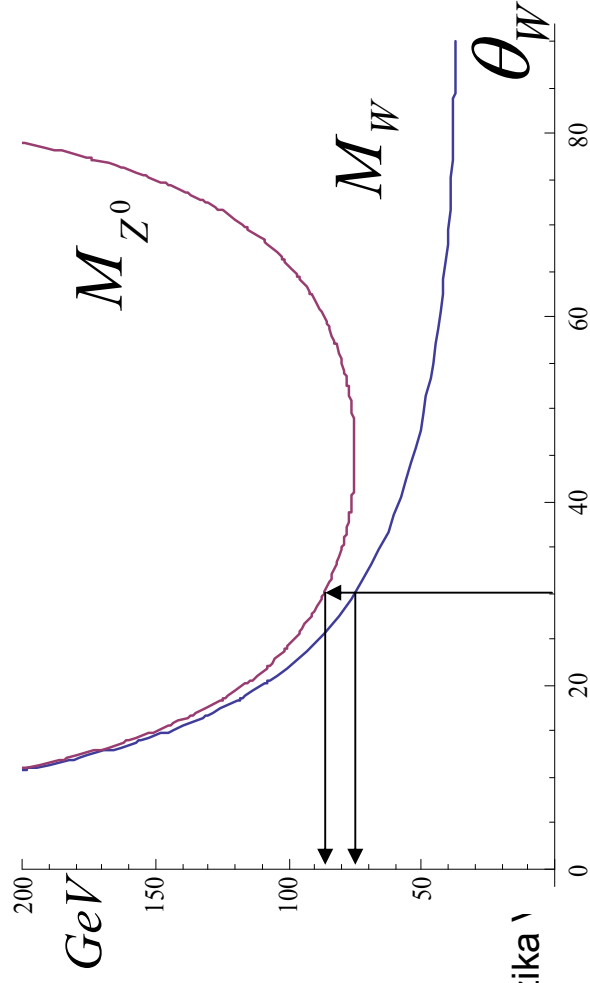
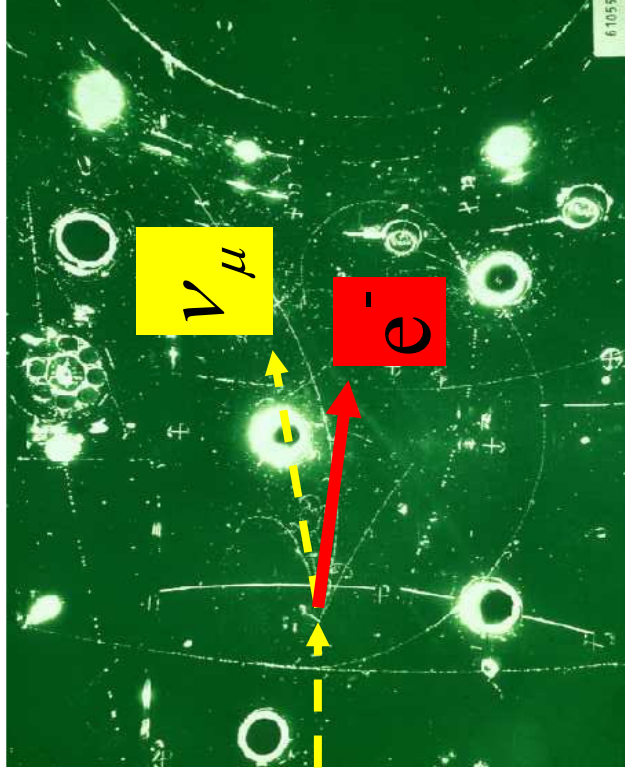
# Objev slabých neutrálních proudů

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

$$\nu_\mu + n / p \rightarrow \nu_\mu + \text{hadrons}$$



$\nu_\mu$



$$M_W = 80,23 \text{ GeV}$$

$$M_Z = 91,15 \text{ GeV}$$

R. Leitner, Fyzika

Slabá interakce je slabá jen při malých energiích kvůli tomu. Že je zprostředkována velmi těžkými částicemi.

Vazbová konstanta je ve skutečnosti o něco větší než konstanta elektromagnetické interakce.

## Gravitační interakce

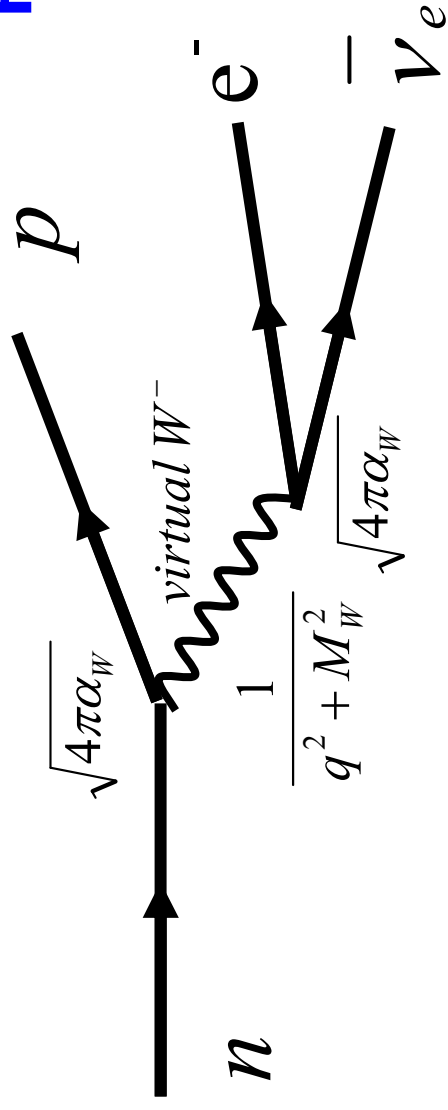
$$V(r) = -\kappa \frac{m_1 m_2}{r} = -\frac{\kappa M^2}{\hbar c} \frac{\hbar c}{M} \frac{m_1}{r} \frac{m_2}{M} = -\alpha_G \mu_1 \mu_2 \frac{\hbar c}{r}$$

$$\alpha_G = 1 \Rightarrow M = \sqrt{\frac{\hbar c}{\kappa}} = \sqrt{\frac{\hbar c}{6,709 \cdot 10^{-39} \hbar c \text{ GeV}^{-2}}} = 1,22 \cdot 10^{19} \text{ GeV} = M_{\text{Planck}}$$

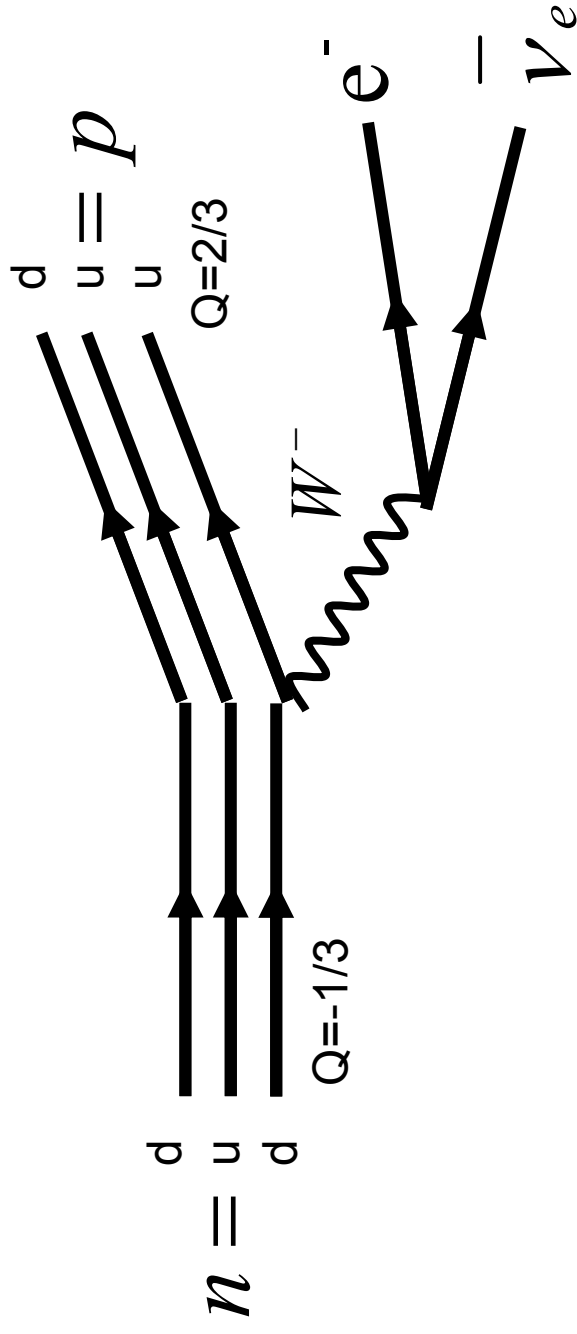
$$M_{\text{Planck}} = 1,22 \cdot 10^{19} \text{ GeV} = \frac{1,22 \cdot 10^{19} \cdot 10^9 \cdot 1,6 \cdot 10^{-19}}{9 \cdot 10^{16}} \text{ kg} = 0,22 \cdot 10^{-7} \text{ kg} = 22 \mu\text{g}$$

Gravitační interakce je mnohem slabší než ostatní síly. Kousky hmoty  $10^{19} \text{ GeV}$  se přitahují stejně silně jako dva elementární náboje.

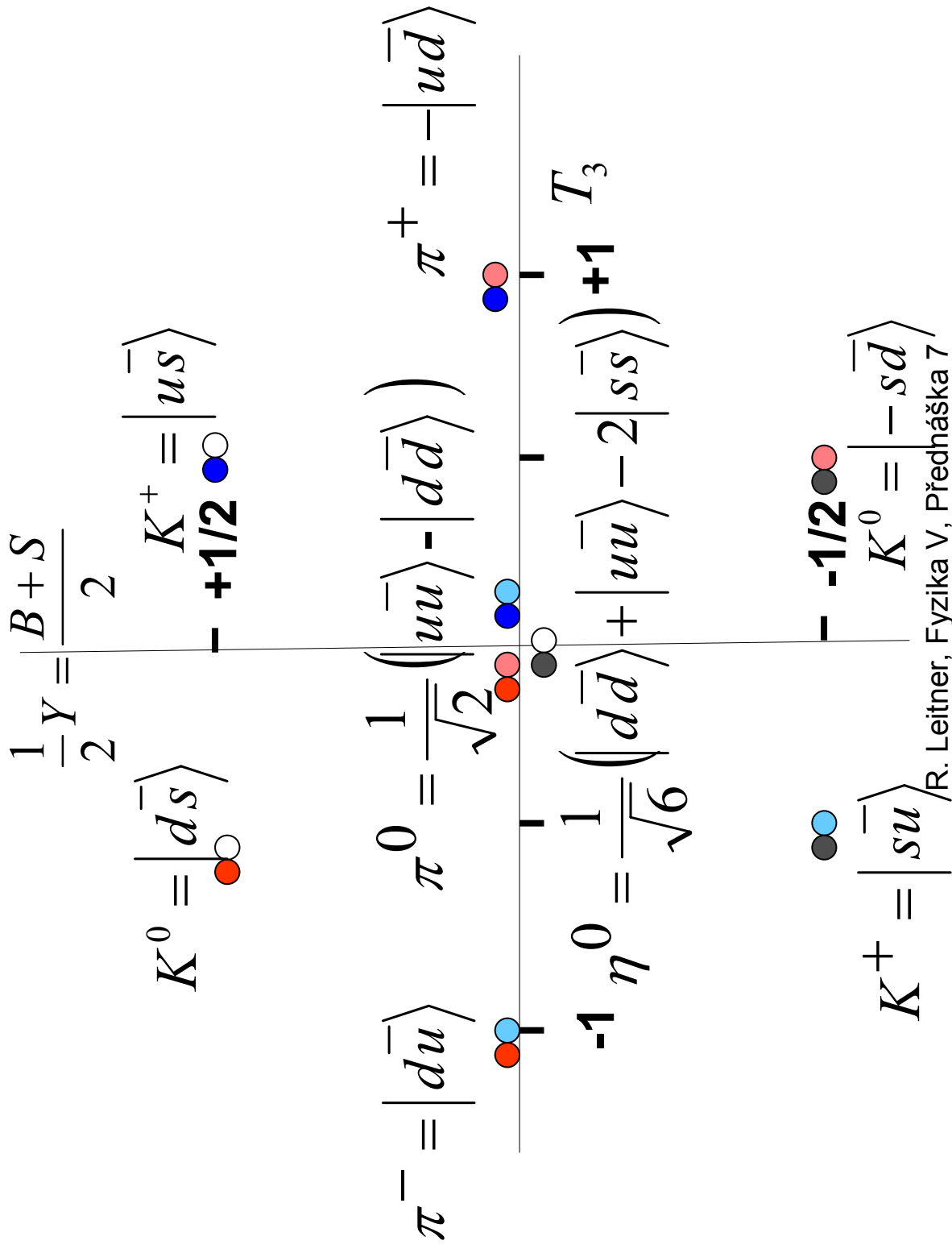
# Rozpad neutronu



## Na úrovni kvarků



# Oktet pseudoskalárních mezonů



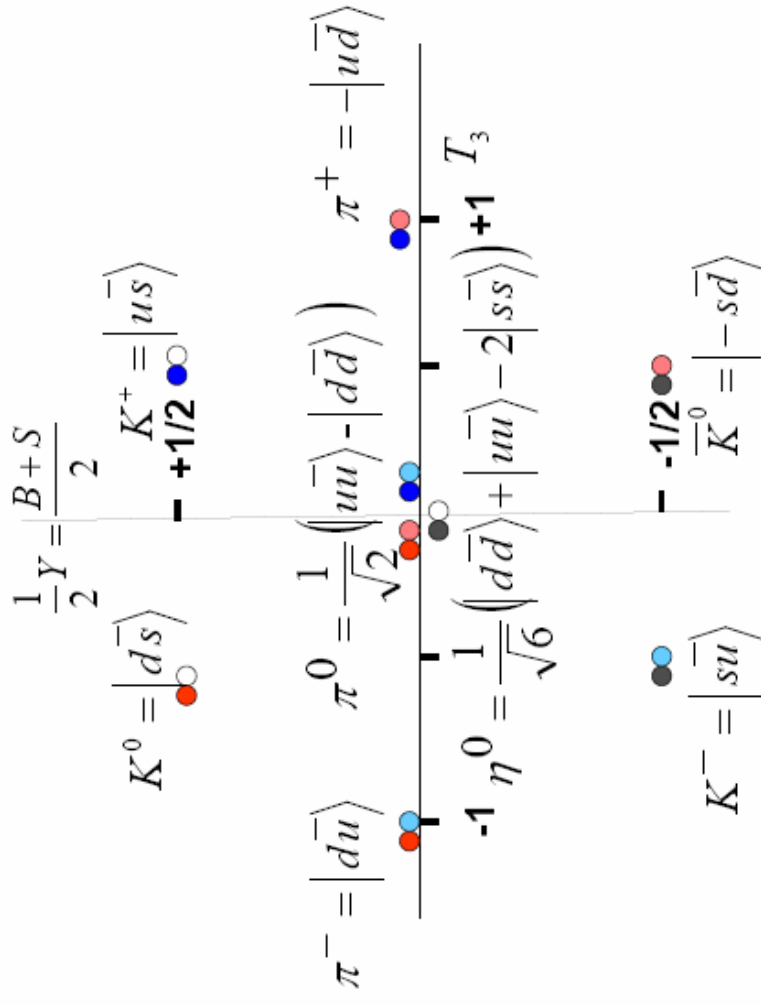
$$J^P = 0^-$$

Spin a parita

$$L_{qq}^- = 0, \quad S_{qq}^- = 0 \Rightarrow J = 0$$

$$P = P_q \cdot P_q^- \cdot (-1)^L = -1$$

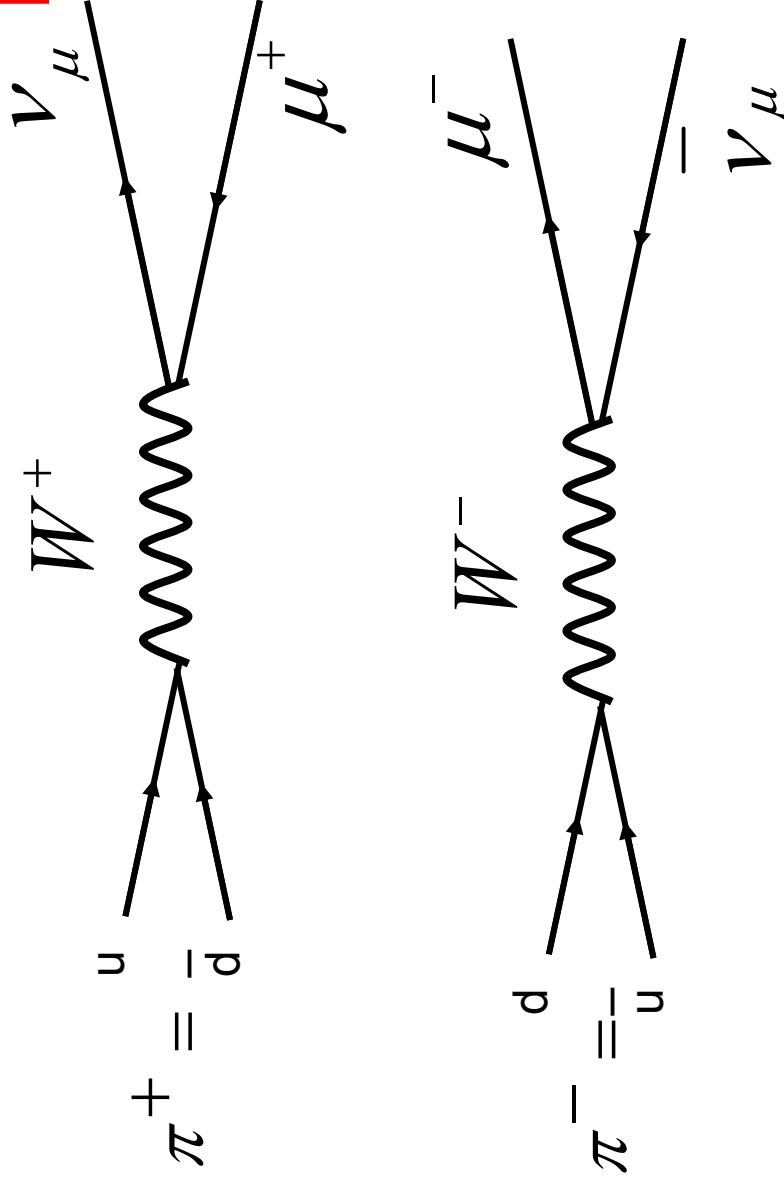
### Oktet pseudoskalárních mezonů



# Triplet pi mezonů

$$\underline{\pi^-}, \pi^0, \underline{\pi^+}$$

$$m_{\pi^\pm} = 140 \text{ MeV} > m_{\mu^\pm} = 106 \text{ MeV}$$



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Oktet pseudoskalárních mezonů

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

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

$$+1/2$$

$$\pi^- = |d\bar{u}\rangle \quad \pi^0 = \frac{1}{\sqrt{2}}(|u\bar{u}\rangle - |d\bar{d}\rangle) \quad \pi^+ = |u\bar{d}\rangle$$

$$-1 \quad \eta^0 = \frac{1}{\sqrt{6}}(|d\bar{d}\rangle + |u\bar{u}\rangle - 2|s\bar{s}\rangle) \quad +1$$

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

$$-1/2$$

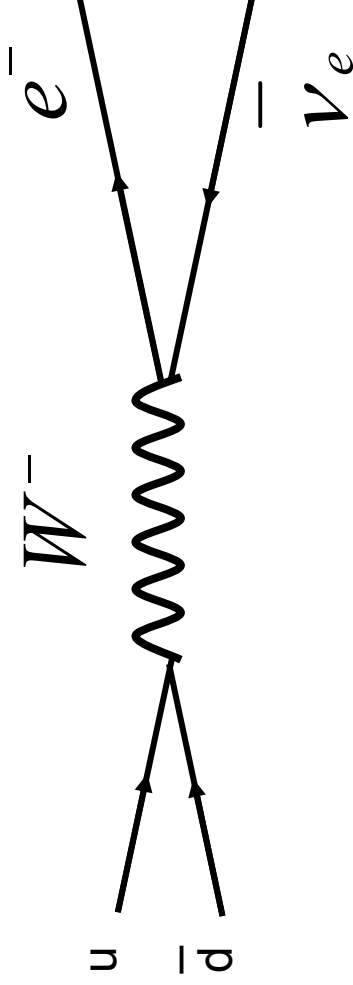
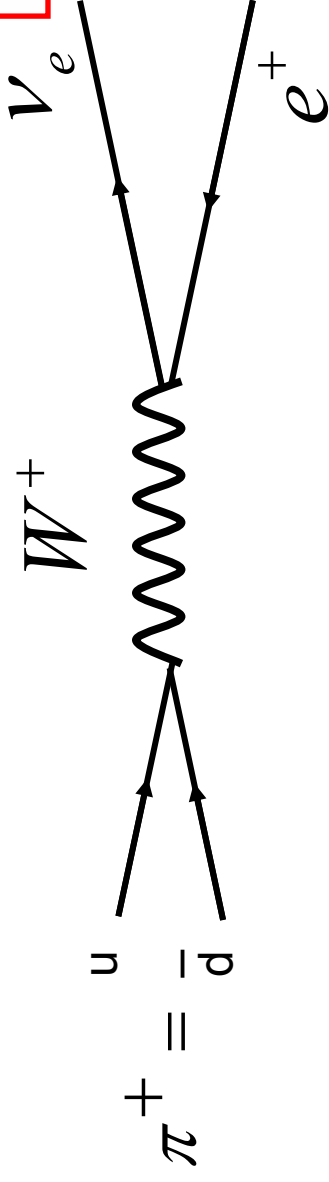
$$\pi \rightarrow \mu + \nu_\mu, \quad 99,9\%$$

$$c\tau = 7,8m$$

$$\tau = \frac{7,8m}{3 \cdot 10^8 m s^{-1}} = 26ns$$

# Triplet pi mezonů

$$\underline{\pi}^{-}, \pi^0, \underline{\pi}^{+}$$



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Oktet pseudoskalárních mezonů

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

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

$$+1/2$$

$$\pi^- = |d\bar{u}\rangle \quad \pi^0 = \frac{1}{\sqrt{2}}(|u\bar{u}\rangle - |d\bar{d}\rangle) \quad \pi^+ = |u\bar{d}\rangle$$

$$-1 \quad \eta^0 = \frac{1}{\sqrt{6}}(|d\bar{d}\rangle + |u\bar{u}\rangle - 2|s\bar{s}\rangle) \quad +1$$

$$K^- = |s\bar{u}\rangle$$

$$-1/2$$

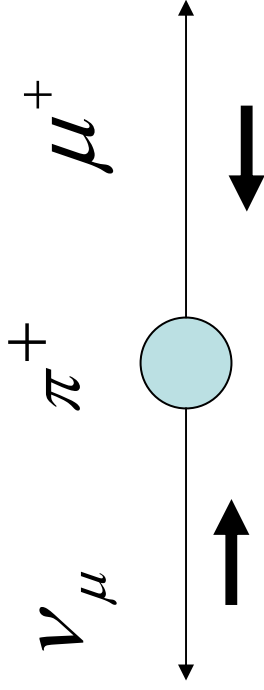
$$\bar{K}^0 = |s\bar{d}\rangle$$

$$\pi \rightarrow e + \nu_e, \quad 1,2 \cdot 10^{-4}$$

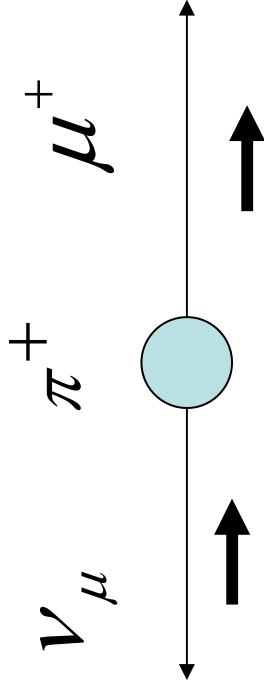
???



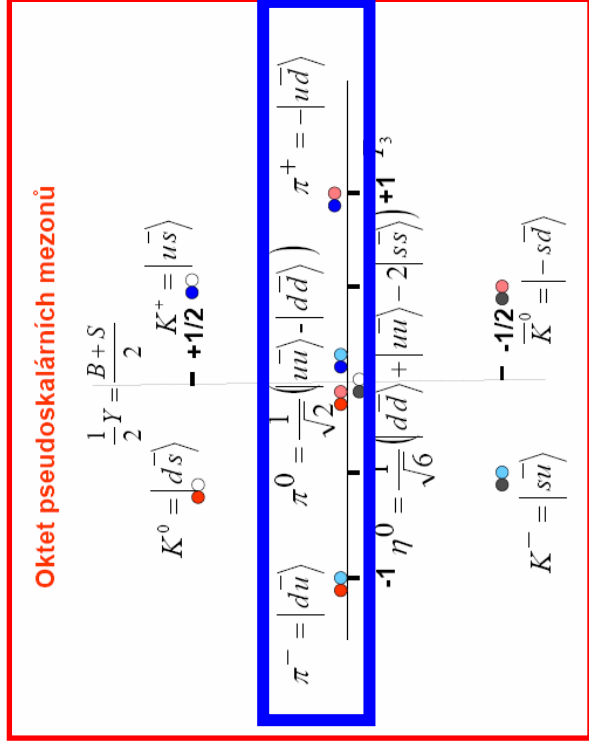
$J=0$



Ale ve slabých interakcích mají být helicity=projekce spinu na směr pohybu  
záporné pro fermiony a kladné pro antifermiony:



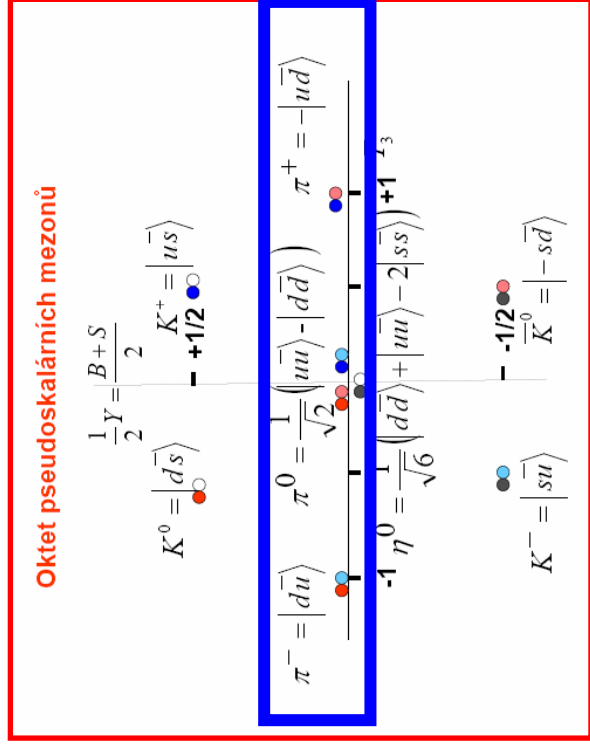
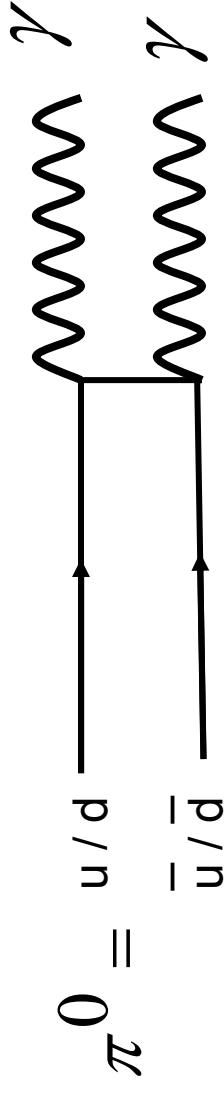
To ale nevyhovuje zákonu zachování momentu hybnosti.



# Triplet pi mezonů

$$\pi^-, \pi^0, \pi^+$$

$$m_{\pi^0} = 135 \text{ MeV} < m_{\pi^\pm} = 140 \text{ MeV}$$



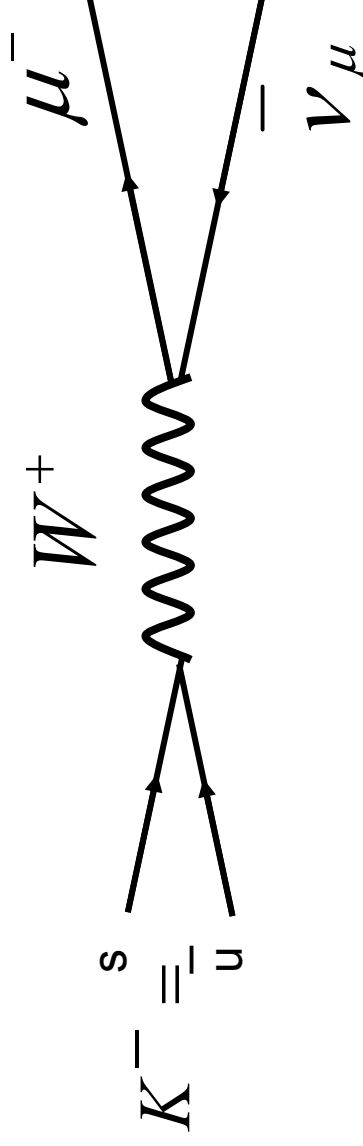
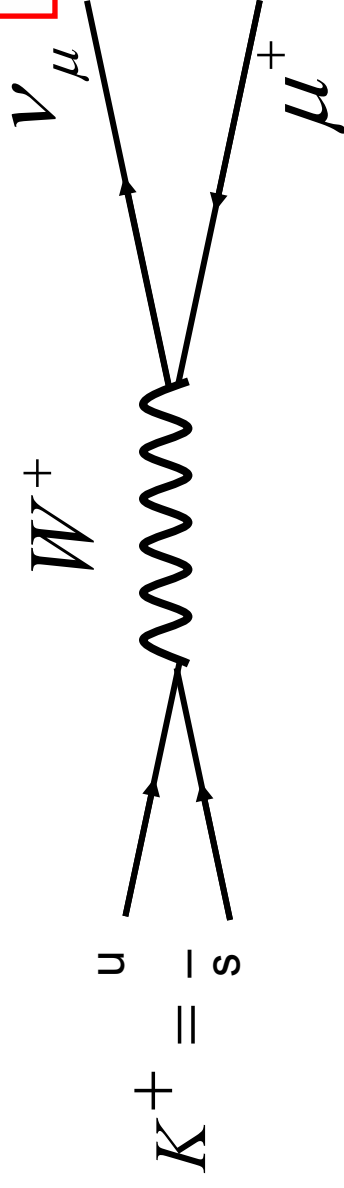
$$\pi^0 \rightarrow \gamma + \gamma, \quad 99,8\%$$

$$c\tau = 25 \text{ nm}$$

# Nabité K-mezony

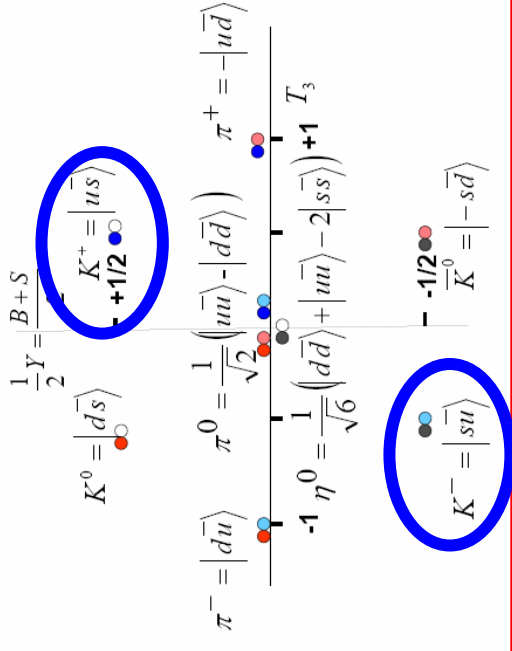
$$K^-, K^+$$

$$m_{K^\pm} = 494 \text{ MeV}$$



R. Leitner, Fyzika V, Přednáška 7

Oktet pseudoskalárních mezonů



Leptonový rozpad

$$K \rightarrow \mu + \nu_\mu, \quad 63\%$$

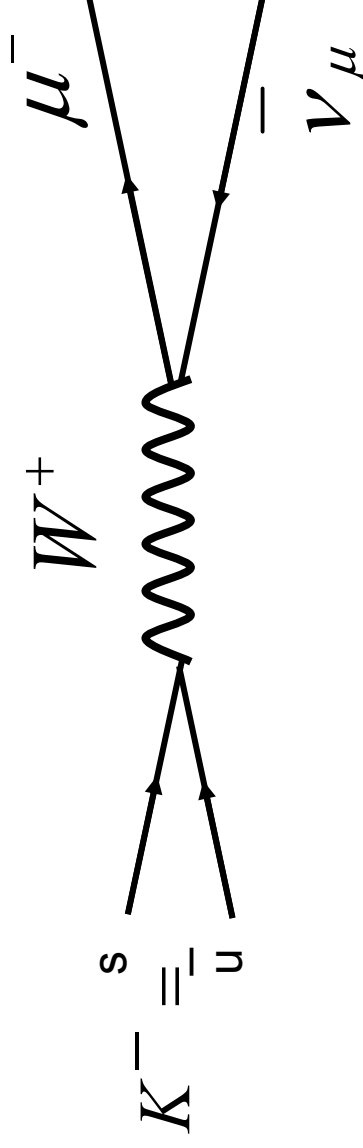
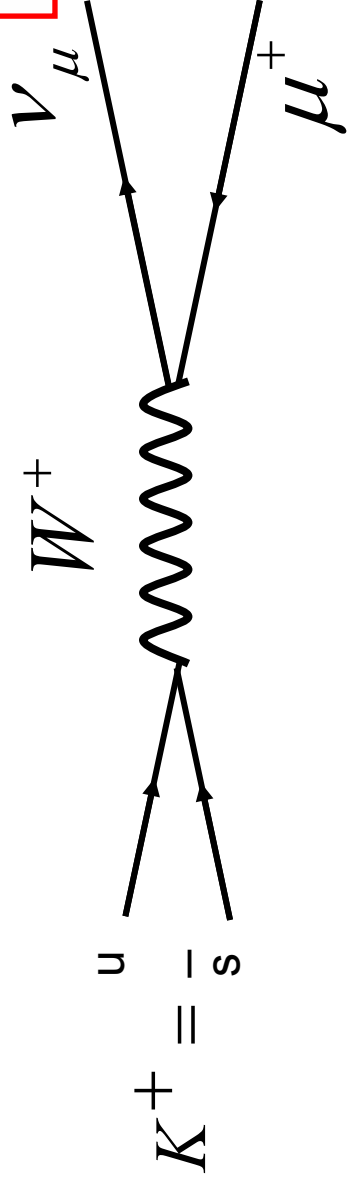
$$c\tau = 3,7m$$

$$\tau = \frac{3,7m}{3 \cdot 10^8 m s^{-1}} = 12 ns$$

# Nabité K-mezony

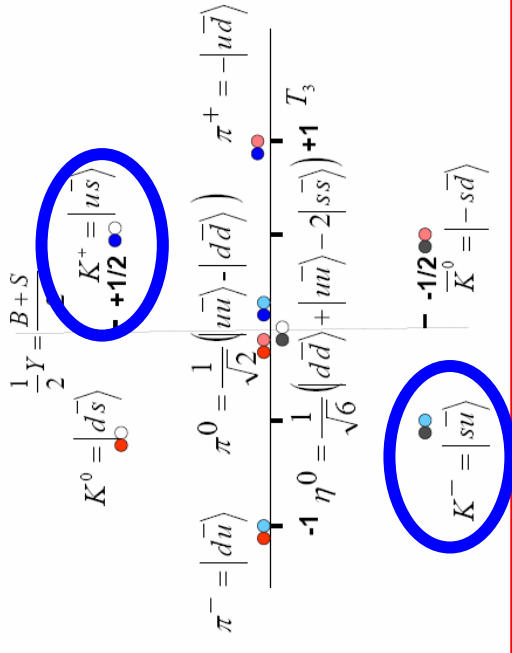
$$K^-, K^+$$

$$m_{K^\pm} = 494 \text{ MeV}$$



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Oktet pseudoskalárních mezonů



$$K \rightarrow \mu + \nu_\mu, \quad 63\%$$

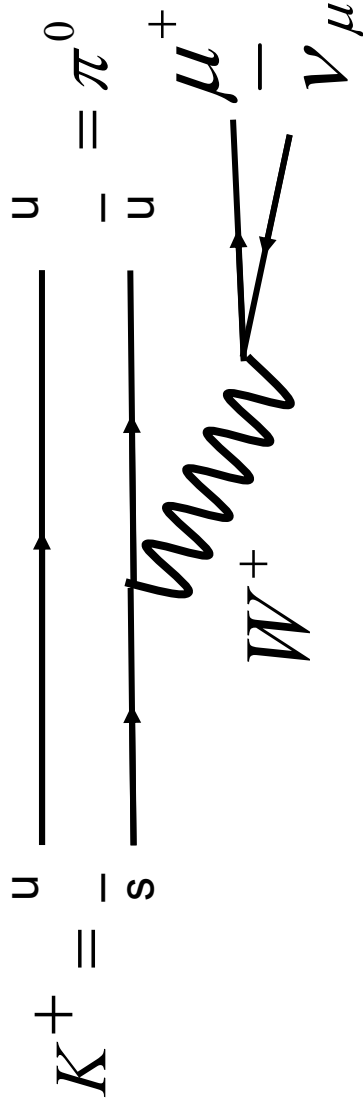
$$c\tau = 3,7m$$

$$\tau = \frac{3,7m}{3 \cdot 10^8 m s^{-1}} = 12 ns$$

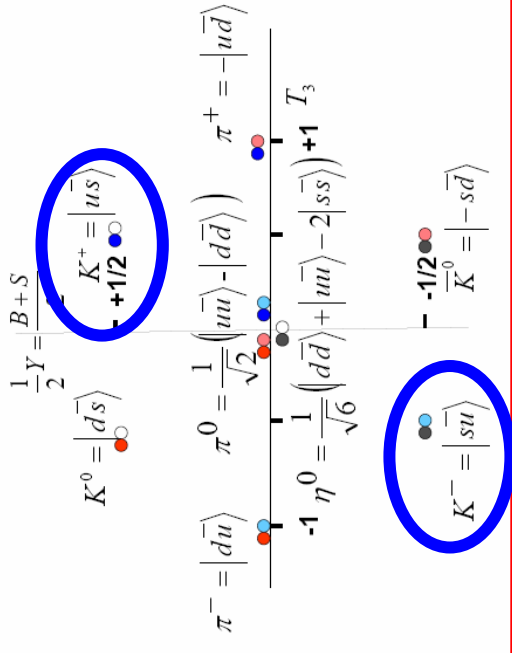
# Nabité K-mezony

$$K^-, K^+$$

$$m_{K^\pm} = 494 \text{ MeV}$$



Oktet pseudoskalárních mezonů



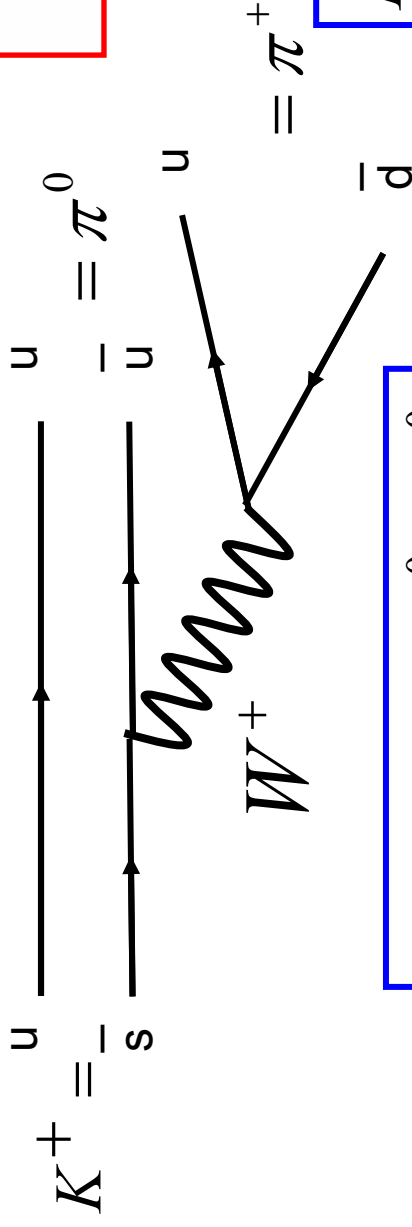
Semileptonový rozpad

$$K \rightarrow \pi^0 + e + \nu_e, \quad 5\%$$

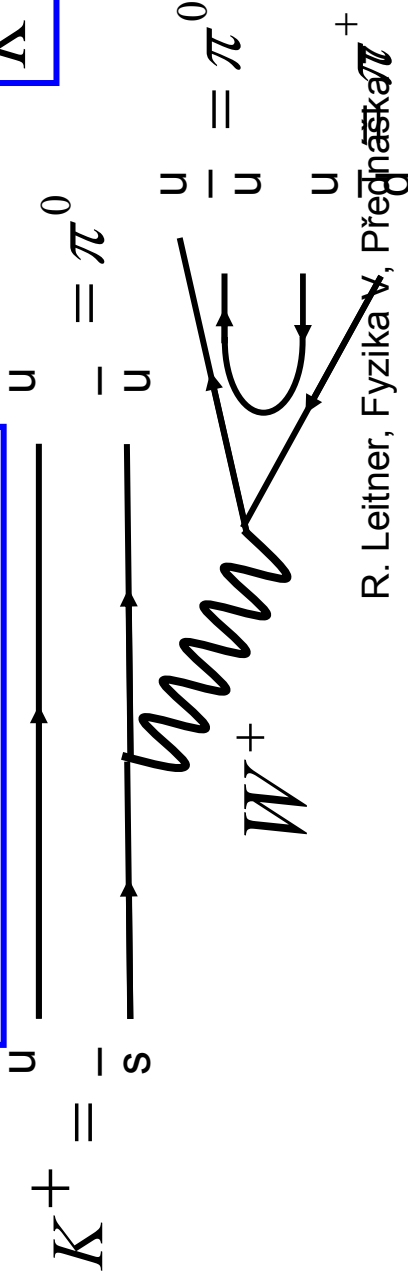
$$K \rightarrow \pi^0 + \mu + \nu_\mu, \quad 3\%$$

# Nabité K-mezony

$$K^-, K^+ \quad m_{K^\pm} = 494 \text{ MeV}$$

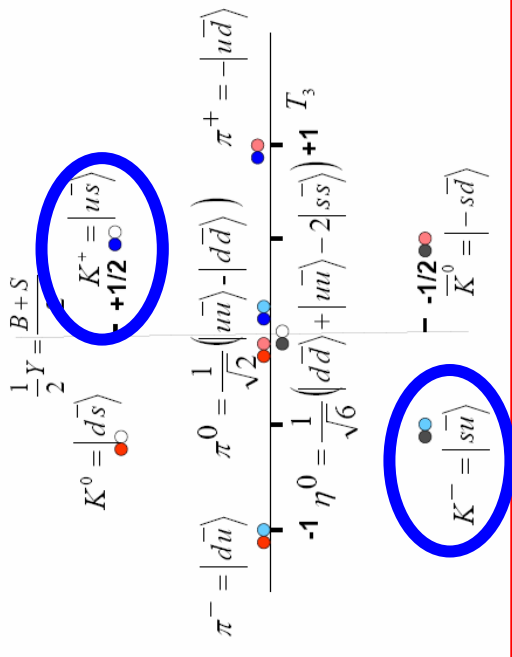


$$K^+ \rightarrow \pi^+ + \pi^0 + \pi^0$$



R. Leitner, Fyzika V, Přednáška 11

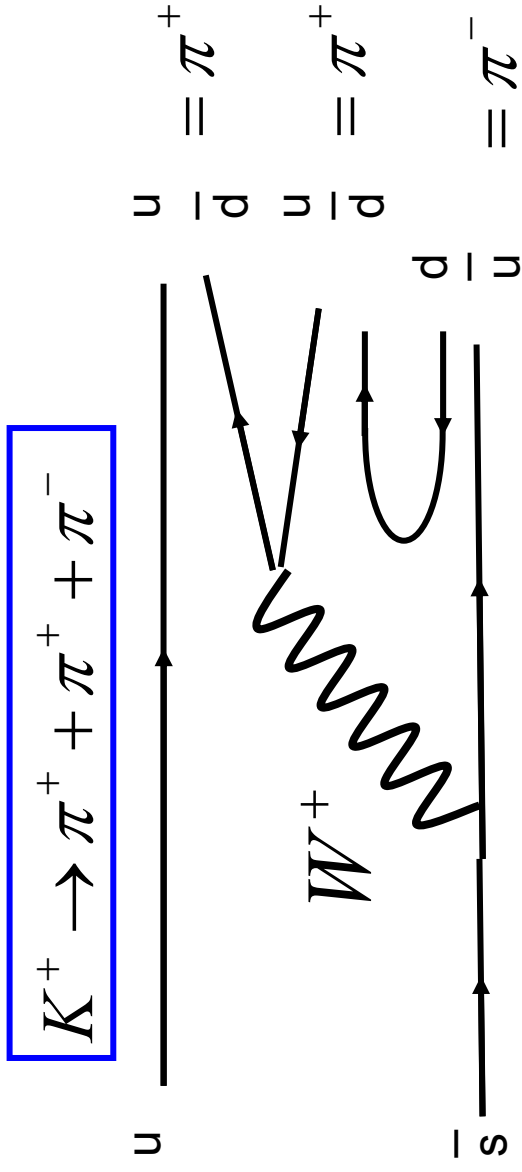
Oktet pseudoskalárních mezonů



Bezleptonový rozpad

$$K \rightarrow \pi^0 + \pi, 21\%$$

$$K \rightarrow \pi + \pi + \pi, 7,5\%$$



$K^+ \rightarrow \pi^+ + \pi^0$

$$P_K = P_\pi \cdot P_\pi \cdot (-1)^{L=0} = +1$$

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

$$P_K = P_\pi (= -1) \cdot P_\pi \cdot P_\pi \cdot (-1)^{L=0} = -1$$

**Zachovává se parita ve slabých rozpadech?**