

# Podivný mikrosvet

Mikuláš Gintner

Katedra fyziky, Žilinská univerzita

ÚTEF ČVUT Praha

2021

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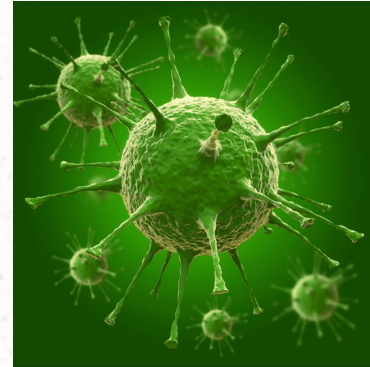
2021



# 1. Mikrosvet

# Mikrosvet ...

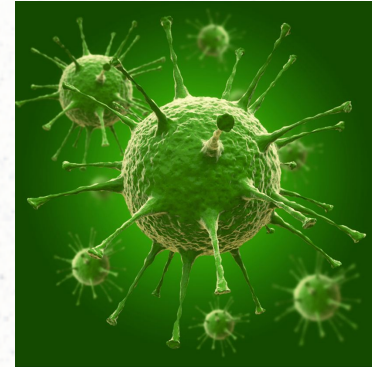
biológov  
 $\mu$ -svet



$\leq 10^{-4}$  m

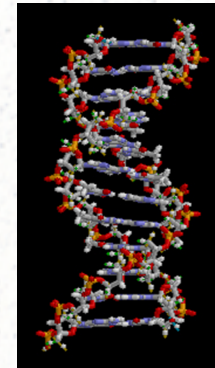
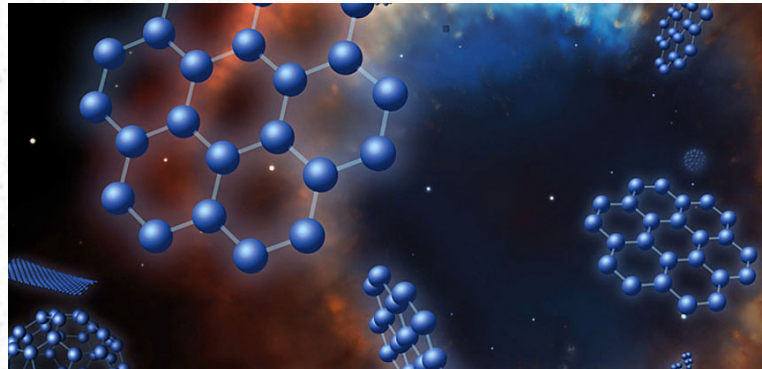
# Mikrosvet ...

biológov  
 $\mu$ -svet



$\leq 10^{-4}$  m

chemikov  
 $\mu$ -svet



$\leq 10^{-9}$  m

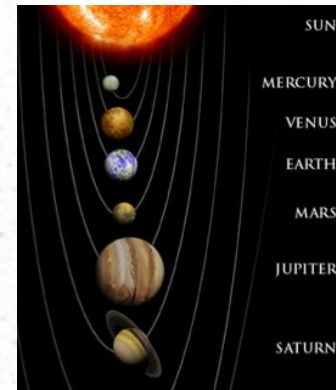
# Mikrosvet ...



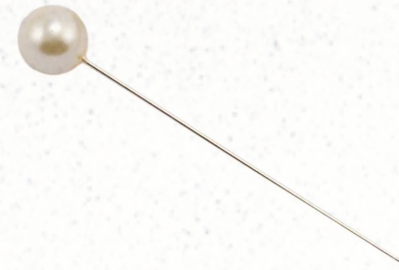
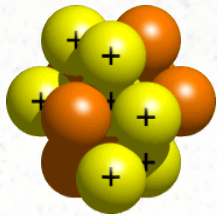
fyzikov  
 $\mu$ -svet



# Fyzikov mikrosvet ...



1 000 000 000 000 000  
×

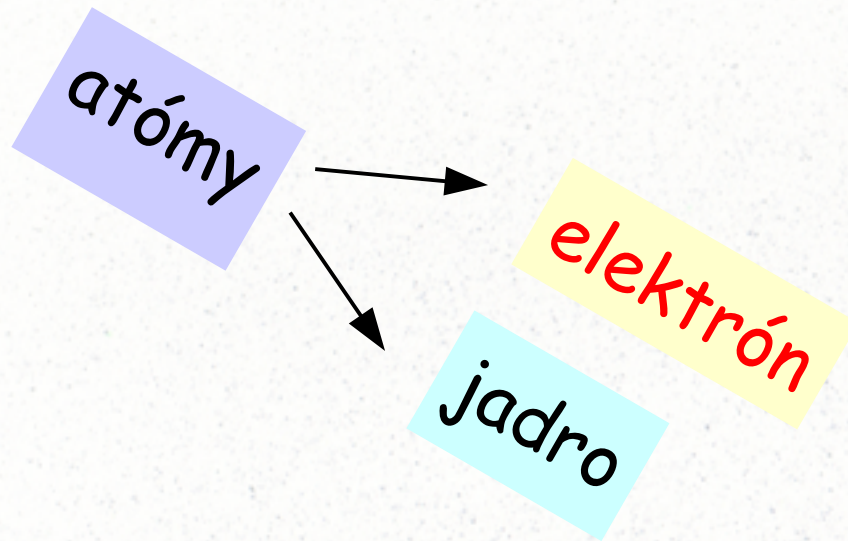


# Fyzikov mikrosvet ...

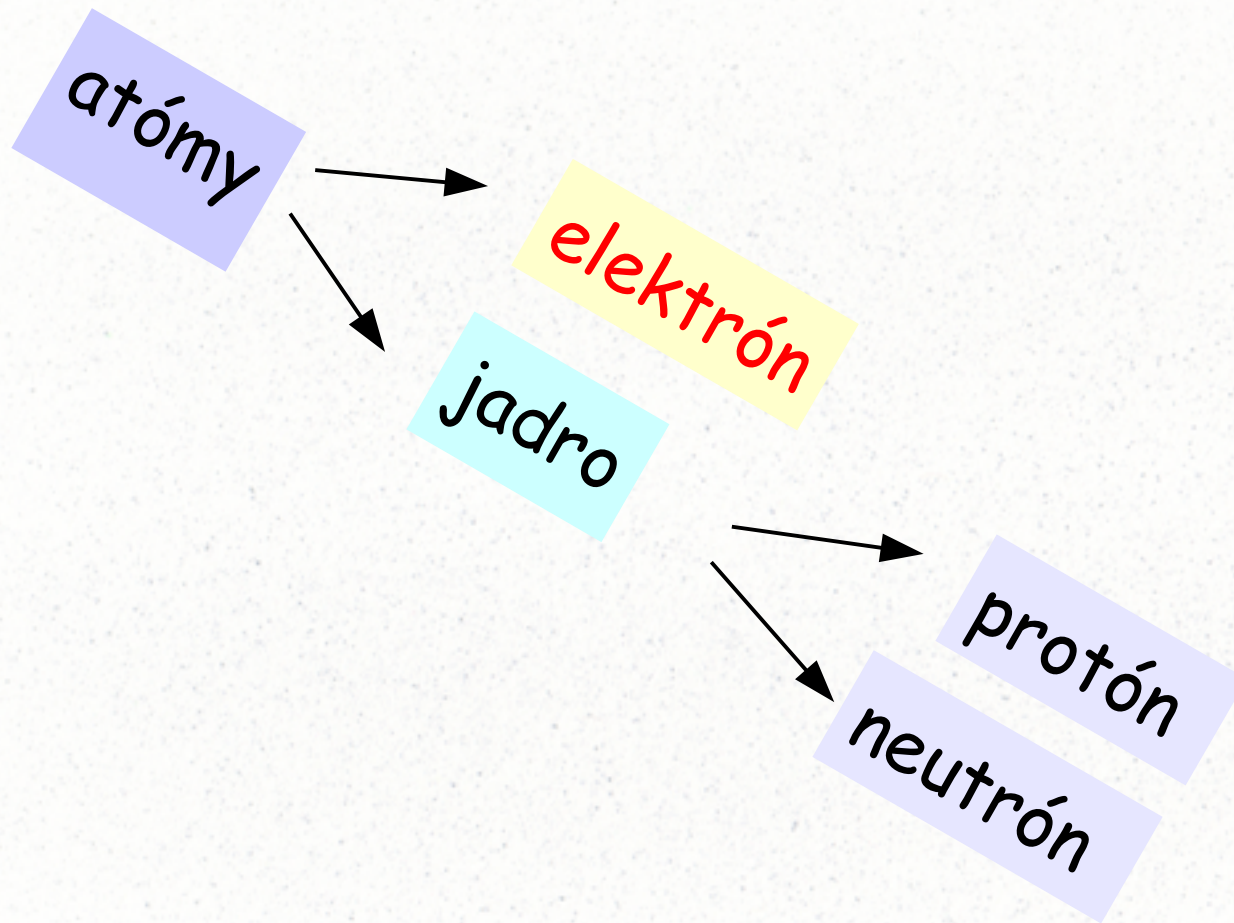
atómy



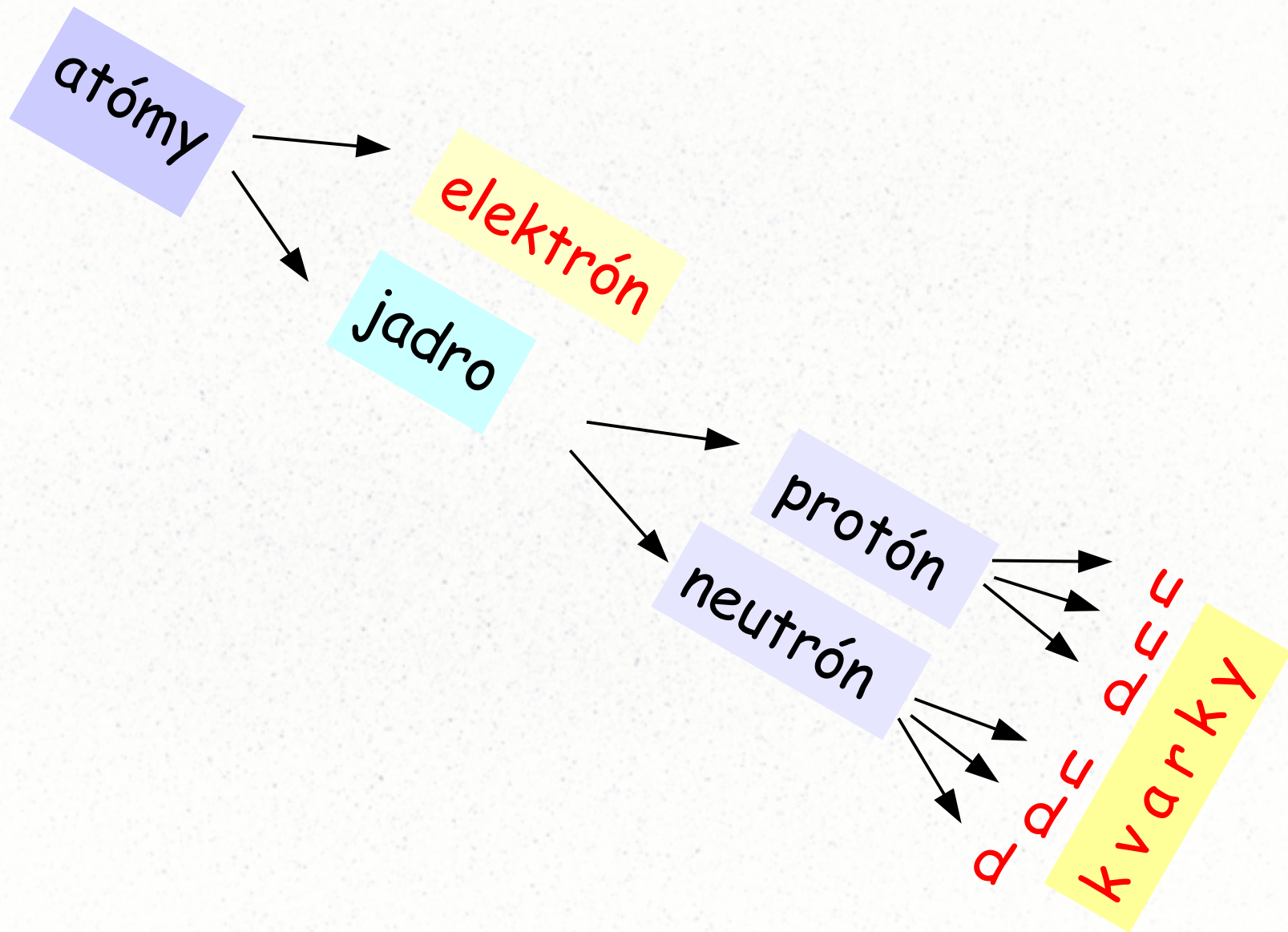
# Fyzikov mikrosvet ...



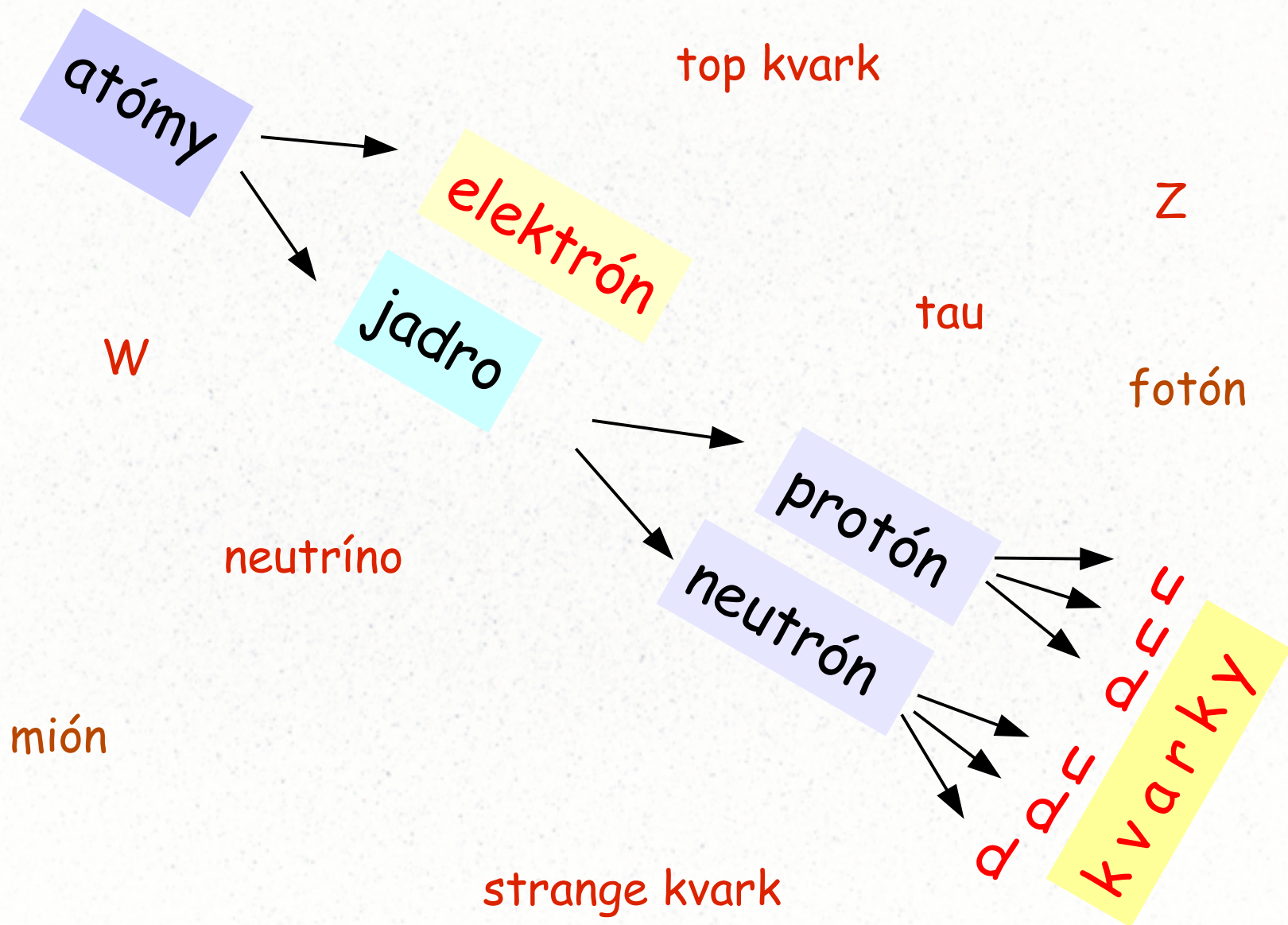
# Fyzikov mikrosvet ...



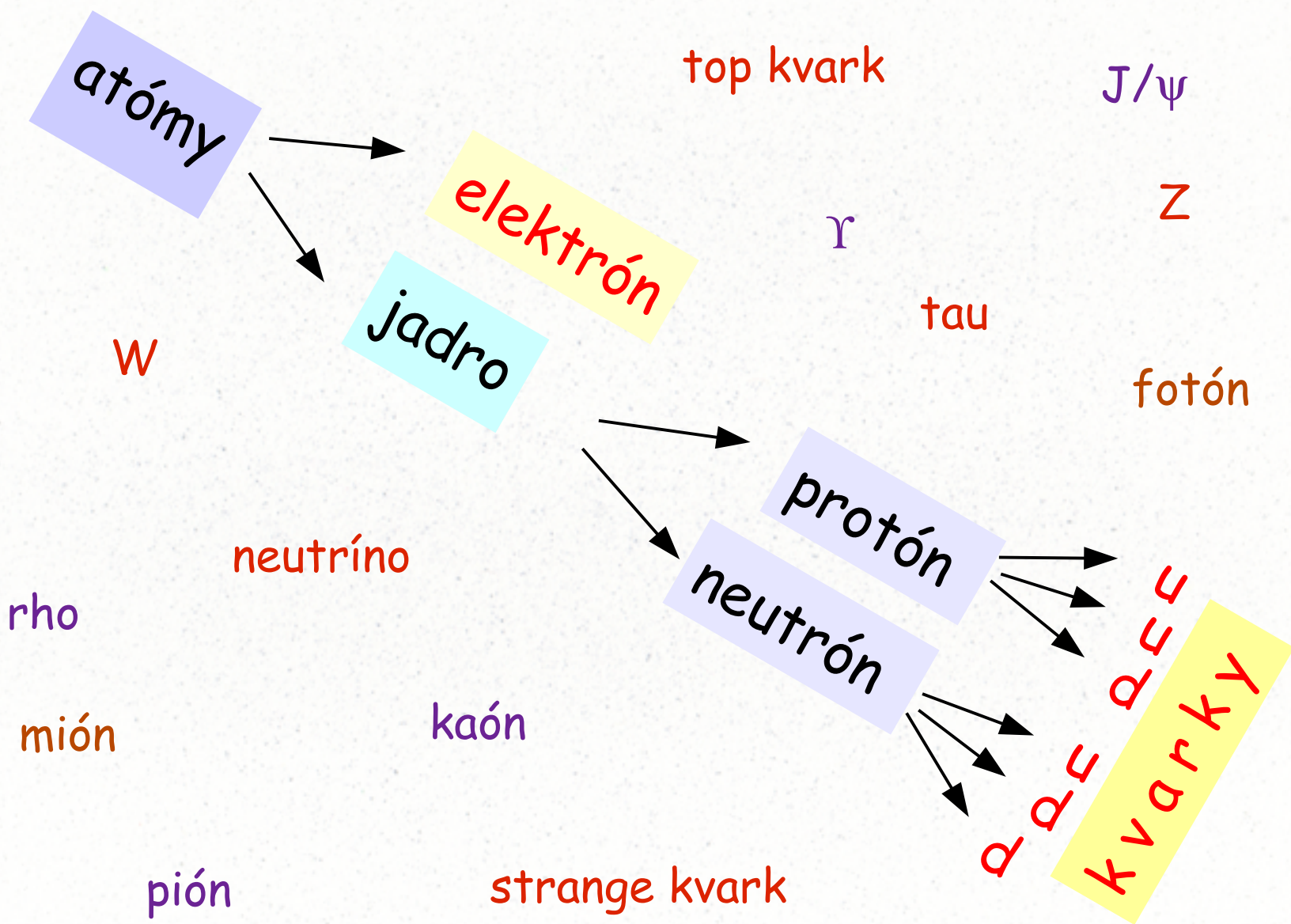
# Fyzikov mikrosvet ...



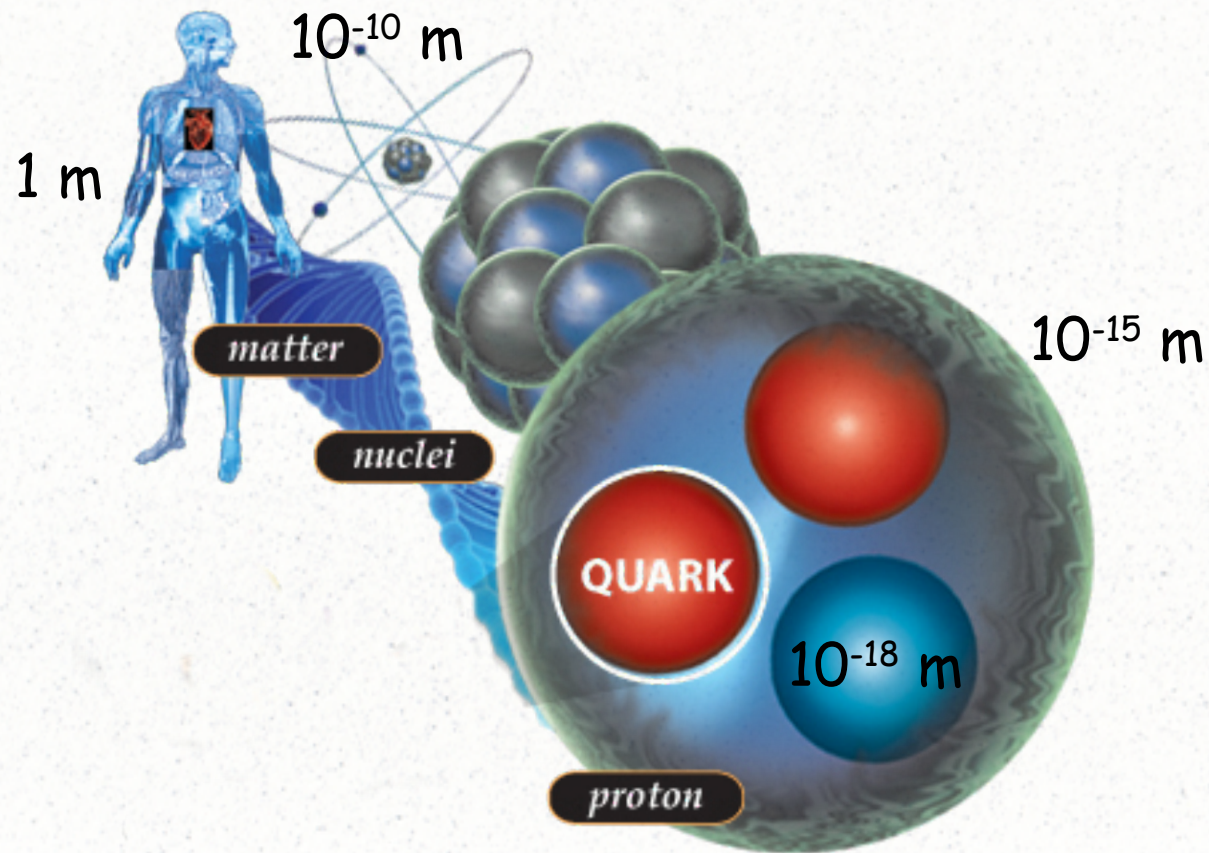
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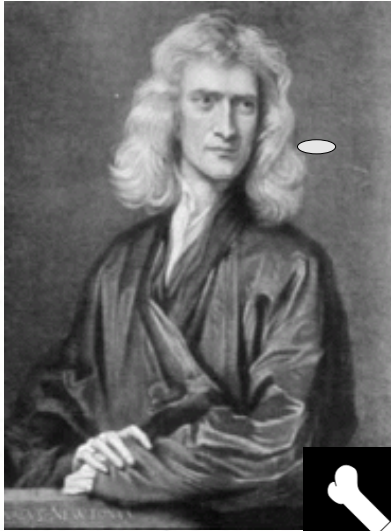
# Fyzikov mikrosvet ...



# Prečo častice držia pokope ?



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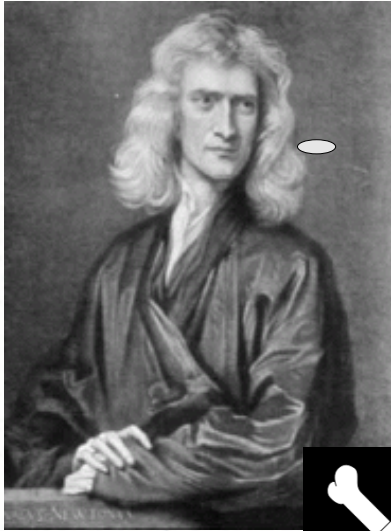


Sily!

you silly!

$$\vec{F} = m \cdot \vec{a}$$

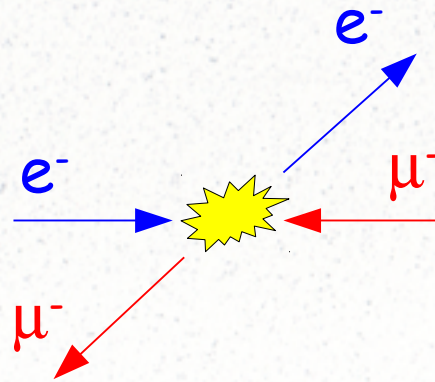
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$$\vec{F} = m \cdot \vec{a}$$





# Profi-športovci sa vždy spoliehali na Newtona ...



Kobe Bryant

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$$\vec{F} = m \cdot \vec{a}$$



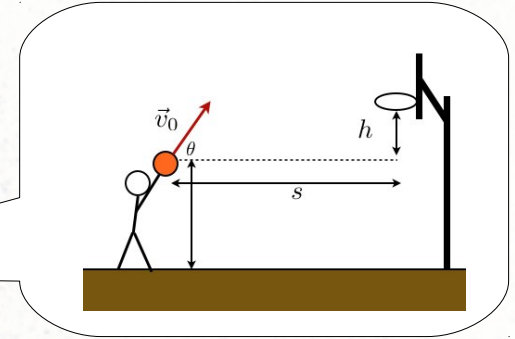
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Kobe Bryant

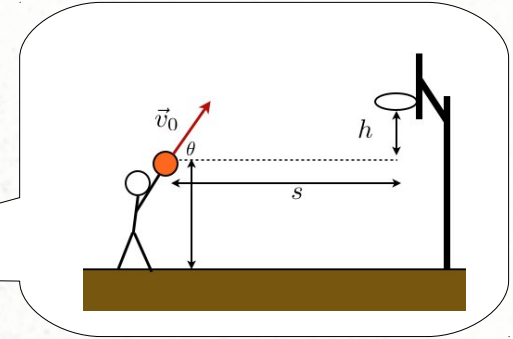


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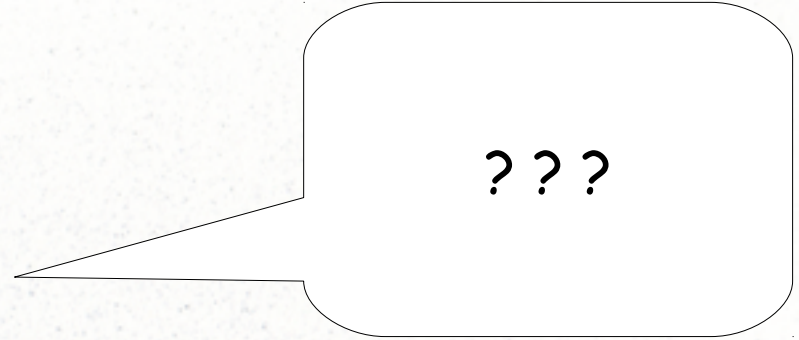
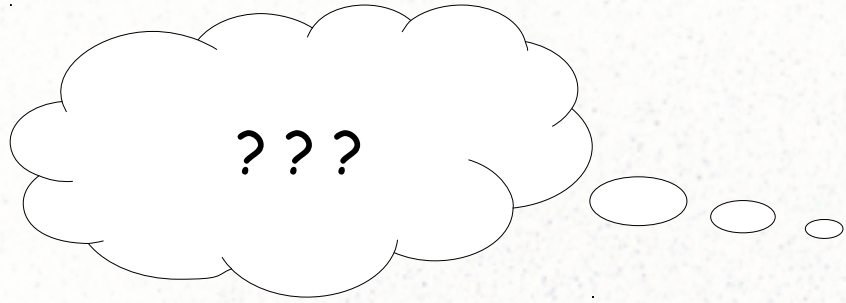
$$\vec{F} = m \cdot \vec{a}$$



Kobe Bryant



# Basketbal v mikrosvete



# Kobeho cesta do mikrosveta ...

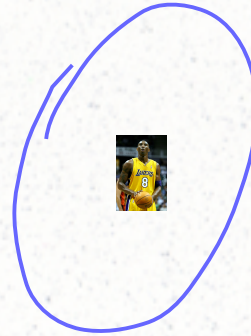


Kobe je tu!



# Kobeho cesta do mikrosveta ...

silná  
sila  
?



Kobe je tu!

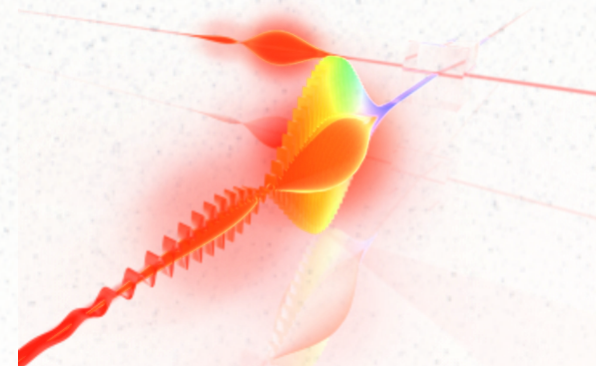
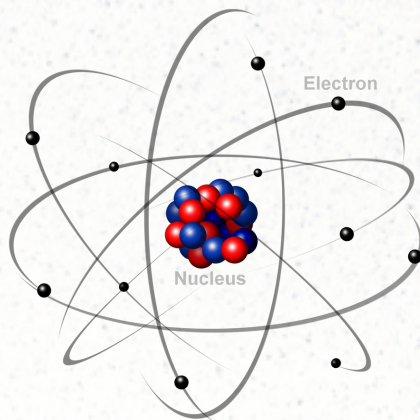
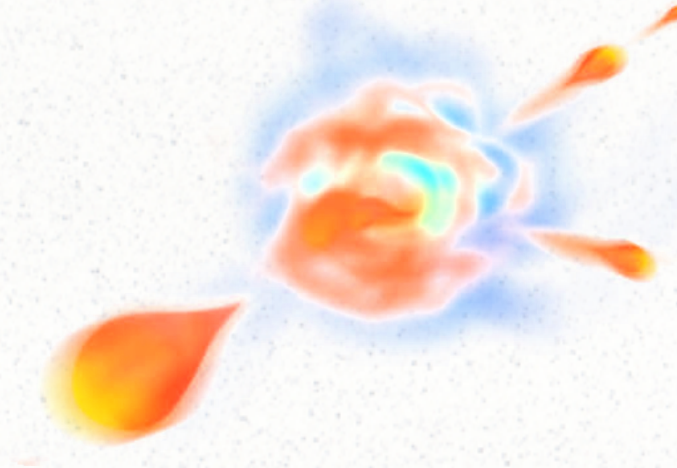
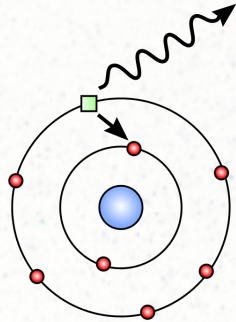


elektrón?



fotón?

# ako nevyzerá atóm, elektrón, fotón ...





# ako vyzerá atóm, elektrón, fotón ...

**Hydrogen Orbitals**       $Z = \text{charge nuclear}$

$= 1$  for Hydrogen  
 $a = r/a_0$   
 $a_0 = \text{Bohr radius}$

$n=1,2,3,\dots$	$l=0,1,2,\dots,n-1$	$m=0, \pm 1, \dots, \pm l$	$\psi_{nlm}$
1s	$n=1, l=0, m=0$		$\psi_{100} = \frac{1}{\sqrt{\pi}} \left(\frac{Z}{a_0}\right)^{3/2} e^{-\sigma}$
2s	$n=2, l=0, m=0$		$\psi_{200} = \frac{1}{\sqrt{32\pi}} \left(\frac{Z}{a_0}\right)^{3/2} (2-\sigma)e^{-\sigma/2}$
	p { $2p_z$	$l=1, m=0$	$\psi_{210} = \frac{1}{\sqrt{32\pi}} \left(\frac{Z}{a_0}\right)^{3/2} \sigma e^{-\sigma/2} \cos \theta$
		$l=1, m=\pm 1$	$\psi_{21\pm 1} = \frac{1}{\sqrt{64\pi}} \left(\frac{Z}{a_0}\right)^{3/2} \sigma e^{-\sigma/2} \sin \theta e^{\pm i\phi}$
3s	$n=3, l=0, m=0$		$\psi_{300} = \frac{1}{81\sqrt{3\pi}} \left(\frac{Z}{a_0}\right)^{3/2} (27-18\sigma+2\sigma^2)e^{-\sigma/3}$
	3p {	$l=1, m=0$	$\psi_{310} = \frac{1}{81} \left(\frac{2}{\pi}\right)^{1/2} \left(\frac{Z}{a_0}\right)^{3/2} (6\sigma-\sigma^2)e^{-\sigma/3} \cos \theta$
		$l=1, m=\pm 1$	$\psi_{31\pm 1} = \frac{1}{81\sqrt{\pi}} \left(\frac{Z}{a_0}\right)^{3/2} (6\sigma-\sigma^2)e^{-\sigma/3} \sin \theta e^{\pm i\phi}$
	3d {	$l=2, m=0$	$\psi_{320} = \frac{1}{81\sqrt{6\pi}} \left(\frac{Z}{a_0}\right)^{3/2} \sigma^2 e^{-\sigma/3} (3\cos^2 \theta - 1)$
		$l=2, m=\pm 1$	$\psi_{32\pm 1} = \frac{1}{81\sqrt{\pi}} \left(\frac{Z}{a_0}\right)^{3/2} \sigma^2 e^{-\sigma/3} \sin \theta \cos \theta e^{\pm i\phi}$
$l=2, m=\pm 2$		$\psi_{32\pm 2} = \frac{1}{162\sqrt{\pi}} \left(\frac{Z}{a_0}\right)^{3/2} \sigma^2 e^{-\sigma/3} \sin^2 \theta e^{\pm 2i\phi}$	

# ako vyzerá atóm, elektrón, fotón ...

**Hydrogen Orbitals**

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	$n=3, l=2, m=\pm 1$	3d <sub>xy, x<sup>2</sup>-y<sup>2</sup></sub>	$\psi_{32\pm 1} = \frac{1}{81\sqrt{\pi}} \left(\frac{Z}{a_0}\right)^{3/2} \sigma^2 e^{-\sigma/3} \sin \theta \cos \theta e^{\pm i\phi}$
	$n=3, l=2, m=\pm 2$	3d <sub>x<sup>2</sup>-y<sup>2</sup></sub>	$\psi_{32\pm 2} = \frac{1}{162\sqrt{\pi}} \left(\frac{Z}{a_0}\right)^{3/2} \sigma^2 e^{-\sigma/3} \sin^2 \theta e^{\pm 2i\phi}$

predstava ≠ pochopenie

predstavit' si  $\neq$  pochopit'



predstavit' si  $\neq$  pochopit'



3

predstavit' si  $\neq$  pochopit'



?

predstavit' si  $\neq$  pochopit'



predstavit' si  $\neq$  pochopit'



15

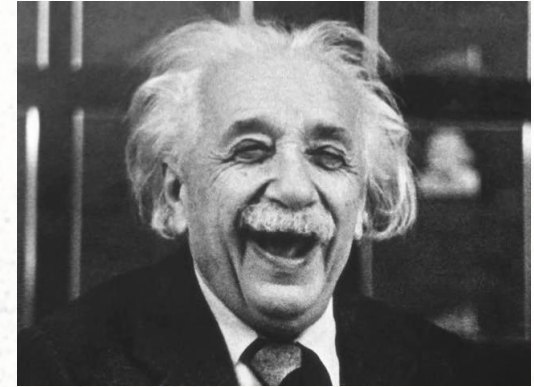
## 2. Hmotnosť



# hmotnosť sa nezachováva...

... je to **forma energie**

$$E = \sqrt{(mc^2)^2 + (\vec{p}c)^2}$$



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napr. *fotón*

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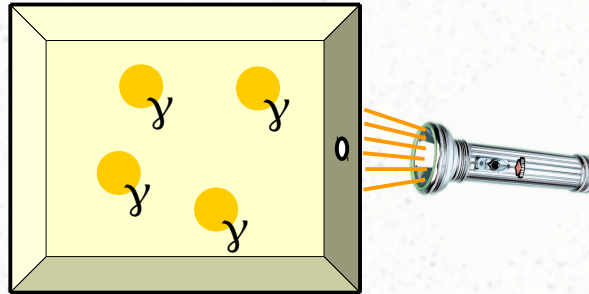
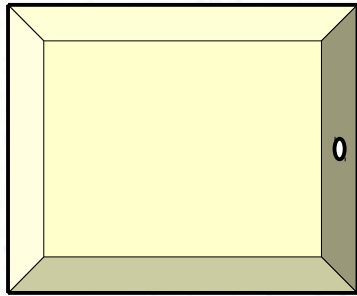
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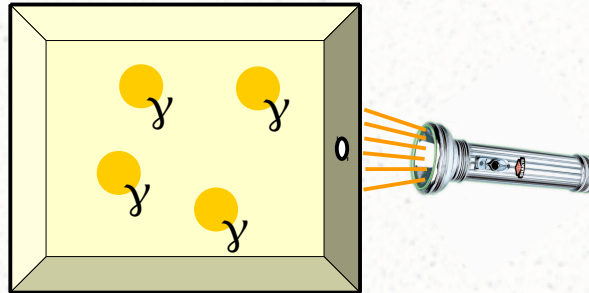
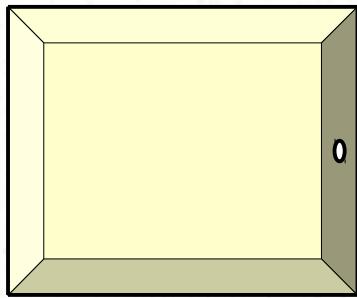
... ale energia áno

# hmotnosť sa nezachováva: Fotóny v krabici



$$M_{\text{box}} < M_{\text{box}'}$$

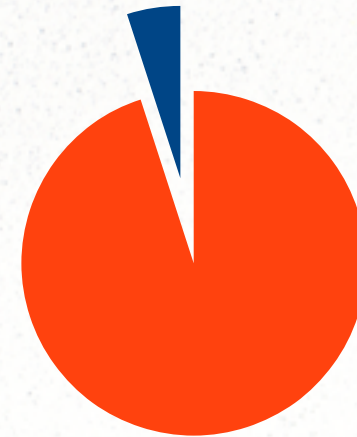
# hmotnosť sa nezachováva: Fotóny v krabici



$$M_{\text{box}} < M_{\text{box}'}$$



hmotnosť častíc 5%



energia častíc 95%





# hmotnosti v $\mu$ -svete ...

$$\left. \begin{array}{l} E = mc^2 \\ [E] = \text{eV} \end{array} \right\} \Rightarrow [m] = \text{eV}/c^2$$

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elektrón	1	0.5 MeV/c <sup>2</sup>
protón	1 880	1 GeV/c <sup>2</sup>
top kvark	344 000	175 GeV/c <sup>2</sup>
jadro Au	370 000	
jablko	1x10 <sup>29</sup>	

# hmotnosť sa nezachováva: Rozpady a zrážky

... časť  $M$  sa môže premeniť na **kinetickú energiu** ...



... alebo **naopak** ...



$$M \geq m_1 + m_2$$

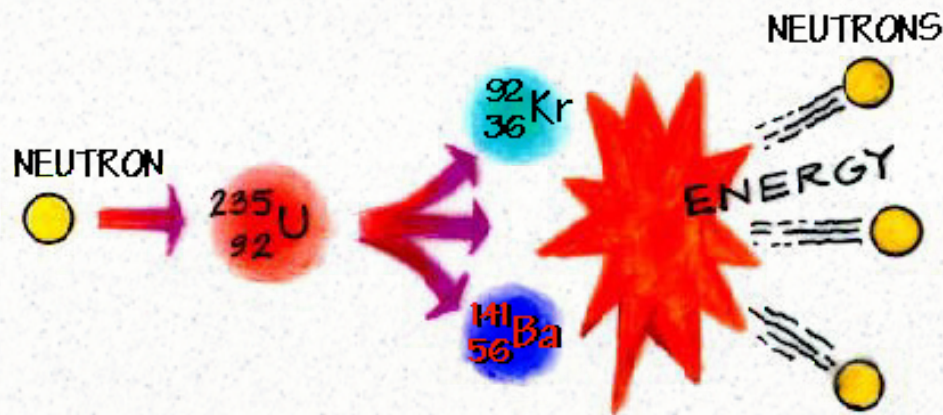
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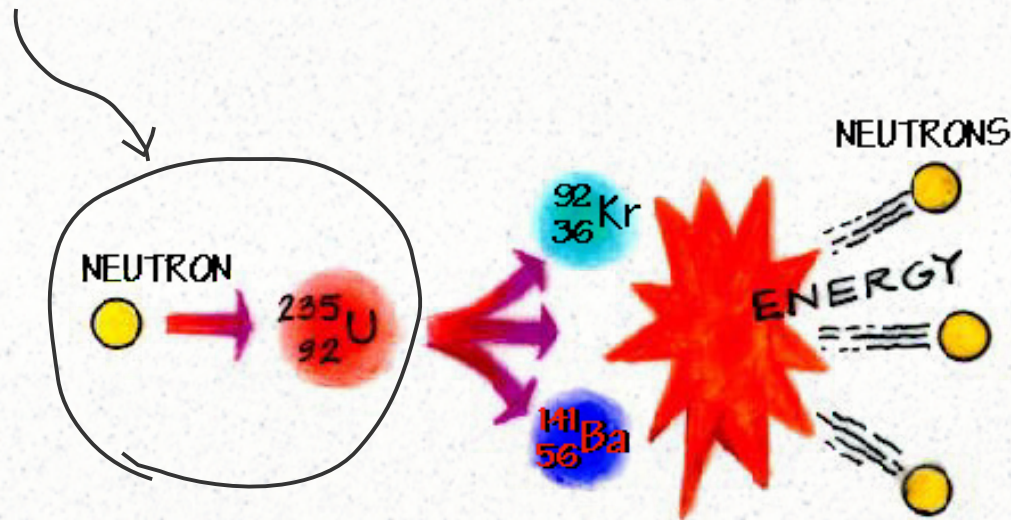


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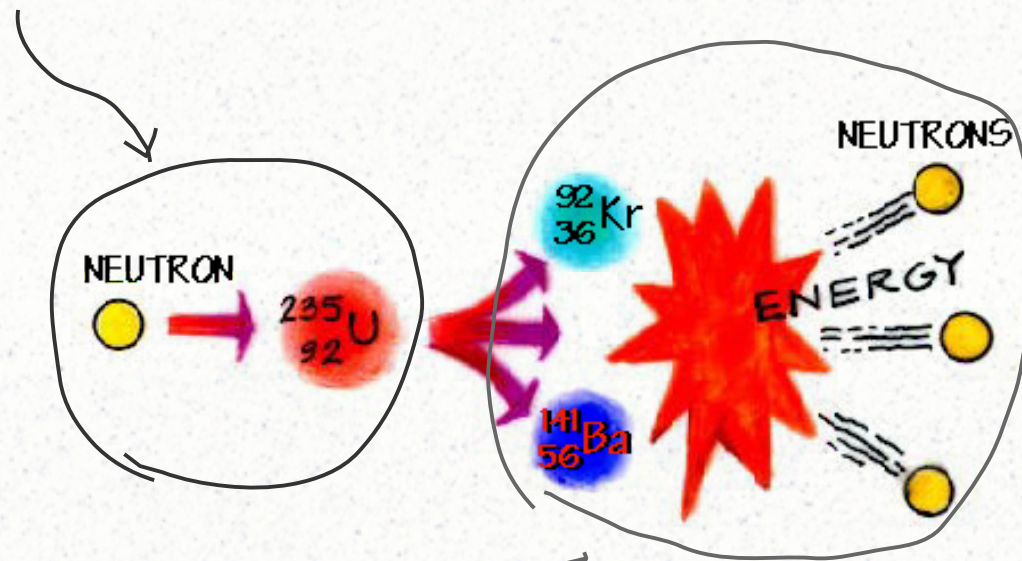
pred:  $m_n + M_U = 219881.6 \text{ MeV}/c^2$





# hmotnosť sa nezachováva: Jadrová reakcia

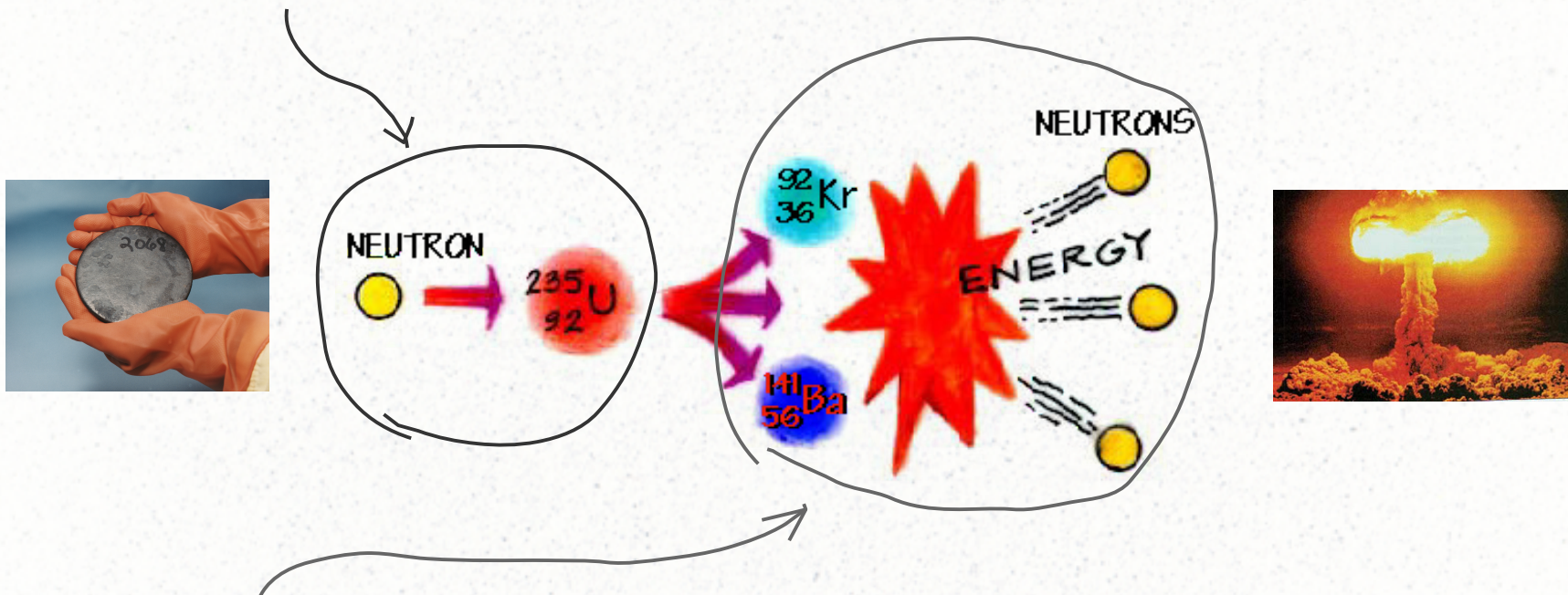
pred:  $m_n + M_U = 219881.6 \text{ MeV}/c^2$



po:  $M_{\text{Kr}} + M_{\text{Ba}} + 3m_n = 219707.7 \text{ MeV}/c^2$

# hmotnosť sa nezachováva: Jadrová reakcia

$$\text{pred: } m_n + M_U = 219881.6 \text{ MeV}/c^2$$



$$\text{po: } M_{\text{Kr}} + M_{\text{Ba}} + 3m_n = 219707.7 \text{ MeV}/c^2$$

$$\Delta M = 173.9 \text{ MeV}/c^2 \quad \Rightarrow \quad E = \Delta M \cdot c^2 = 173.9 \text{ MeV}$$

## 3. Sily v $\mu$ -svete

# 4 fundamentálne sily

*silná*

**elmag**

slabá

gravitačná

# 4 fundamentálne sily

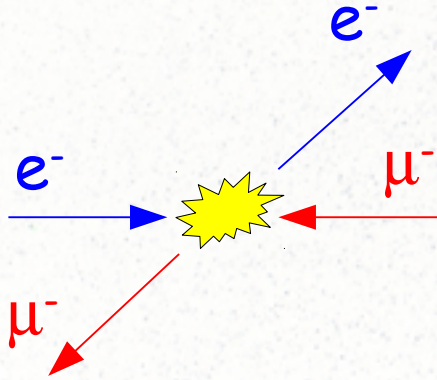


# 4 fundamentálne sily



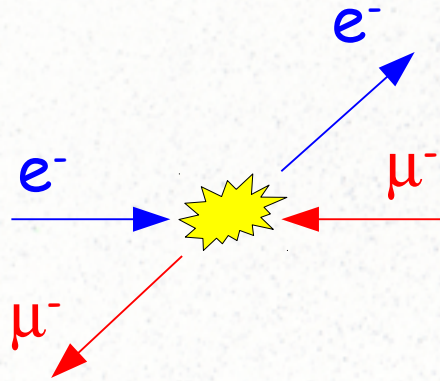
# сила в $\mu$ -svete ...

... zmena smeru a rýchlosti pohybu:

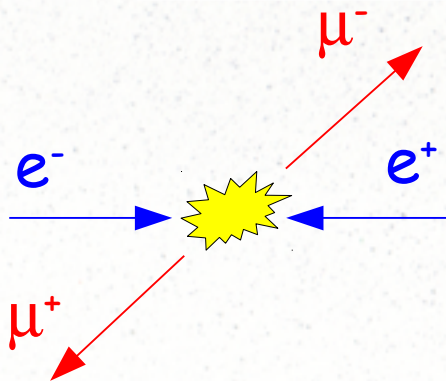


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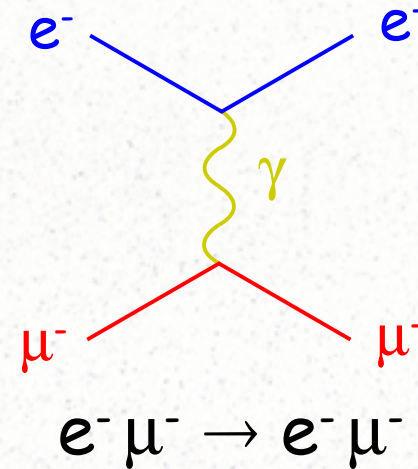
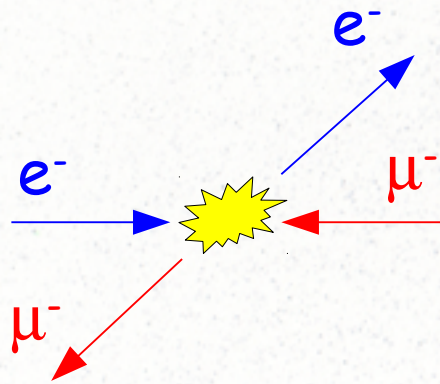
... vznik a zánik častíc:



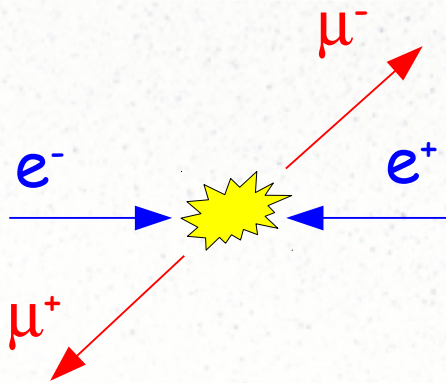


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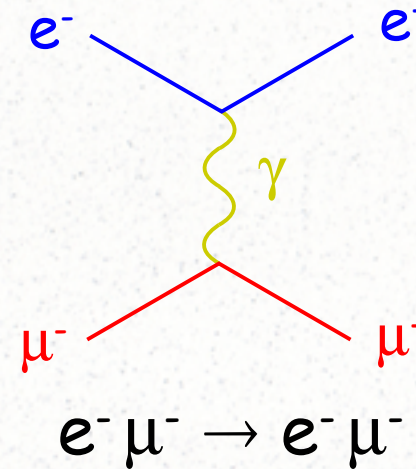
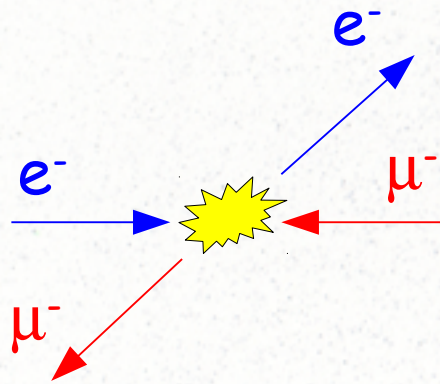


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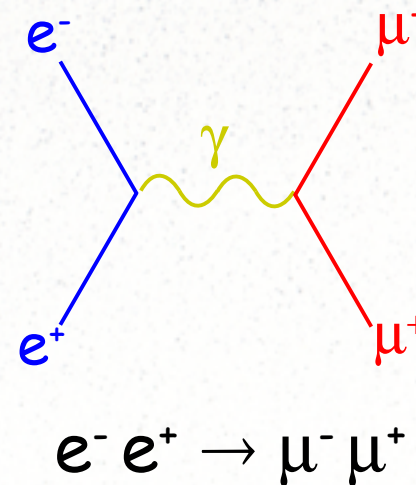
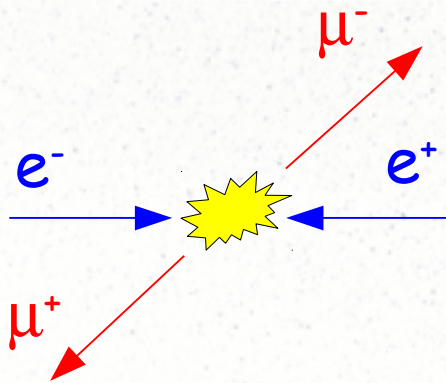


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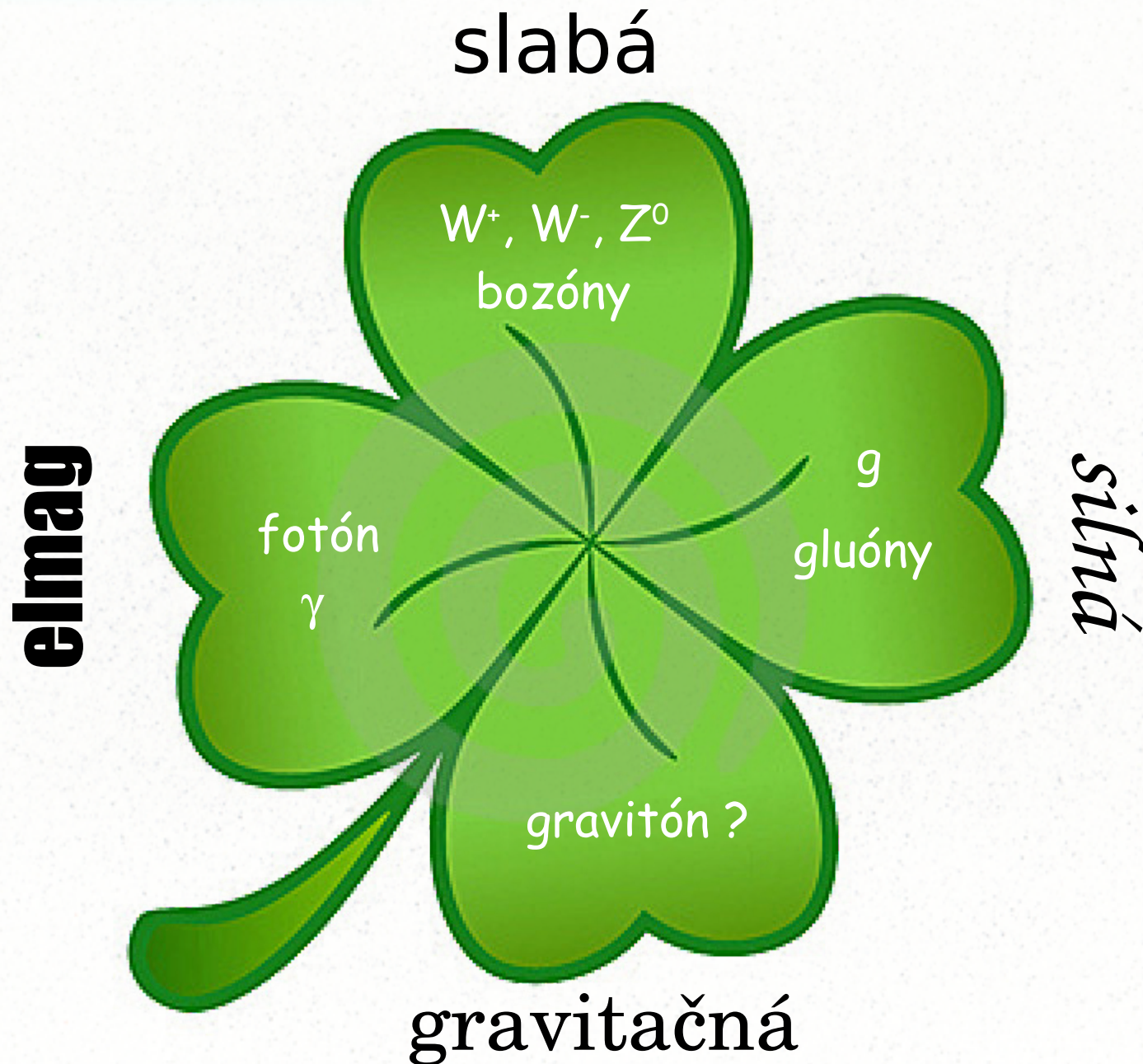


... vznik a zánik častíc:



сила в  $\mu$ -svete ...

interakcia



# fermióny ...

leptóny

$\nu_e$
$e$
$u$
$d$

neutríno  
elektrón

kvarky

$\nu_\mu$
$\mu$
$c$
$s$

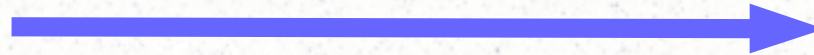
neutríno  
mión

$\nu_\tau$
$\tau$
$t$
$b$

neutríno  
taón

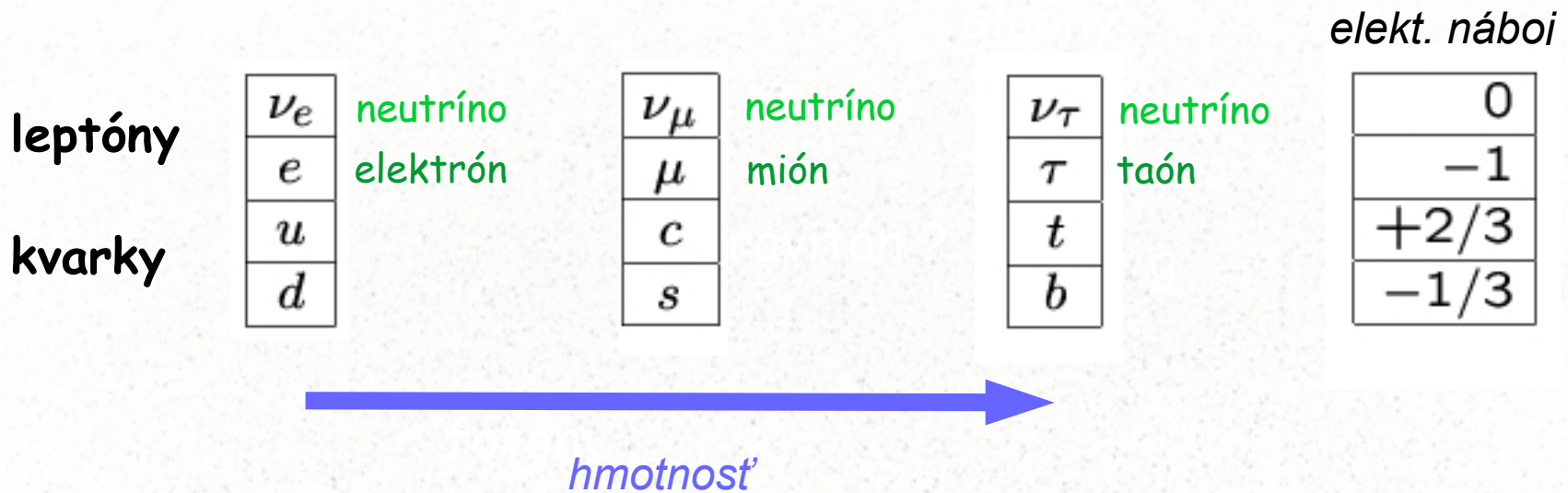
elekt. náboj

0
-1
+2/3
-1/3



*hmotnosť*

# fermióny ...



## interakcie:

- |                      |                     |              |
|----------------------|---------------------|--------------|
| • neutrálne leptóny: | slabo               | } gravitačne |
| • nabité leptóny:    | slabo, elmag        |              |
| • kvarky:            | slabo, elmag, silno |              |



# silná interakcia: väzeňské blues ...

silná interakcia je silná



HADRÓNY

BARYÓNY

$qqq$

MEZÓNY

$q\bar{q}$



# silná interakcia: väzeňské blues ...

silná interakcia je silná



HADRÓNY

BARYÓNY

$qqq$

MEZÓNY

$q\bar{q}$

silná interakcia narastá so vzdialenosťou

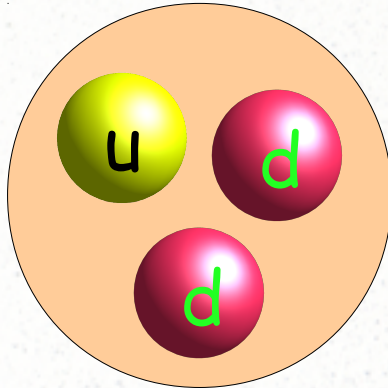


uväznenie kvarkov



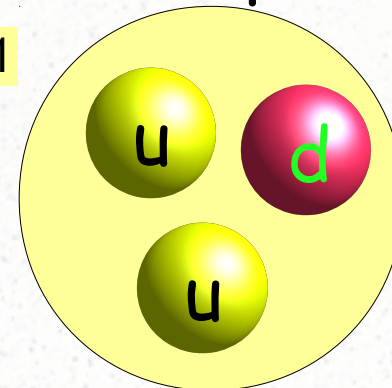
silná sila  $\Rightarrow$  protón, neutrón, ...

neutrón



$q = 0$

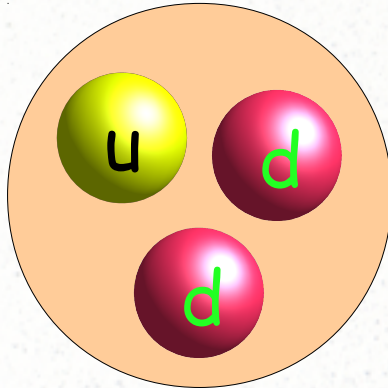
protón



$q = +1$

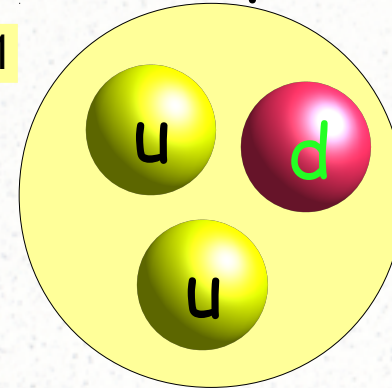
# silná sila $\Rightarrow$ protón, neutrón, ...

neutrón  $+\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$



$$q = 0$$

$+\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$  protón

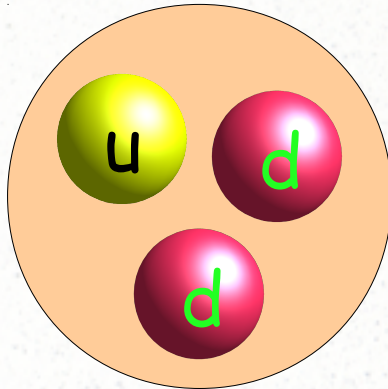


$$q = +1$$

částica	náboj
u	$+\frac{2}{3}$
d	$-\frac{1}{3}$

# silná sila $\Rightarrow$ protón, neutrón, ...

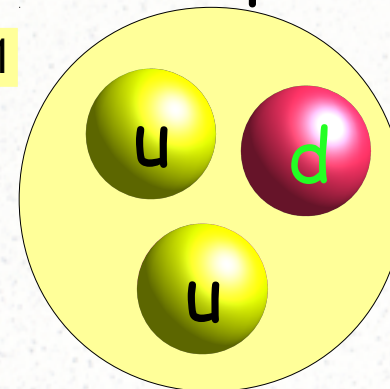
neutrón



$$q = 0$$

$$m_n = 939.57 \text{ MeV}/c^2$$

protón

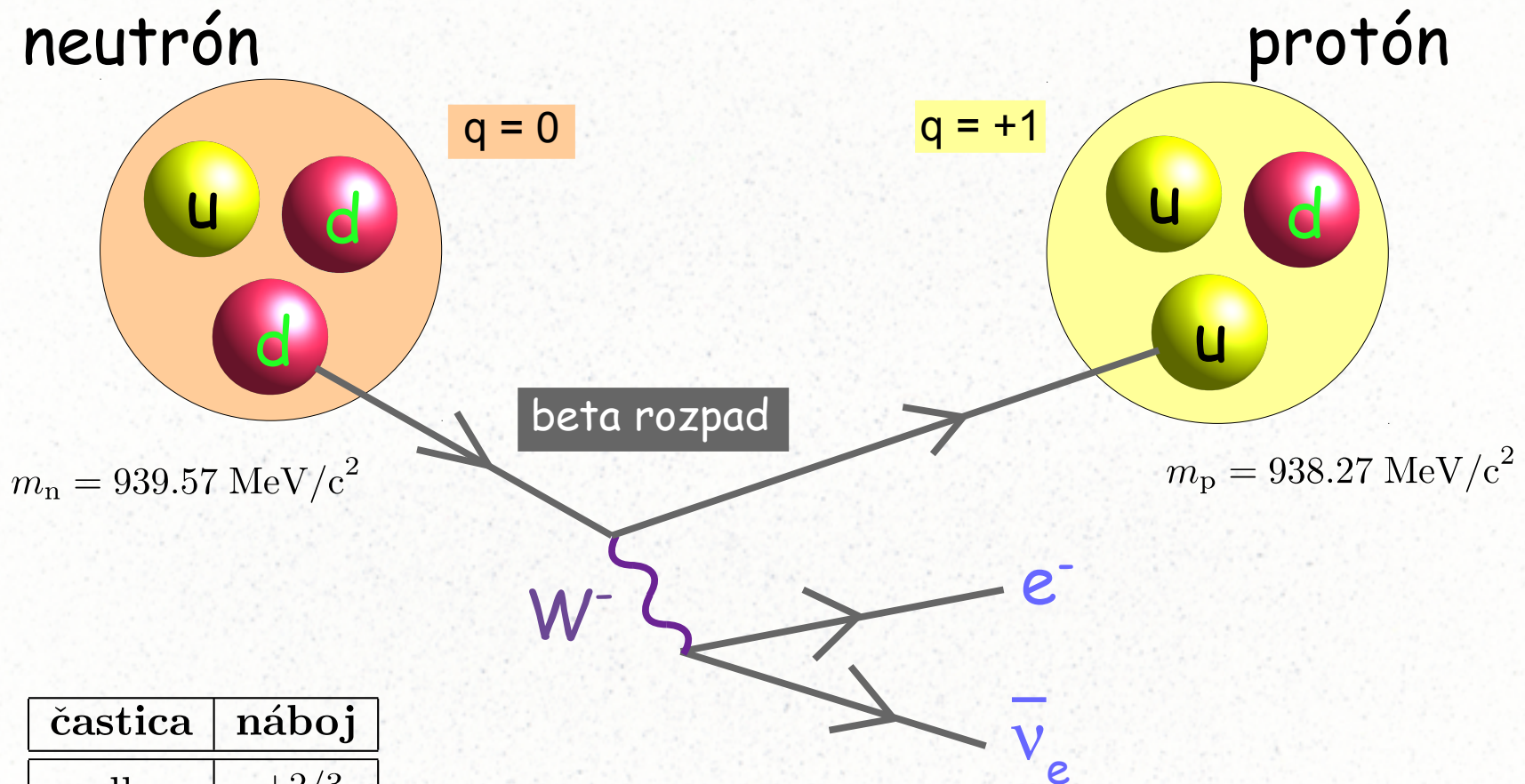


$$q = +1$$

$$m_p = 938.27 \text{ MeV}/c^2$$

částica	náboj
u	+2/3
d	-1/3

# slabá sila $\Rightarrow$ beta rozpad



častica	náboj
u	+2/3
d	-1/3
$e^-$	-1
$\bar{\nu}_e$	0
$W^-$	-1

## 4. Nejednoznačnosť

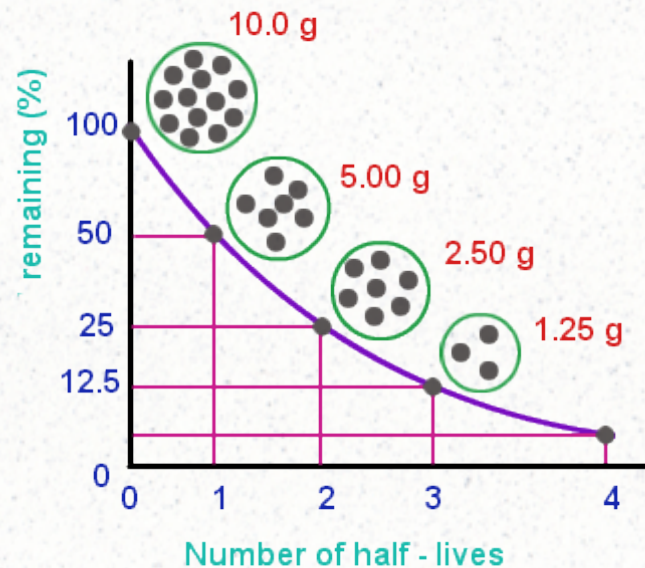
# Kedy sa neutrón rozpadne?

polčas rozpadu neutrónu  $\approx 15$  minút

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polčas rozpadu neutrónu  $\approx 15$  minút

- rozpadne sa polovica zo všetkých neutrónov

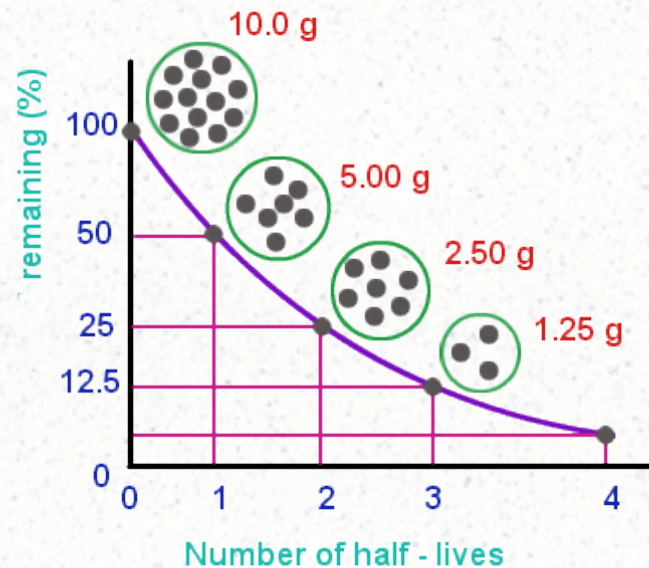




# Kedy sa neutrón rozpadne?

polčas rozpadu neutrónu  $\approx 15$  minút

- rozpadne sa polovica zo všetkých neutrónov



- kedy sa rozpadne konkrétny neutrón ?

# Nejednoznačnosť mikrosveta ...

teória: Kvantová mechanika

- možné výsledky merania
- ich pravdepodobnosť

# Nejednoznačnosť mikrosveta ...

teória: Kvantová mechanika

- možné výsledky merania
- ich pravdepodobnosť

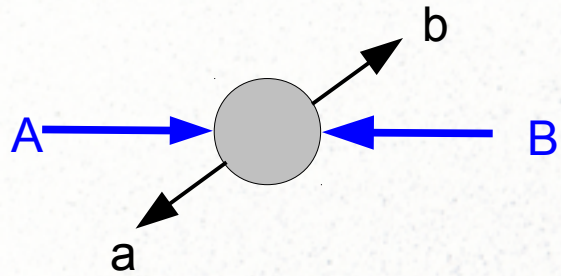
$Z \rightarrow$	$e^+ e^-$	$\mu^+ \mu^-$	$\tau^+ \tau^-$	$\nu \bar{\nu}$	$q \bar{q}$
P(%)	3.4	3.4	3.4	20.0	69.9

$$M_Z \approx 91 \text{ GeV}/c^2$$

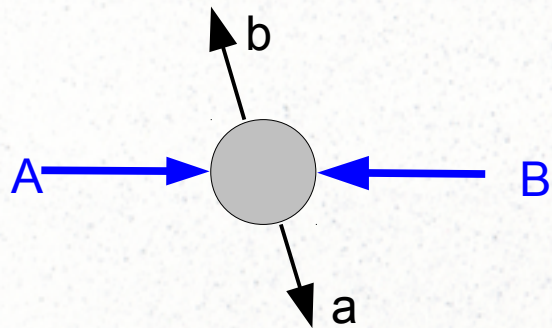
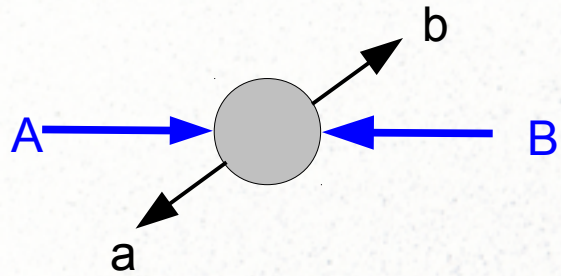
$W^\pm \rightarrow$	$e^\pm \nu$	$\mu^\pm \nu$	$\tau^\pm \nu$	$q \bar{q}'$
P(%)	10.8	10.8	10.8	67.6

$$M_W \approx 80 \text{ GeV}/c^2$$

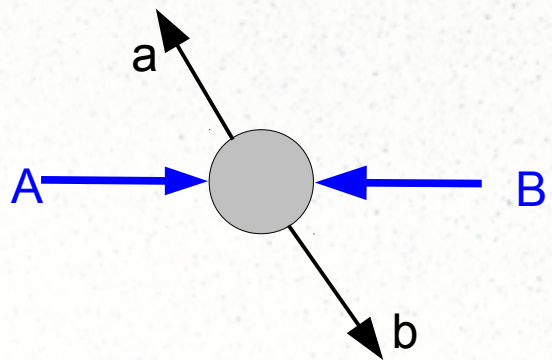
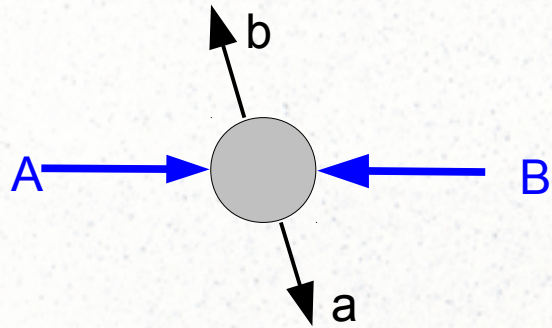
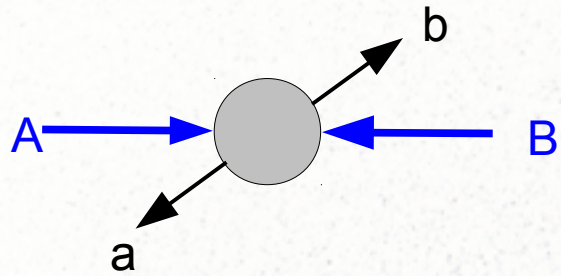
# Nejednoznačnost' mikrosveta ...



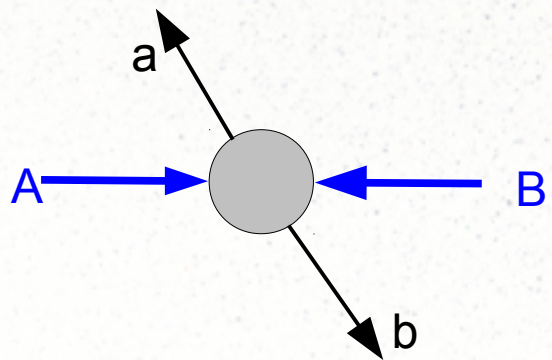
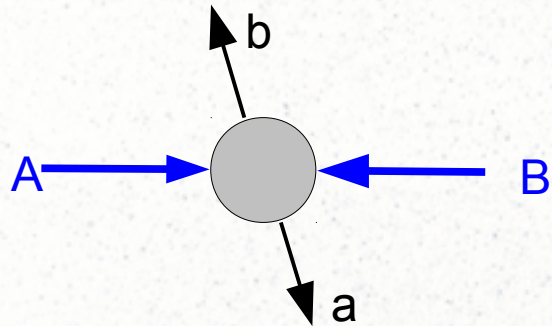
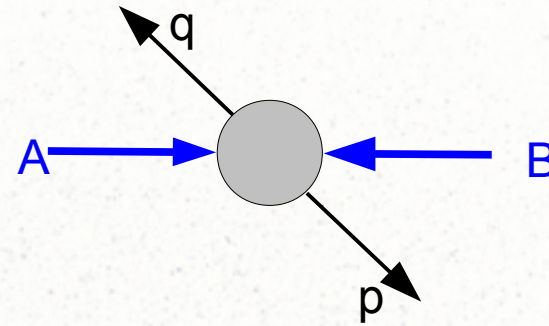
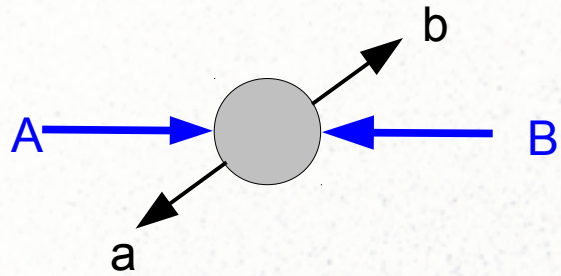
# Nejednoznačnost' mikrosveta ...



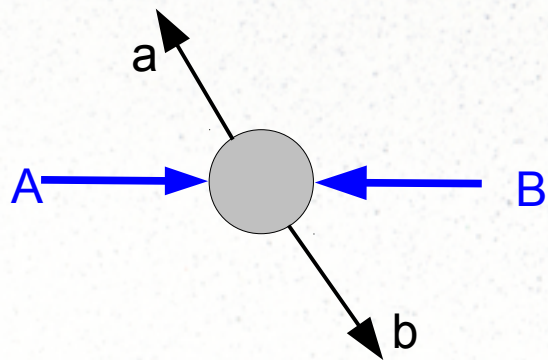
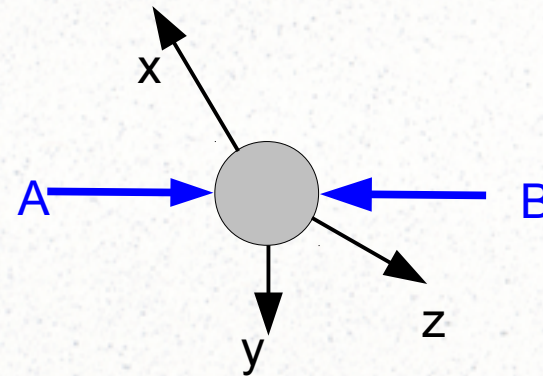
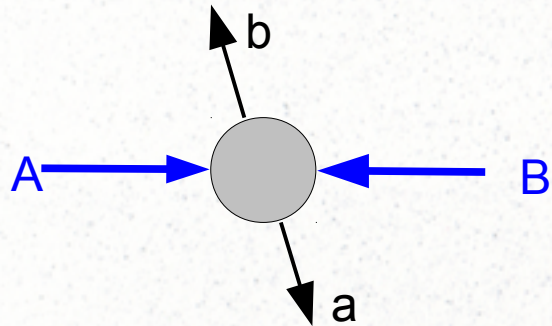
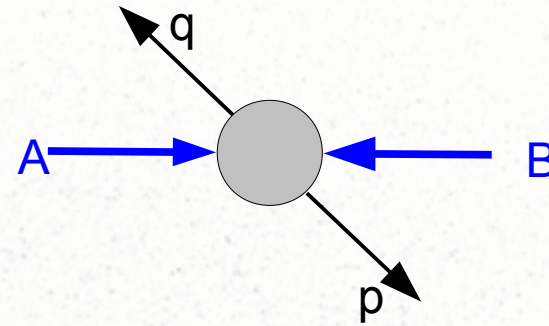
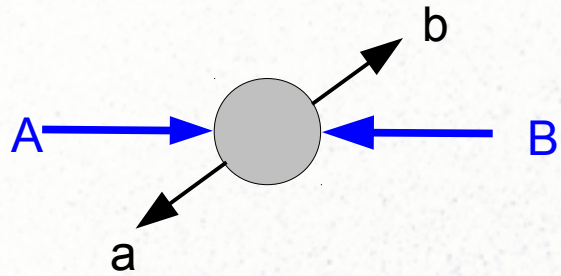
# Nejednoznačnost' mikrosveta ...



# Nejednoznačnost' mikrosveta ...

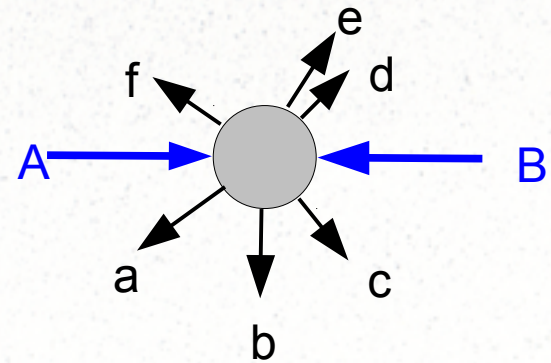
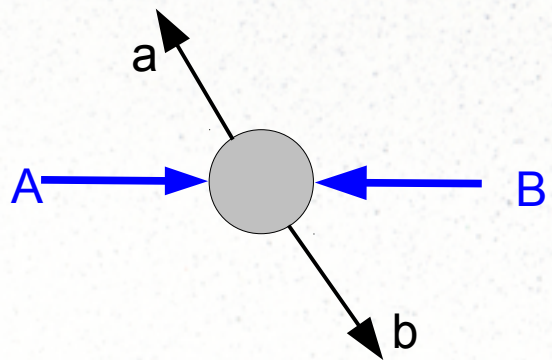
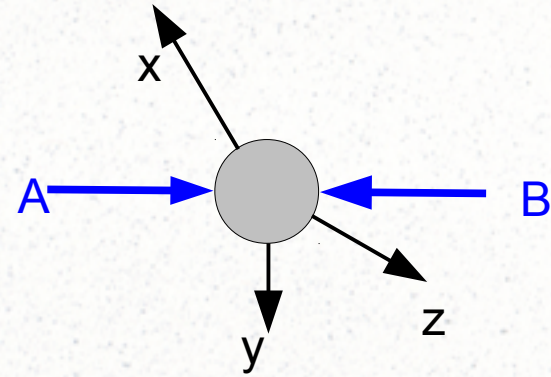
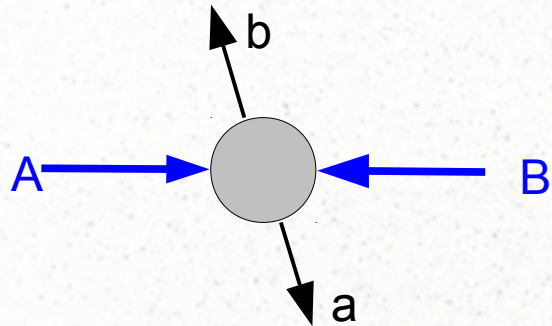
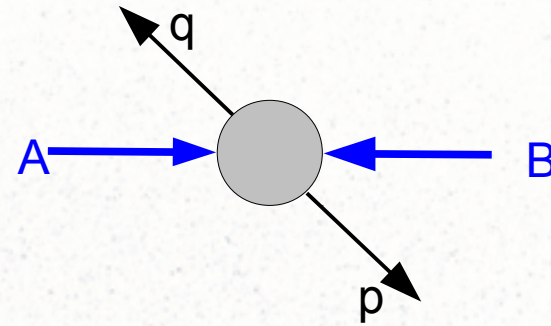
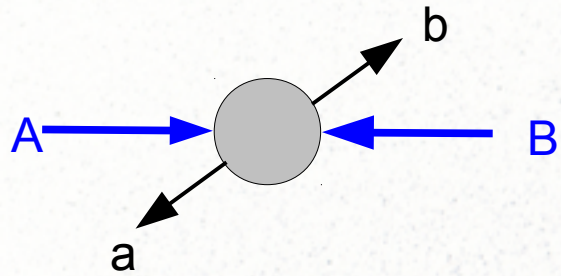


# Nejednoznačnost' mikrosveta ...





# Nejednoznačnost' mikrosveta ...



# elektrónový basketbal

kvantová  
mechanika  
:-)

hmotnosť sa  
nezachováva  
:-)



Kobe Bryant

nejednoznačné  
predpovede  
:-)

lopta môže  
anihilovať  
:-)

# elektrónový basketbal

kvantová  
mechanika  
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hmotnosť sa  
nezachováva  
:-(



nejednoznačné  
predpovede  
:-(

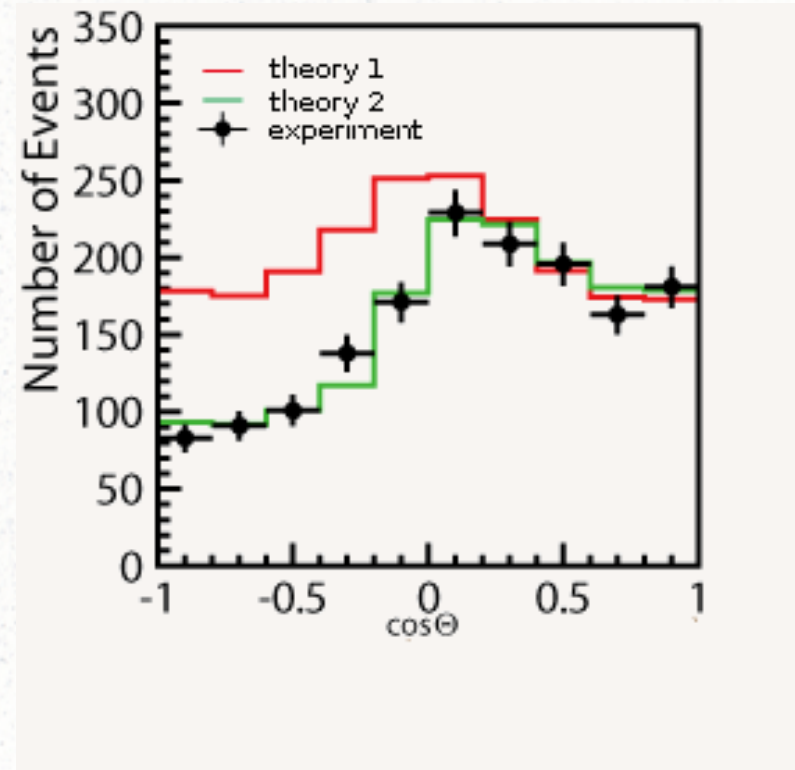
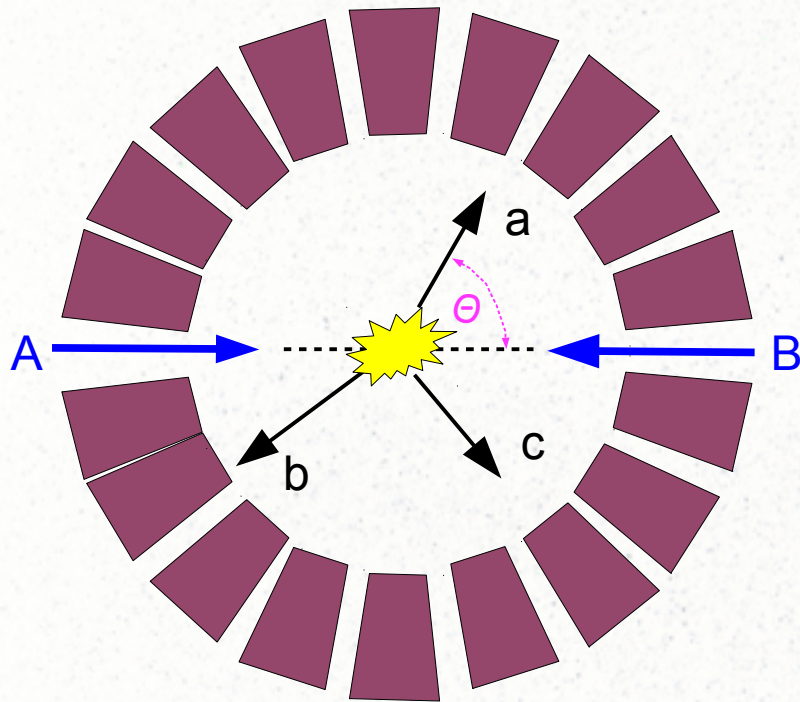
lopta môže  
anihilovať  
:-(



Kobe Bryant

# 5. Experiment

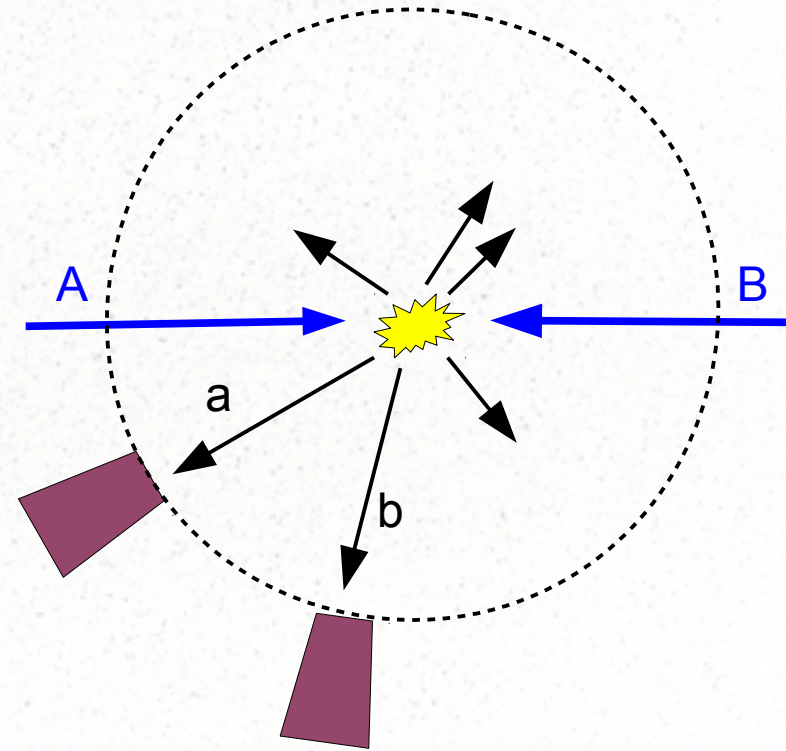
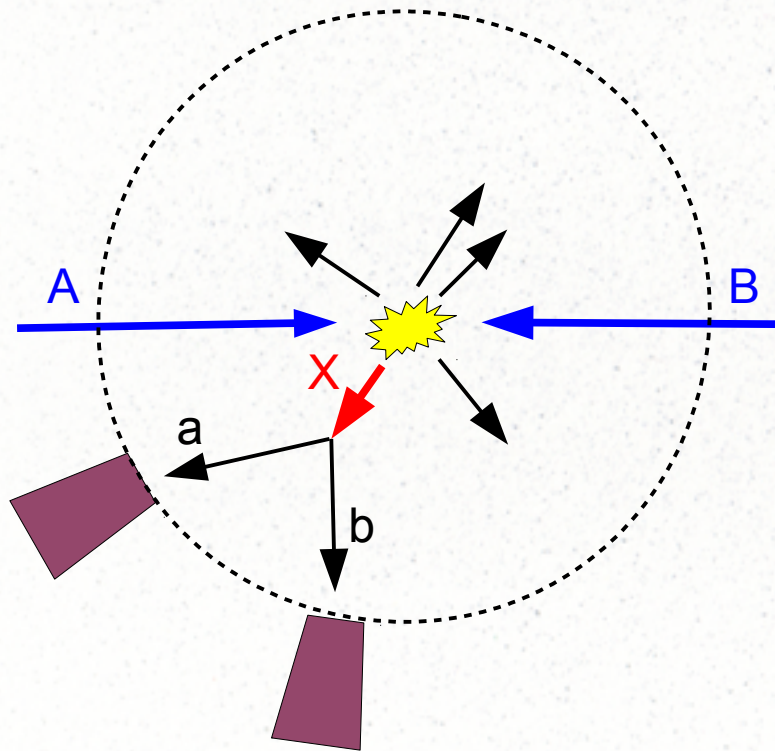
# testovanie predpovede ...



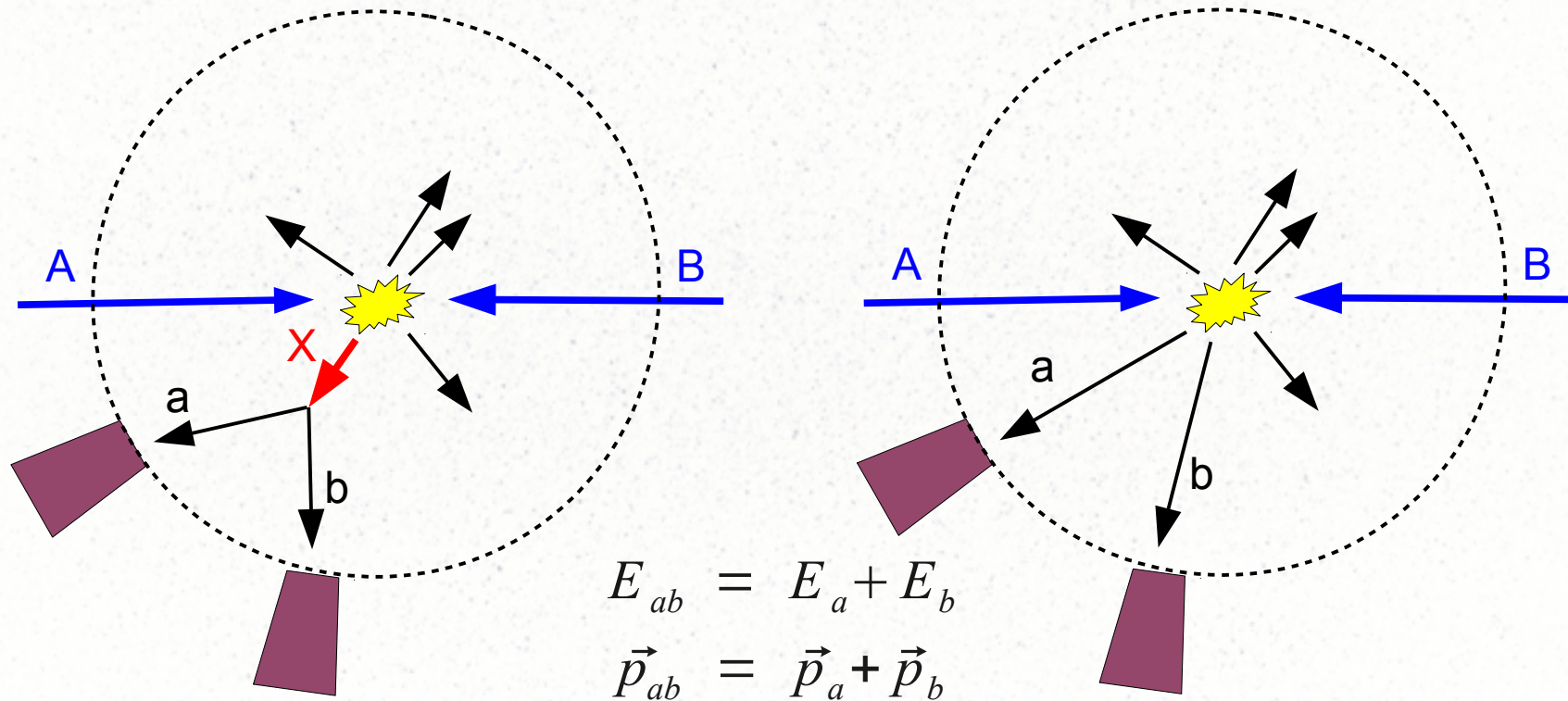
# Problém nestabilných častíc

napr.  $W^\pm, Z$ :

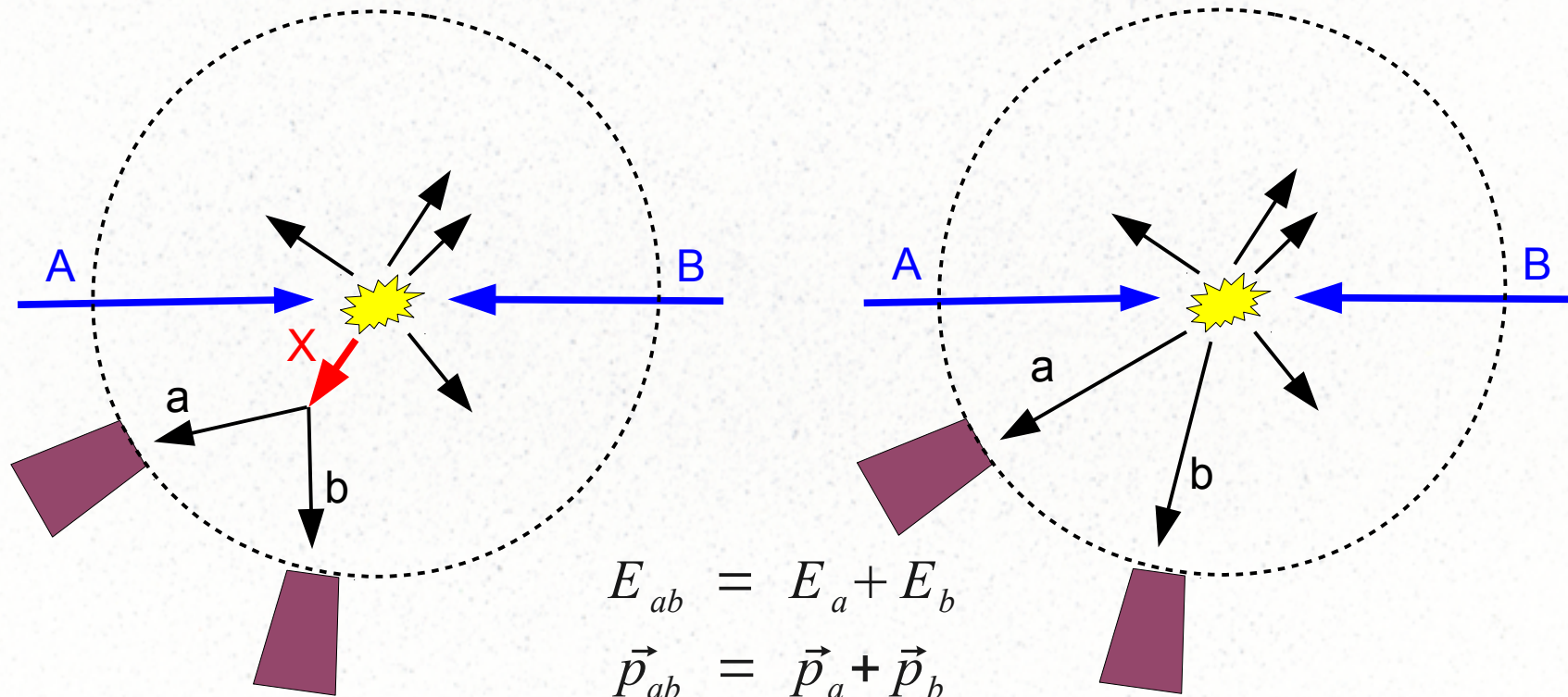
$$\tau \approx 3 \times 10^{-25} \text{ s} \Rightarrow c \cdot \tau \approx 10^{-16} \text{ m}$$



# nobelovský trik ...



# nobelovský trik ...



$$E_{ab} = E_a + E_b$$

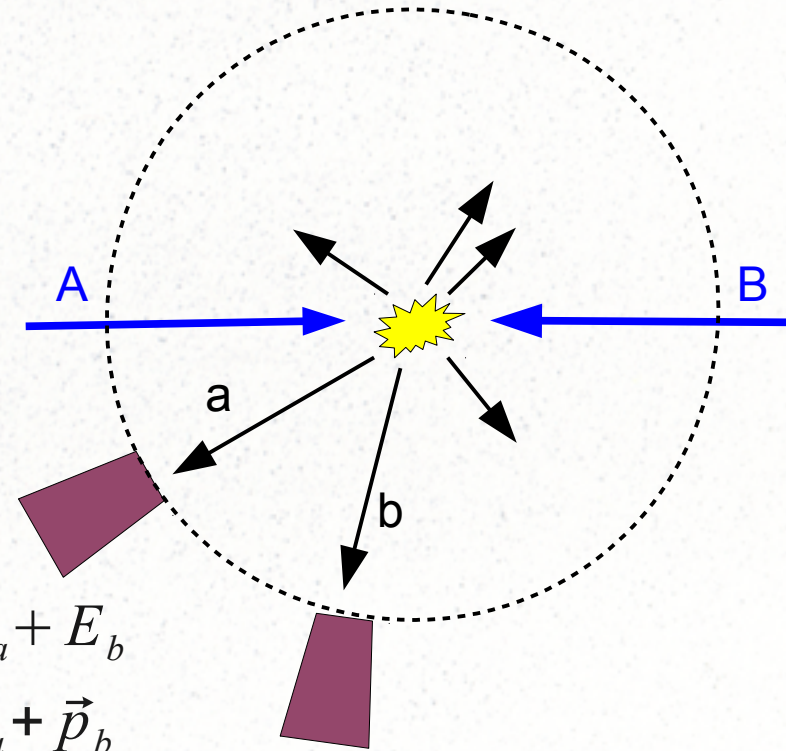
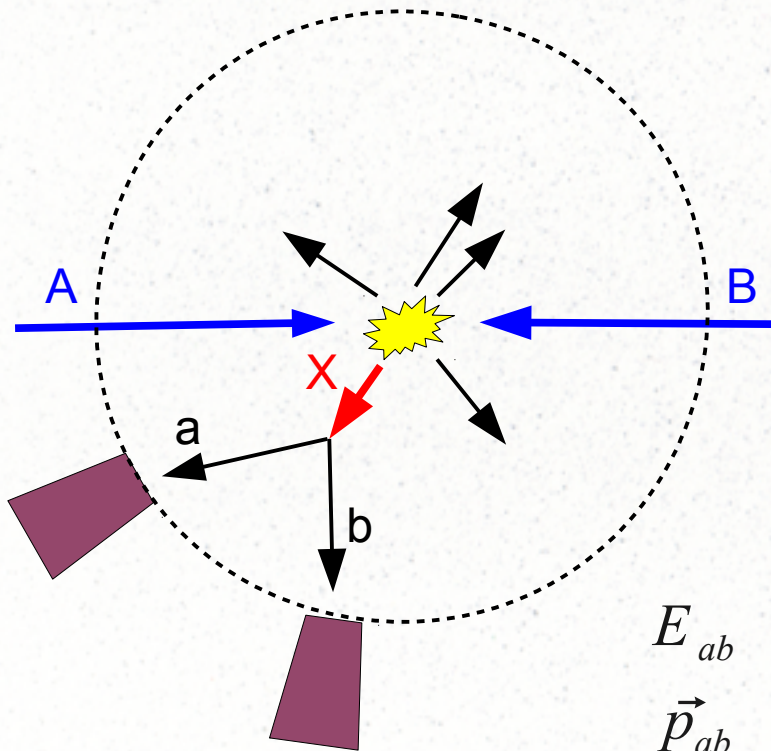
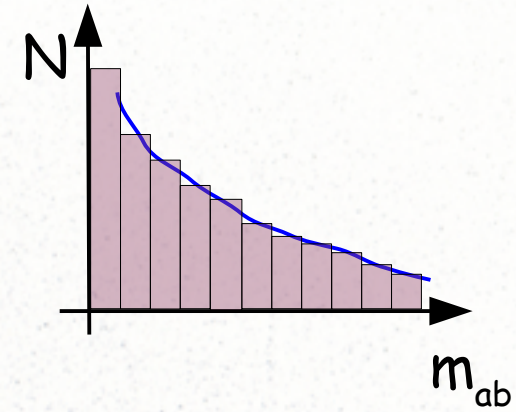
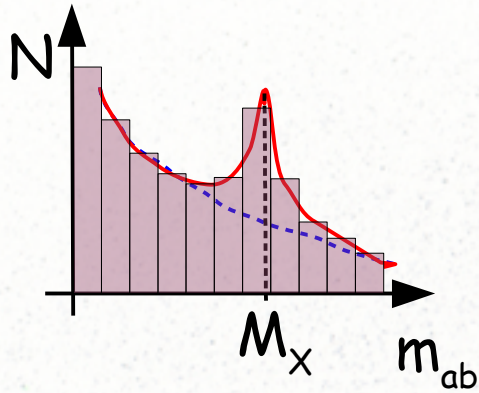
$$\vec{p}_{ab} = \vec{p}_a + \vec{p}_b$$

invariantná hmotnosť:

$$m_{ab} = \sqrt{E_{ab}^2 - \vec{p}_{ab}^2}$$



# nobelovský trik ...



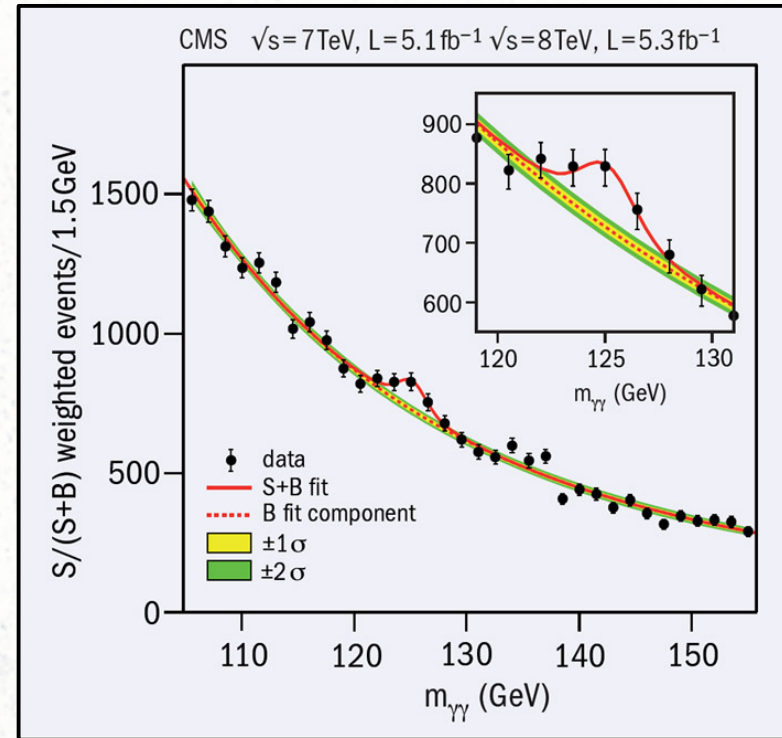
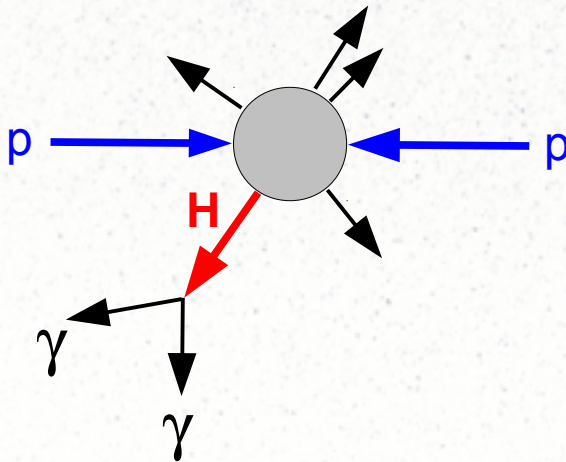
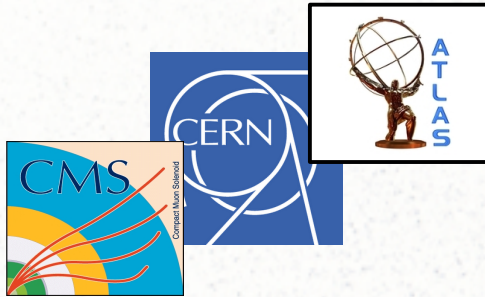
$$E_{ab} = E_a + E_b$$

$$\vec{p}_{ab} = \vec{p}_a + \vec{p}_b$$

invariantná hmotnosť:

$$m_{ab} = \sqrt{E_{ab}^2 - \vec{p}_{ab}^2}$$

# Higgsov bozón...



častica o hmotnosti  
125 GeV

# CERN a LHC ...



## ... a Hollywood v CERNe



*Morgan Freeman v tuneli LHC ... držiteľ Oscara*

*... Nobelova cena za fyziku mu zatiaľ uniká*



Prečo ?!

*Morgan Freeman v tuneli LHC ... držiteľ Oscara*

*... Nobelova cena za fyziku mu zatiaľ uniká*



*Morgan Freeman v tuneli LHC ... držiteľ Oscara*

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