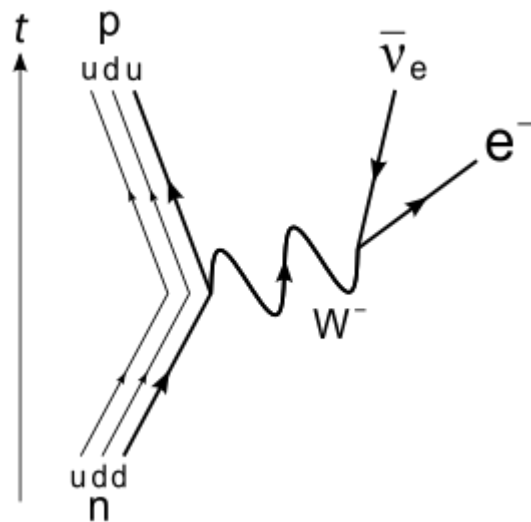
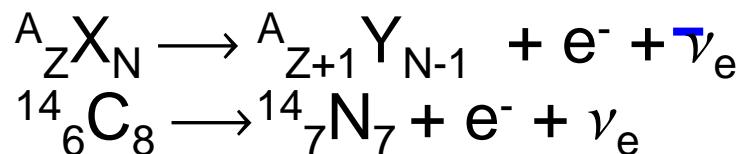
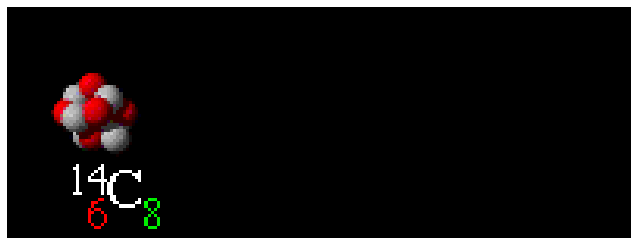


# Слабо взаимодействие

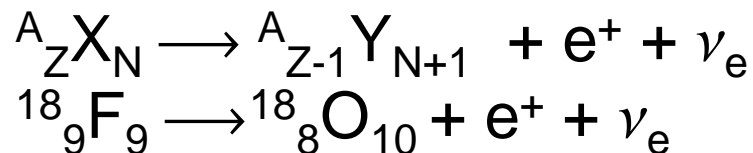
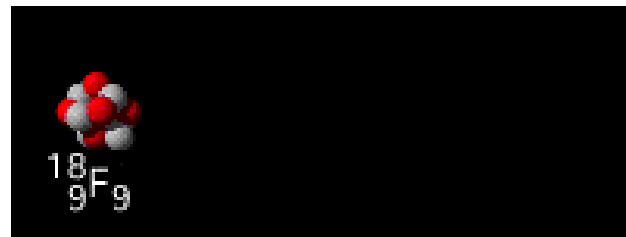


# $\beta$ - разпадане

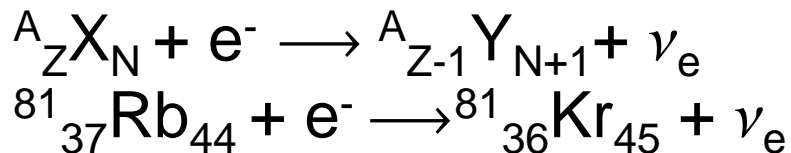
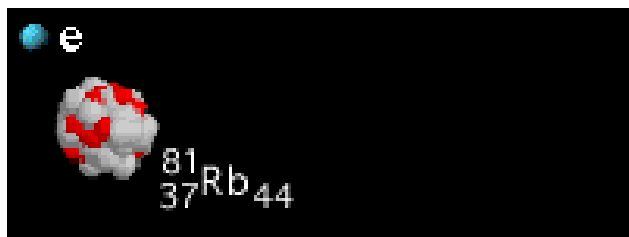
$\beta$  - минус



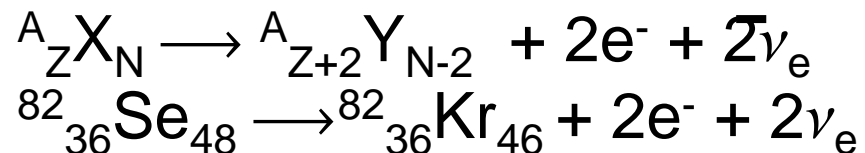
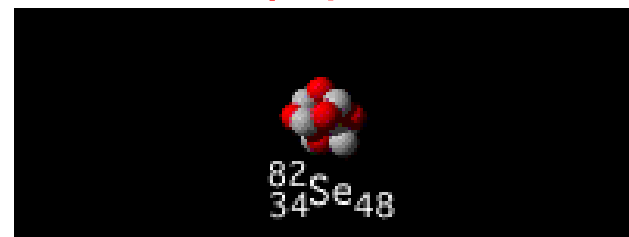
$\beta$  - плюс



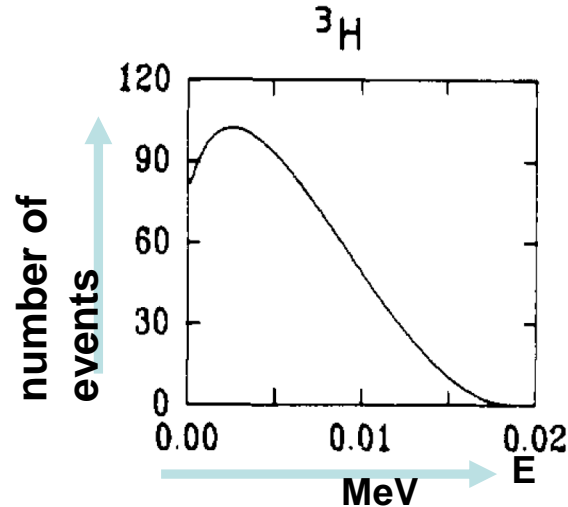
електронен захват



двоен  $\beta$ -разпад



Спектър на електроните по енергии при  $\beta$ -разпадане



Писмо на Волфганг Паули от 4.12.1930

Dear Radioactive Ladies and Gentlemen,

1930

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that **there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle** and which further differ from light quanta in that they do not travel with the velocity of light. **The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses.** The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

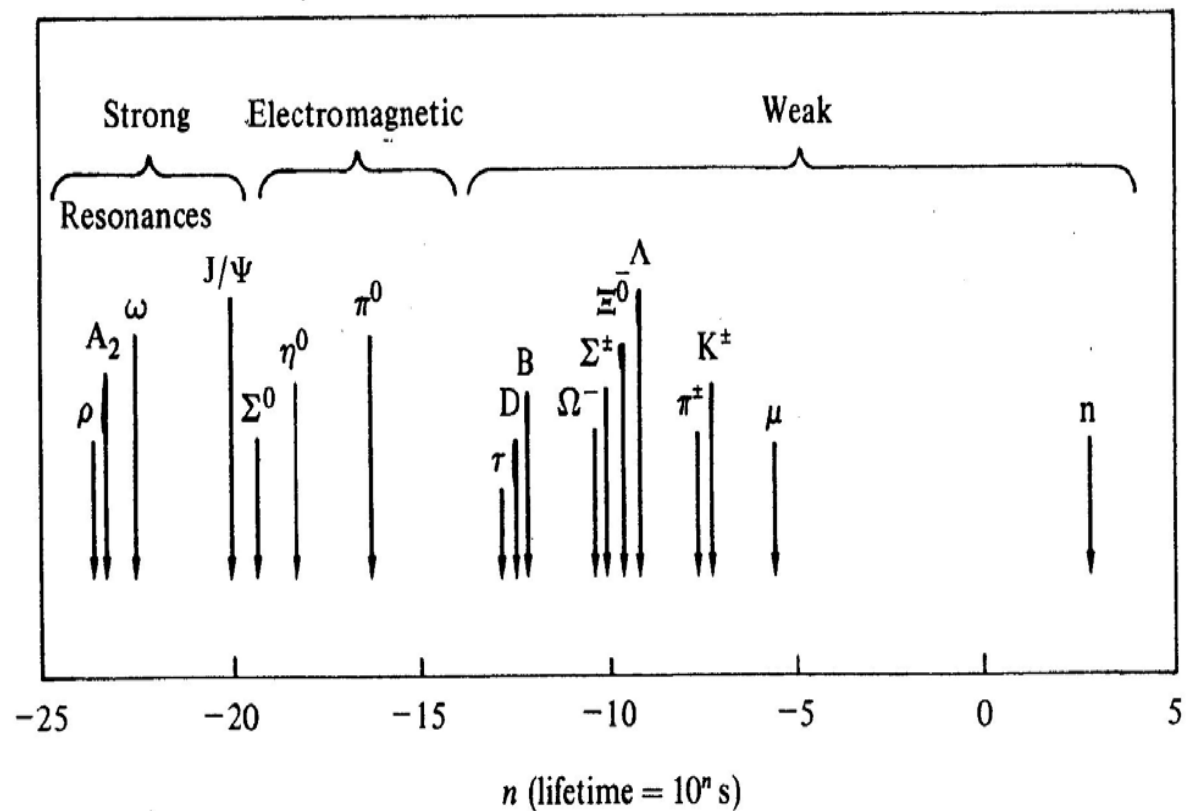
I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

**Unfortunately, I cannot appear in Tübingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December.** With my best regards to you, and also to Mr. Back.

Your humble servant

W. Pauli

translation: L.M. Brown, Phys. Today,



Слаби разпади:

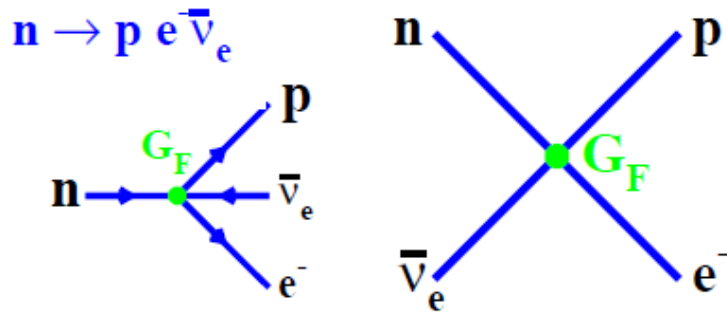
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu,$$

$$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau,$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu,$$

$$n \rightarrow p e^- \bar{\nu}_e, \dots$$

$$d\Gamma_n = \frac{(2\pi)^4}{2M} |\mathcal{M}|^2 d\Phi_n(P; p_1, p_2, \dots, p_n)$$

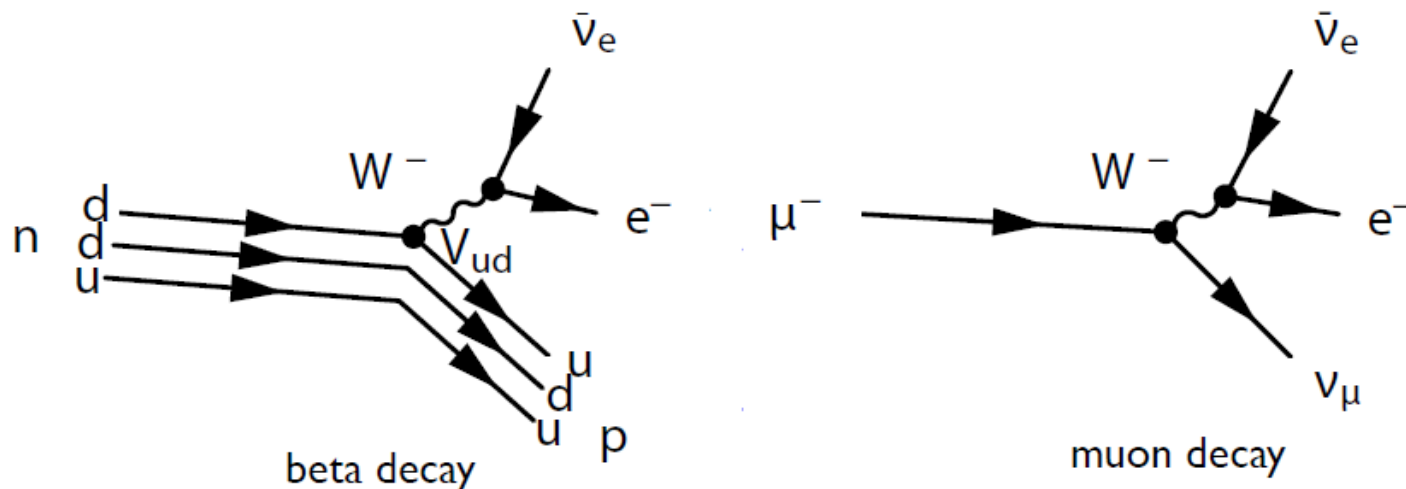


$$|\langle p e^- \bar{\nu}_e | H_W | n \rangle| = |\langle n e^+ | H_W | \nu_e p \rangle|$$

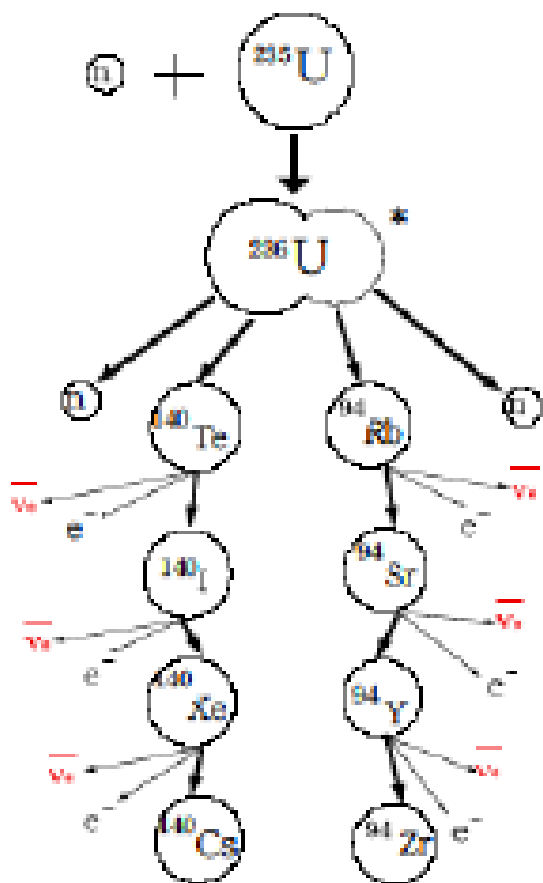
$$M = \langle n | J_\mu^{wk} | p \rangle \langle e \nu | J_\mu^{wk} | 0 \rangle$$

$$M = \langle n | J_\mu^{wk} | p \rangle \langle e | J_\mu^{wk} | \bar{\nu} \rangle$$

- Предполагаме аналогия между слабото и електромагнитното взаимодействие – и двете са взаимодействия между токове.
- Предполагаме съществуването на масивен преносител на взаимодействието.



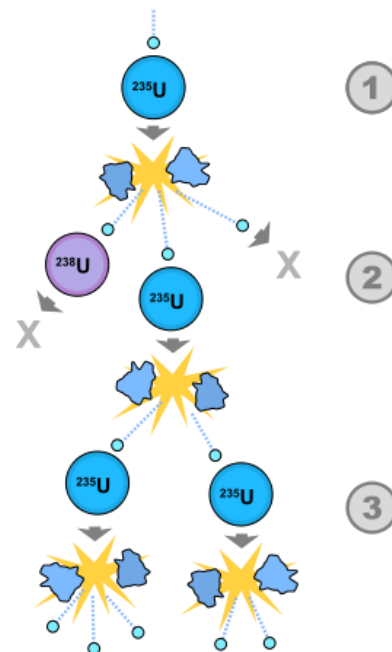
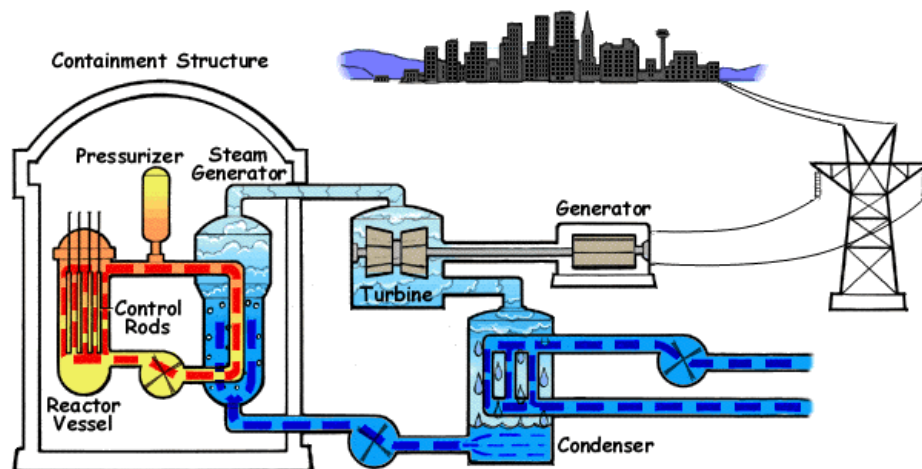
# Ядреният реактор като източник на (анти)неутрина



$\sim 6\nu/\text{fission} \text{ \& } \sim 200\text{MeV}/\text{fission}$



$\sim 6 \times 10^{20} \bar{\nu}_e / \text{s} / \text{reactor (1GWe)}$



## Пряко регистриране на $\nu$

Източник на (анти)неутрина  
– ядрен реактор

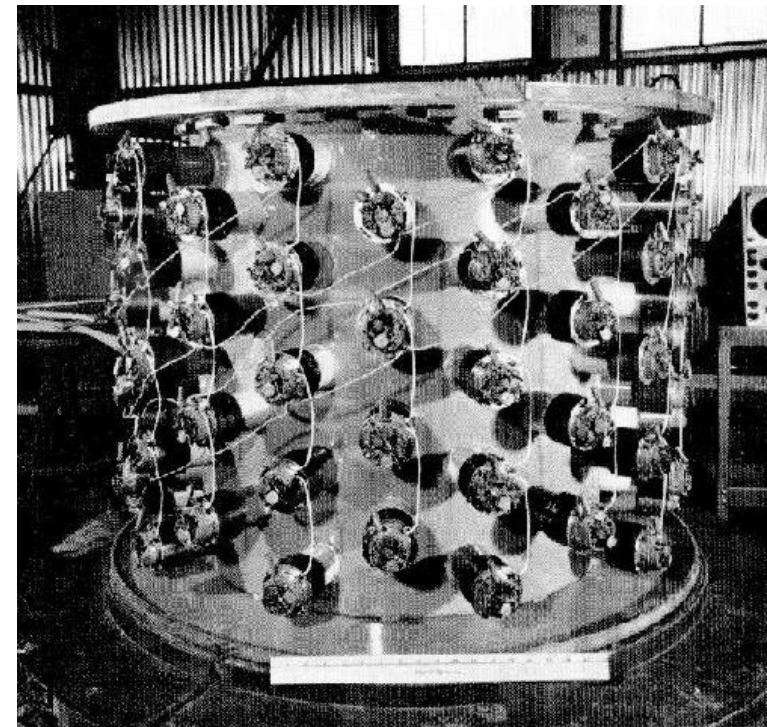
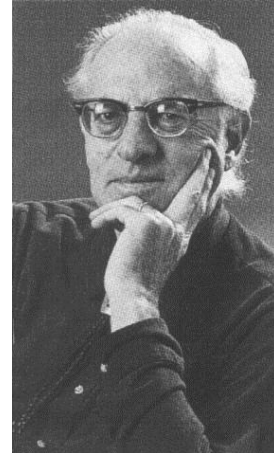


- Позитронът анихилира с електрон от средата и се генерират два едновременни гама-кванта:  $e^+ + e^- \rightarrow \gamma\gamma$ .
- Неутронът се забавя в средата за около 15  $\mu s$  и с голяма вероятност се поглъща от Cd ядро, което остава във възбудено състояние. Възбуждането се сменя чрез 2 гама-прехода. Регистрирането на всичките 4 фотона чрез 4-кратни задържани съвпадения идентифицира еднозначно реакцията.

## Reines and Cowan

Мишената се  
състои от 400 l  
вода, в която е  
разтворен  $CdCl_2$

1953



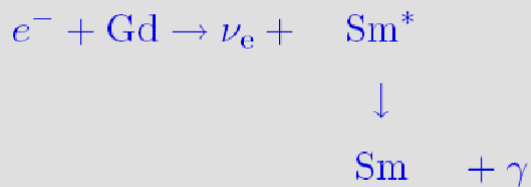


# Двукomпонентният модел

**1956** Незапазване на пространствената четност в  $\beta$ -разпадането на  $^{60}\text{Co}$ : излъченият електрон има лява спиралност (C.S. Wu et al.)

**1957** Измерване на спиралността на неутриното (M. Goldhaber, L. Grodzins, A.W. Sunyar):  
неутрината имат лява спиралност.

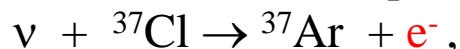
поляризацията на  $\gamma$ -квантите се измерва чрез Комптъновото им разсейване от намагнитено желязо



**1959** Ray Davis установява, че (анти) неутрината от ядрен реактор не взаимодействат с Cl, за да генерират Ar:



Излъчените при разпадането неутрина не осъществяват реакцията



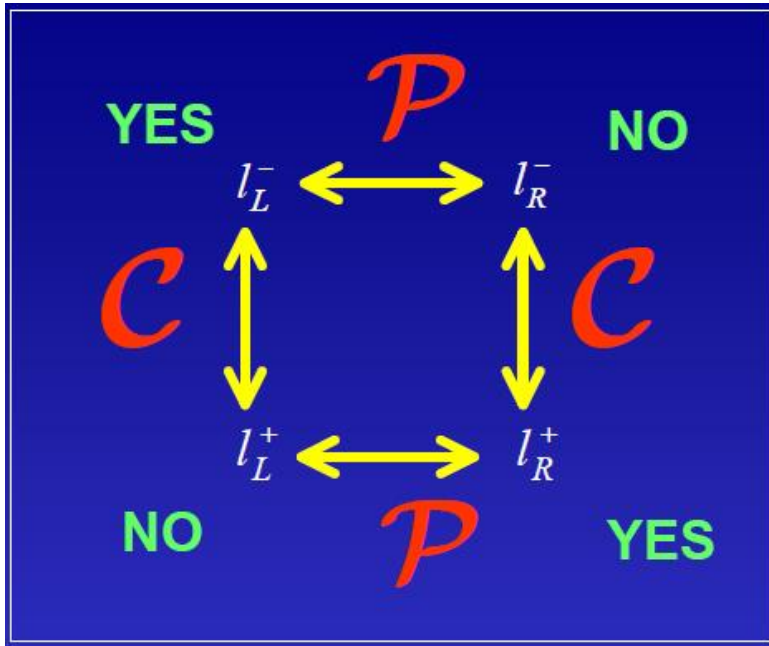
т.е. те са **антинейтрино**.

Science and Jazz in the NY Daily News  
Sunday September 21, 1958





# CP-инвариантность

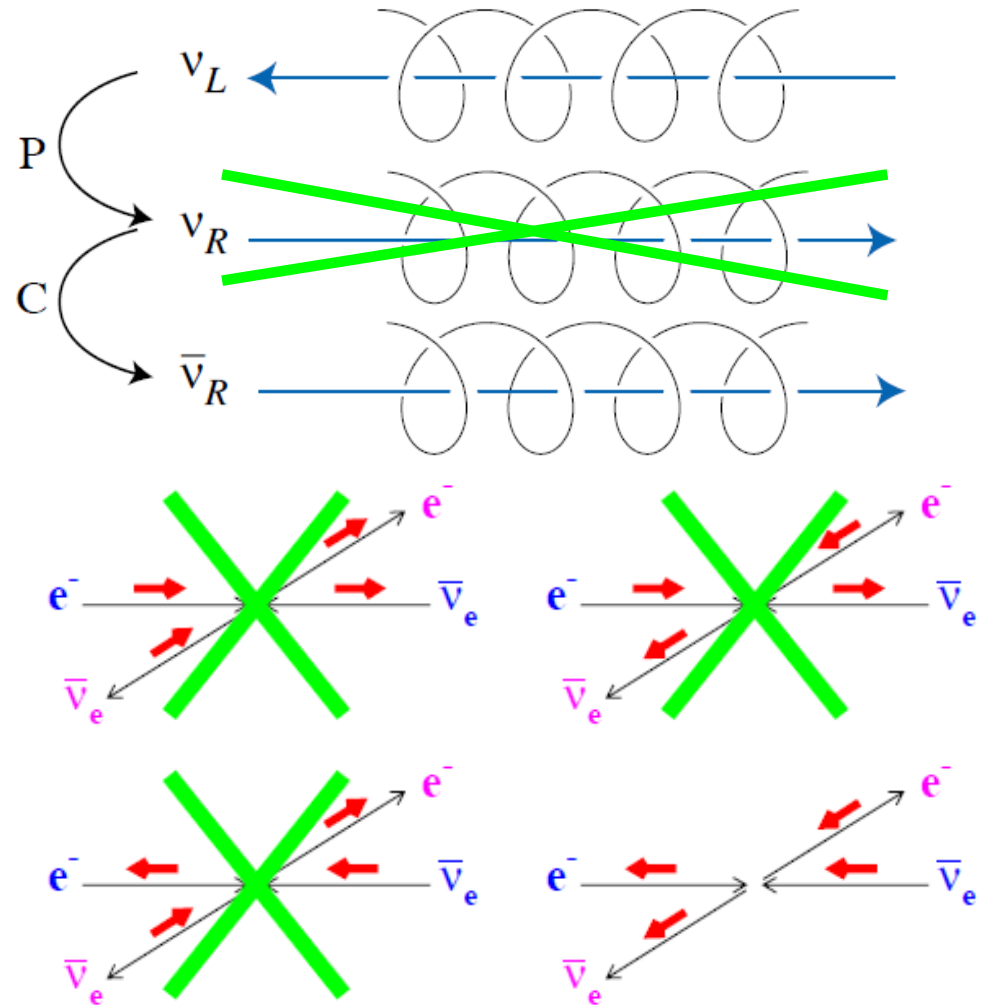


$$\langle \bar{u}_\nu | \gamma^\mu (1 - \gamma_5) | u_e \rangle$$

**V-A**

$$u_L = \frac{1}{2}(1 - \gamma_5)u$$

- Единствено левовинтовите неутрина и десновинтовите антинейтрино участват в слабите взаимодействия.



## Различни лептонни числа: $L_e$ и $L_\mu$

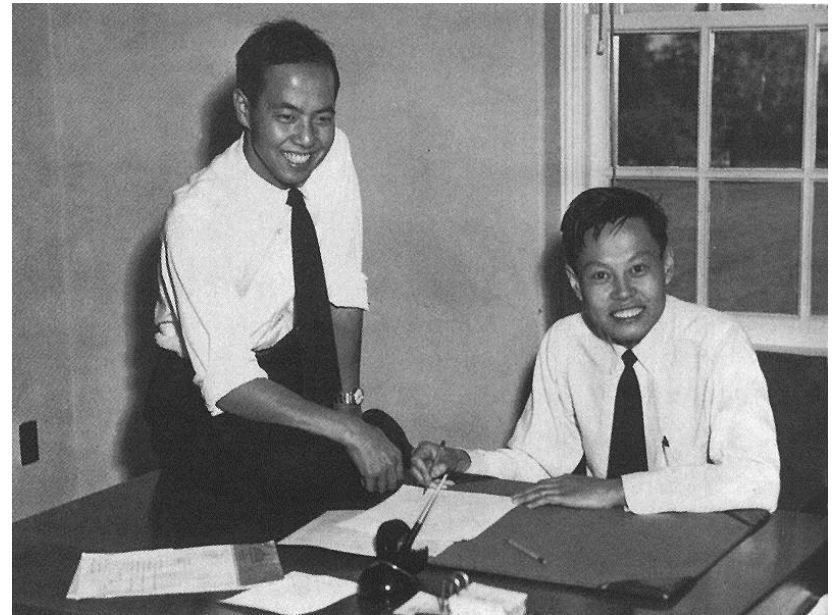
1960

**1960** Lee и Yang предполагат, че отсъствието на разпадане от типа

$$\mu^- \rightarrow e^- + \gamma \text{ (BR} < 5 \times 10^{-13}, 2013)$$

е указание за наличието на 2 типа неутрина:  $\nu_\mu$  и  $\nu_e$ :

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$



Chen Ning Lee and Tsung-Dao Yang

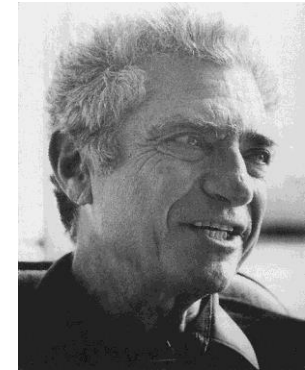
# Пряка проверка за наличието на два типа неутрина



Schwartz



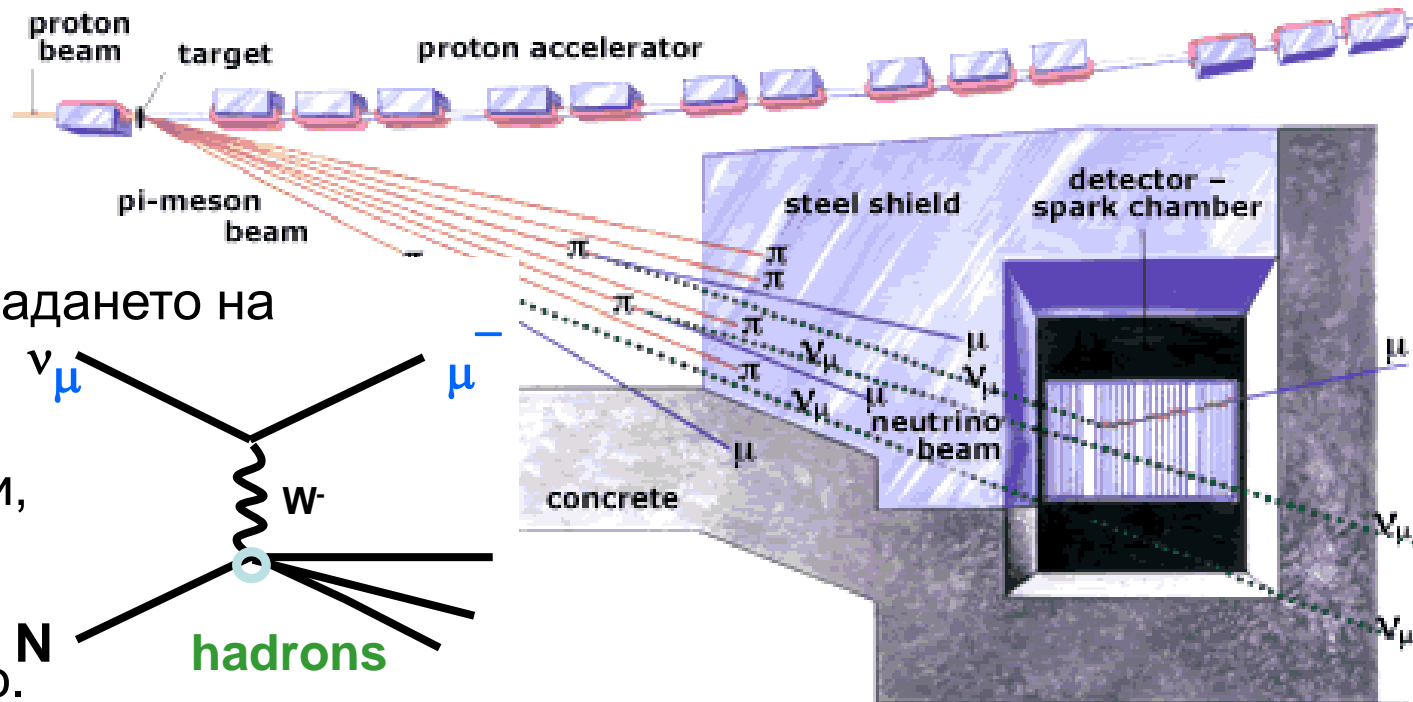
Lederman



Steinberger

протонен сноп от  
AGS (33 GeV)

1962



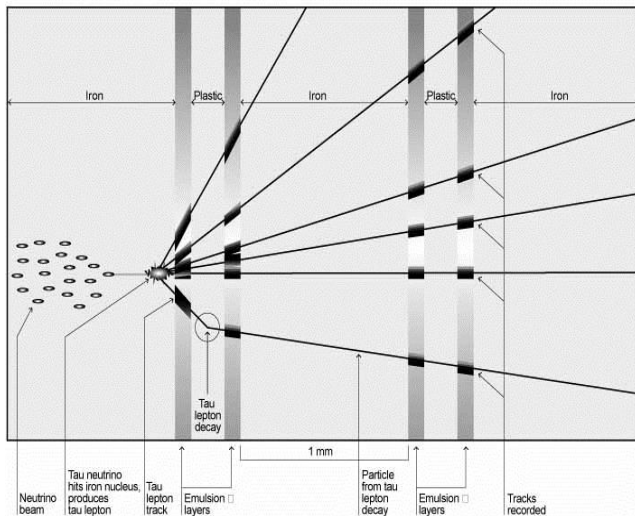
Неутрината от разпадането на  
пионите:  
 $\pi^+ \rightarrow \mu^+ + \nu_\mu$   
раждат само мюони,  
но не и електрони,  
когато взаимодей-  
стват с веществото.

# Третото поколение лептони

**Donut – пряко регистриране на  $\tau$ -неутриното**

**2000**

**Detecting a Tau Neutrino**



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

М. Perl и сътр., SLAC-LBL, 1974-77, Нобелова награда 1995 г.

**1975**

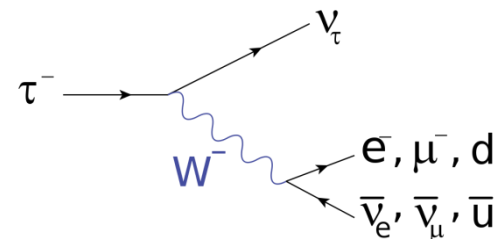


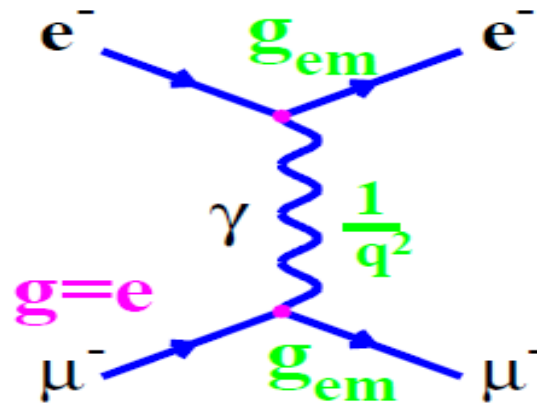
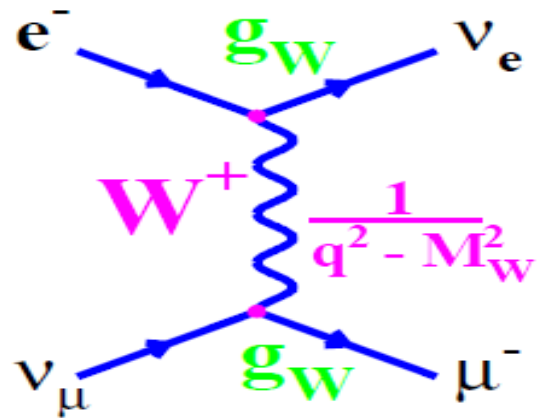
**tau lepton**  
 $1776.84 \pm 0.17 \text{ MeV}/c^2$   
 $2.9 \times 10^{-13} \text{ s}$

*Evidence for Anomalous Lepton Production in  $e^+ - e^-$  Annihilation; Physical Review Letters, Vol. 35, Issue 22, 1489-1492; 1975*

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \text{at least 2 undetected particles}$$

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \rightarrow e^\pm + \mu^\mp + 4\nu$$





$$M \sim g_W \langle \bar{u}_\nu | \gamma^\mu (1 - \gamma_5) | u_e \rangle \quad \text{ток}$$

$$\times \frac{1}{q^2 - M_W^2}$$

пропагатор

$$\times g_W \langle \bar{u}_\nu | \gamma^\mu (1 - \gamma_5) | u_\mu \rangle \quad \text{ток}$$

За  $q^2 \ll M_W^2$  получаваме

$$M \sim \frac{g_W^2}{M_W^2}$$

$$M \sim e \langle \bar{u}_e | \gamma^\mu | u_e \rangle$$

$$\times \frac{1}{q^2}$$

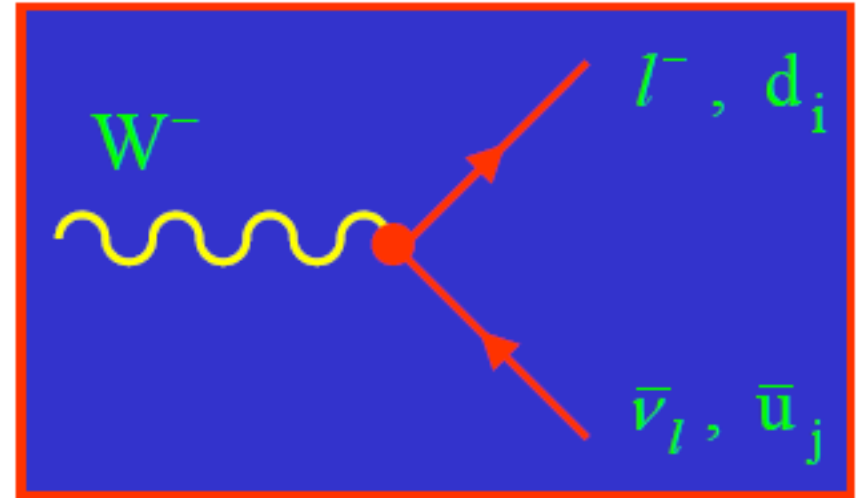
$$\times e \langle \bar{u}_\mu | \gamma^\mu | u_\mu \rangle$$

$$M \sim \frac{e^2}{q^2}$$

Обяснява защо при малки предадени импулси  $q^2 \ll M_W^2$  слабото взаимодействие е слабо.

# Лептонни процеси - универсалност

$$W^- \rightarrow e^- \bar{\nu}_e, \mu^- \bar{\nu}_\mu, \tau^- \bar{\nu}_\tau$$



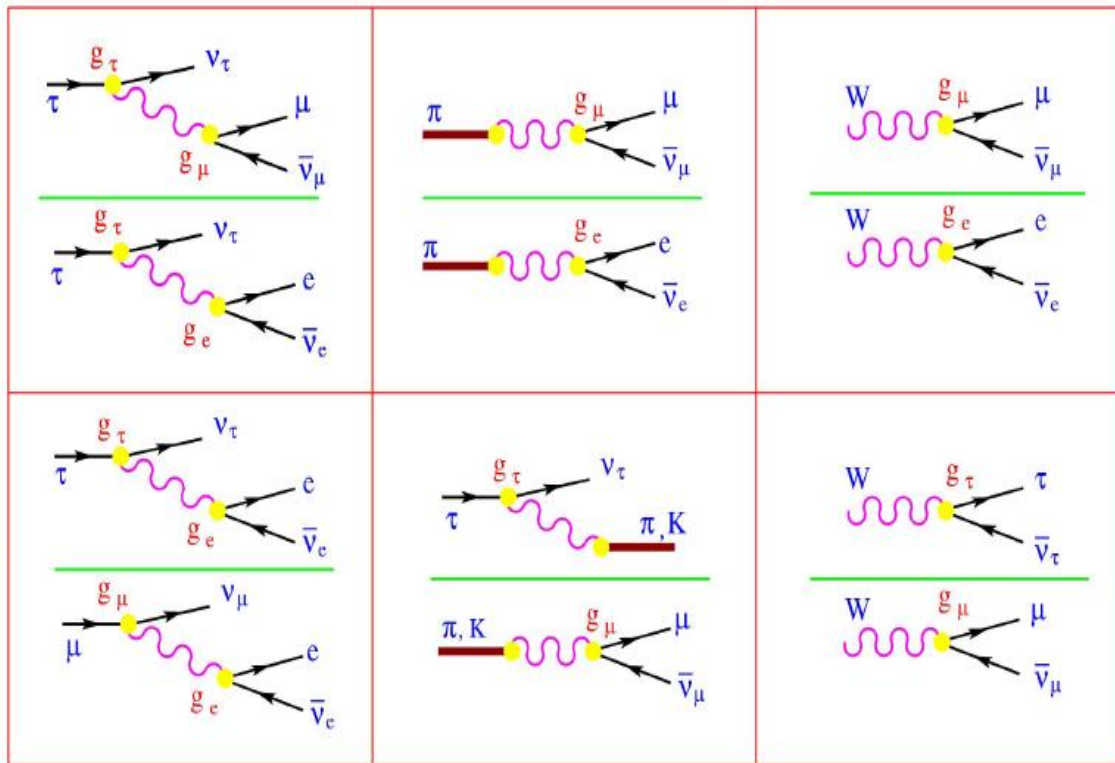
$$\text{Br}(W^- \rightarrow l^- \bar{\nu}_l) \equiv \frac{\Gamma(W^- \rightarrow l^- \bar{\nu}_l)}{\Gamma(W^- \rightarrow \text{all})} = \frac{1}{3 + 2 N_c} = 11.1\%$$

- Эксперимент:  
 $\text{Br}(W^- \rightarrow e^- \bar{\nu}_e) = (10.59 \pm 0.17)\%$   
 $\text{Br}(W^- \rightarrow \mu^- \bar{\nu}_\mu) = (10.55 \pm 0.16)\%$   
 $\text{Br}(W^- \rightarrow \tau^- \bar{\nu}_\tau) = (11.20 \pm 0.22)\%$

# Лептонни процеси - универсалност

$$\frac{g_\mu}{g_e}$$

$$\frac{g_\tau}{g_\mu}$$



$$|g_\mu/g_e|$$

$B_{\tau \rightarrow \mu} / B_{\tau \rightarrow e}$	$0.9999 \pm 0.0020$
$B_{\pi \rightarrow \mu} / B_{\pi \rightarrow e}$	$1.0017 \pm 0.0015$
$B_{W \rightarrow \mu} / B_{W \rightarrow e}$	$0.998 \pm 0.011$

$$|g_\tau/g_e|$$

$B_{\tau \rightarrow \mu} \tau_\mu / \tau_\tau$	$1.0002 \pm 0.0022$
$B_{W \rightarrow \tau} / B_{W \rightarrow e}$	$1.028 \pm 0.013$

$$|g_\tau/g_\mu|$$

$B_{\tau \rightarrow e} \tau_\mu / \tau_\tau$	$1.0004 \pm 0.0023$
$\Gamma_{\tau \rightarrow \pi} / \Gamma_{\pi \rightarrow \mu}$	$0.9999 \pm 0.0036$
$\Gamma_{\tau \rightarrow K} / \Gamma_{K \rightarrow \mu}$	$0.979 \pm 0.017$
$B_{W \rightarrow \tau} / B_{W \rightarrow \mu}$	$1.030 \pm 0.013$

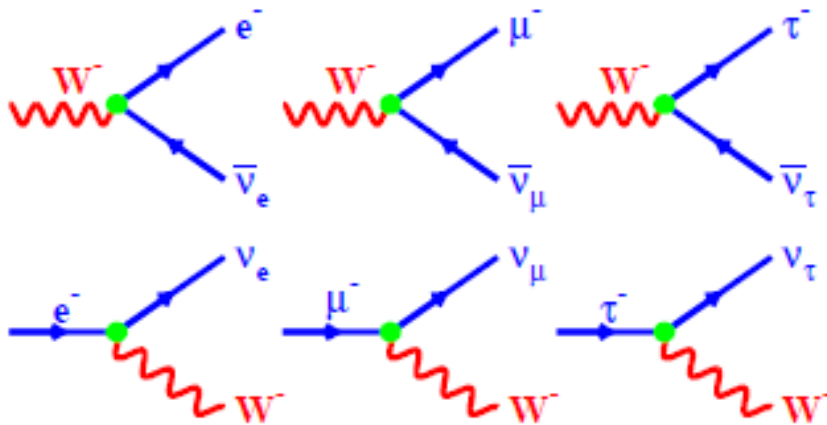


# Лептонни процеси - обобщение

- Лептоните участват в слабото взаимодействие като дублети:

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}, \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$

- Зарядът** на слабите взаимодействия се нарича **слаб изоспин**;
- W бозоните свързват само частиците от един и същ дублет:

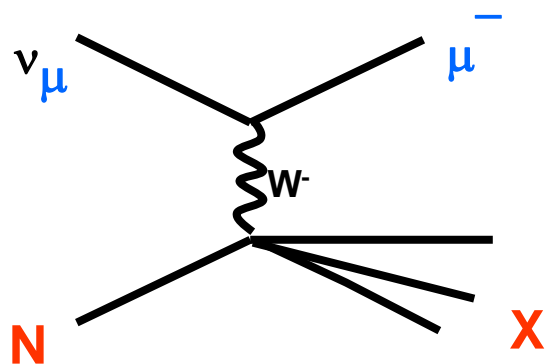


+ ермитово спрегнати (**W<sup>+</sup>**)

- Константата на слабите взаимодействия за лептонните процеси е универсална.

# Взаимодействие на неутриното с веществото

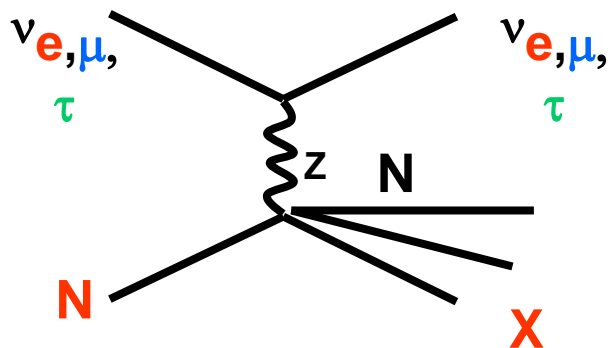
charged current (CC)



$$\nu_\mu + N \rightarrow \mu^- + X$$

$$\tilde{\nu}_\mu + N \rightarrow \mu^+ + X$$

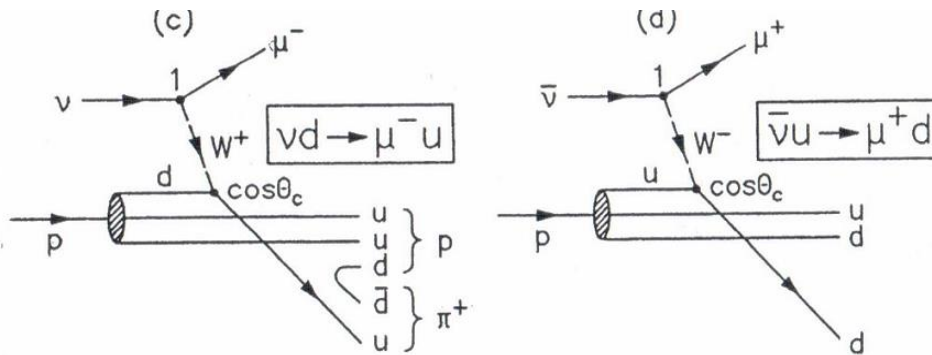
neutral current (NC)



$$\nu_\mu + N \rightarrow \nu_\mu + X$$

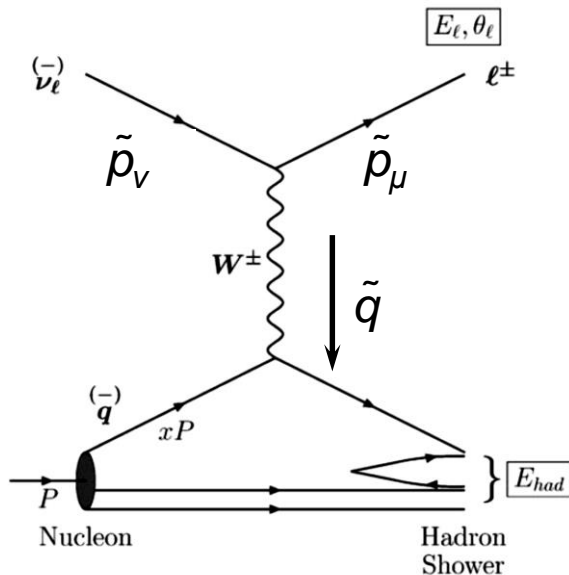
$$\tilde{\nu}_\mu + N \rightarrow \tilde{\nu}_\mu + X$$

# Кварк-партонна картина на взаимодействието на неутрината с веществото



$$\nu_{\mu} + N \rightarrow \mu^{-} + X$$

$$\bar{\nu}_{\mu} + N \rightarrow \mu^{+} + X$$

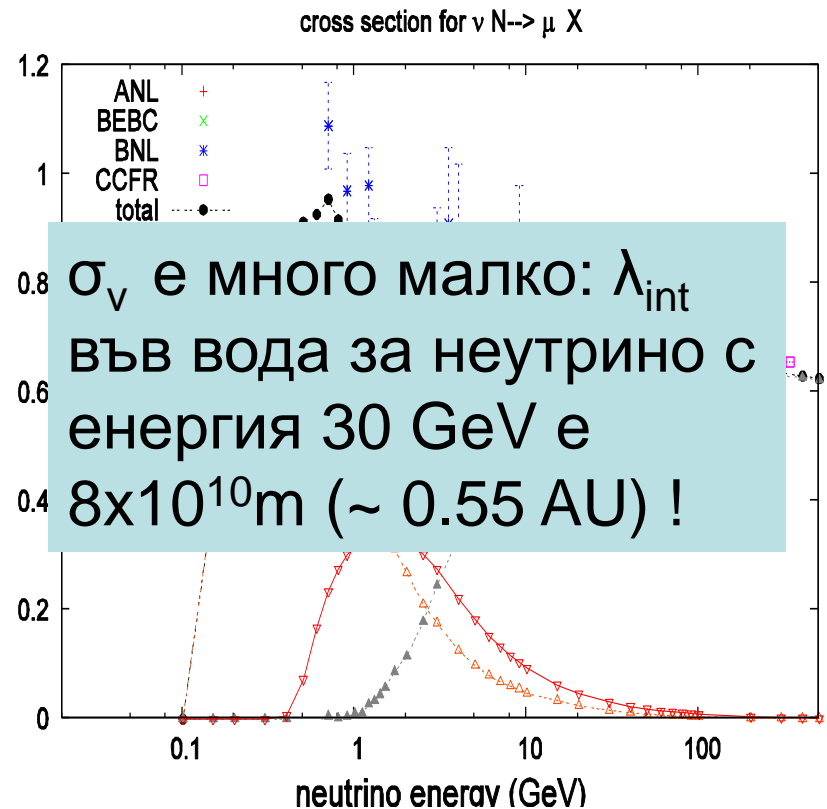
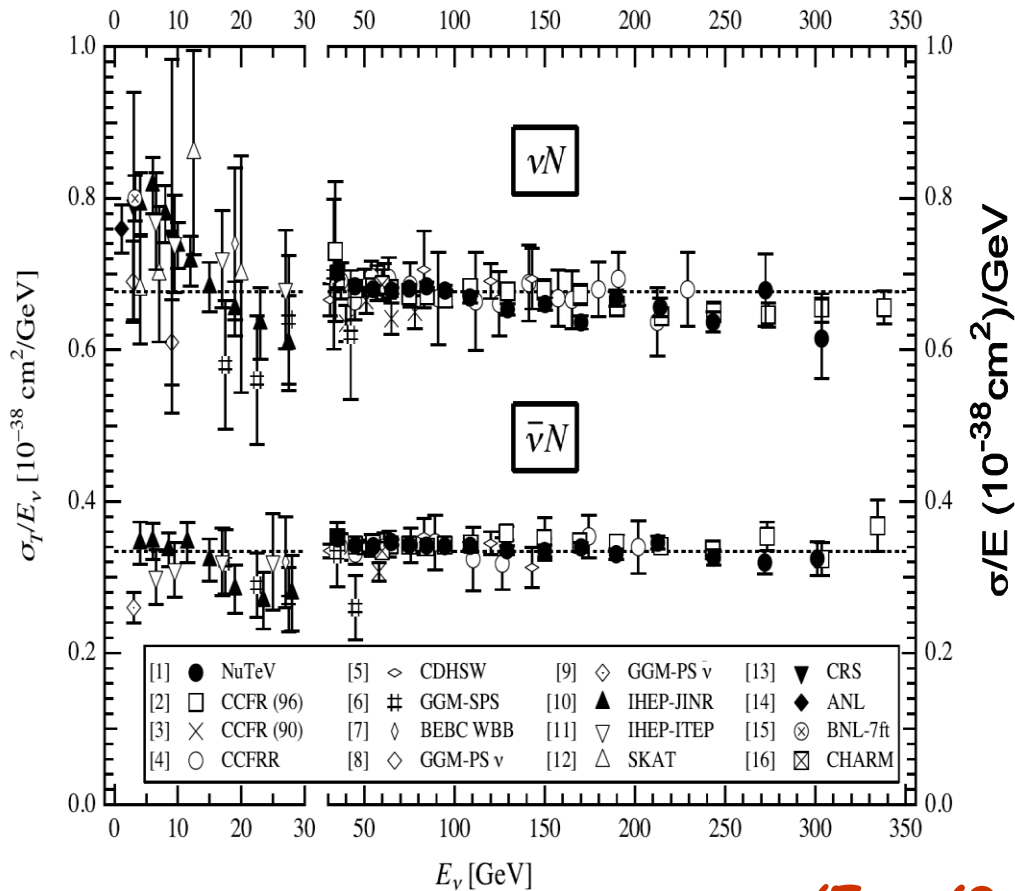


$$\tilde{q}^2 = (\tilde{p}_\nu - \tilde{p}_\mu)^2 = -Q^2 < 0$$

$$\nu = E_\nu - E_\mu = E_{had} - M_N = (\tilde{q} \cdot \tilde{p}_{had})/M_N$$

$$x_{Bjorken} = \frac{-\tilde{q}^2}{2\tilde{q} \cdot \tilde{p}_{had}} = \frac{Q^2}{2M\nu}$$

# Пълно сечение на СС - взаимодействие на неутрино с веществото

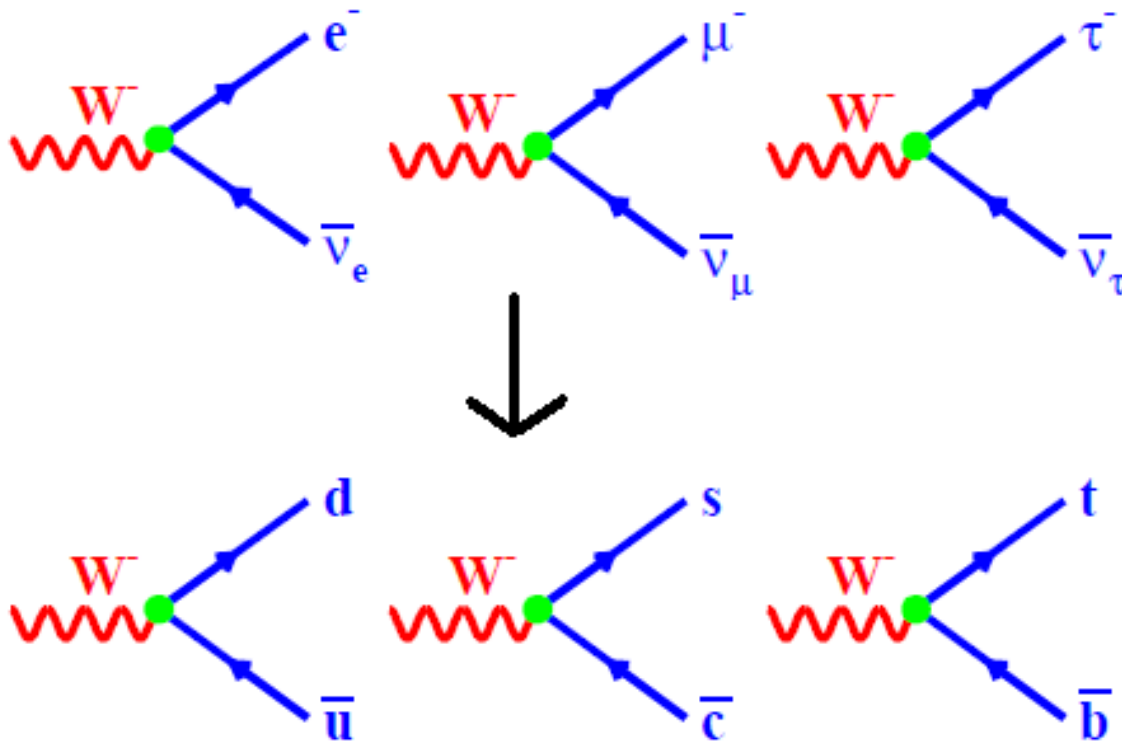


$$\sigma_\nu/E_\nu = (0.677 \pm 0.014) \times 10^{-38} \text{ cm}^2/\text{GeV}$$

$$\sigma_{\bar{\nu}}/E_{\text{anti-}\nu} = (0.334 \pm 0.008) \times 10^{-38} \text{ cm}^2/\text{GeV}$$

## Слаби процеси с кварки

- Можем ли да приложим същия подход тук?



За съжаление не е толкова просто...

# Слаби процеси с кварки

- Състоянията, участващи в слабите взаимодействия (собствените състояния на слабия изоспин) са линейни комбинации на ароматните състояния:

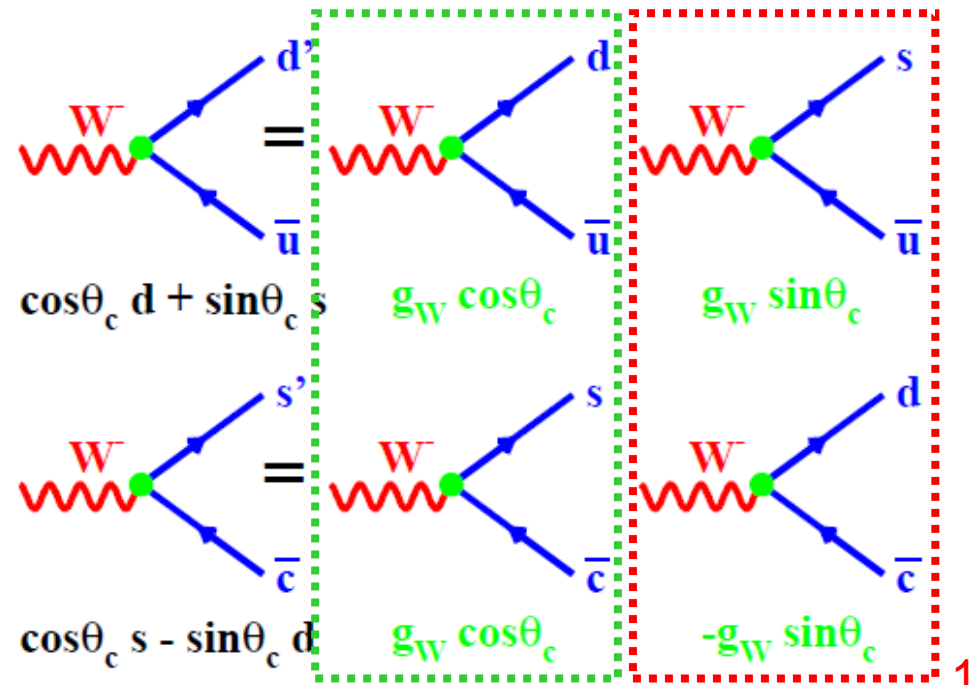
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos \theta_c & \sin \theta_c \\ -\sin \theta_c & \cos \theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

- Ако съществуват само 4 вида кварки (u, d, s, c) то смесването може да се опише с един единствен параметър  $\theta_c$  - ъгъл на Кабибо (Cabibbo).

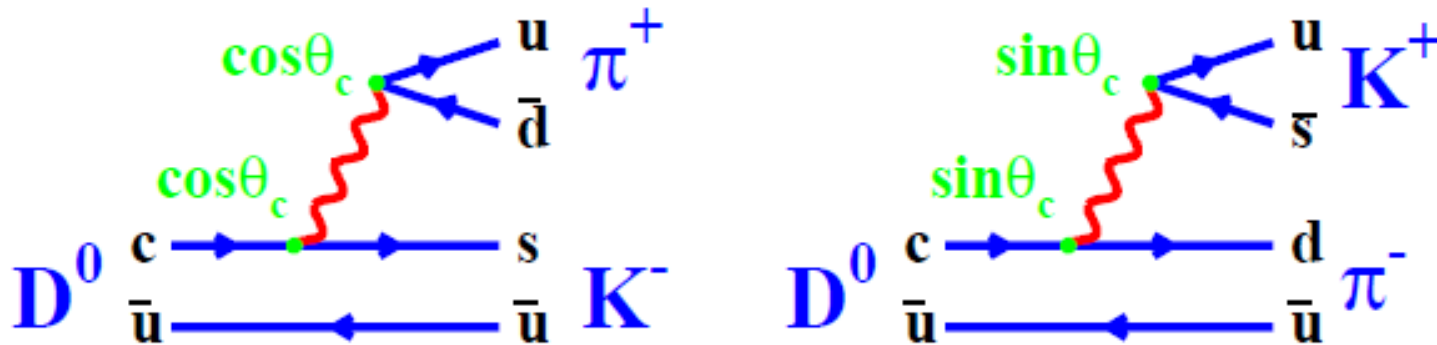
- Експериментално:  $\theta_c = 13^\circ$

• Кабибо разрешени

• Кабибо потиснати



# Слаби процеси с кварки



$$\frac{\Gamma(D^0 \rightarrow K^+ \pi^-)}{\Gamma(D^0 \rightarrow K^- \pi^+)} = \frac{\sin^4 \theta_c}{\cos^4 \theta_c} \approx 0.0028 \quad \text{Очаквано}$$

$$\text{Измерено} \quad 0.0038 \pm 0.0008$$

$D^0 \rightarrow K^+ \pi^-$  е двойно Кабибо потиснат процес.



# Слаби процеси с кварки

- Съществуват 6 кварка – *u, d, s, c, b, t*.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Матрица на **Cabibbo–Kobayashi–Maskawa**.

$$U_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Унитарна матрица, стандартно се параметризира с 3 Ойлерови ъгъла и една комплексна фаза.

# Обединение на електромагнитното и слабото взаимодействие

- Модел на Glashow-Weinberg-Salam

$$\begin{pmatrix} W^+ \\ W^0 \\ W^- \end{pmatrix}, B \rightarrow \begin{pmatrix} W^+ \\ Z^0 \\ W^- \end{pmatrix}, A$$

- Физично наблюдавани полета :

$W^+, W^-, Z^0, A$  (фотон)

$$Z^0 = W^0 \cos \theta_w - B \sin \theta_w$$

$$A = W^0 \sin \theta_w + B \cos \theta_w$$

- $W^+, W^-, Z^0$  получават маса посредством механизма на Higgs.
- Повече подробности в курса "Увод в теорията на елементарните частици".

# Модел на Glashow-Weinberg-Salam за слабото взаимодействие

Неутринните полета  
са леви и безмасови

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

лептони

кварки

$$m(\nu_e) \leq 2.3 \text{ eV}/c^2,$$

$$m(\nu_\mu) \leq 0.19 \text{ MeV}/c^2,$$

$$m(\nu_\tau) \leq 18.2 \text{ MeV}/c^2$$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L \quad \begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$$

$u_R \quad d_R \quad s_R \quad c_R \quad b_R \quad t_R \quad e_R \quad \mu_R \quad \tau_R$

слабо взаимодействие

$$SU_c(3) \times SU_W(2) \times U_Y(1)$$

$$\begin{array}{cccccc}
 \begin{pmatrix} u \\ d' \end{pmatrix}_L & \begin{pmatrix} c \\ s' \end{pmatrix}_L & \begin{pmatrix} t \\ b' \end{pmatrix}_L & \boxed{\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L} & \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L & \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L \\
 u_R & d_R & s_R & b_R & e_R & \mu_R & \tau_R
 \end{array}$$

$$\mathcal{L} = -e \left\{ A_\mu J_{em} + \frac{1}{\sqrt{2} \sin \theta_W} (W_\mu^+ \bar{\nu}_{eL} \gamma^\mu e_L + W_\mu^- \bar{e}_L \gamma^\mu \nu_{eL}) + \frac{1}{\sin \theta_W \cos \theta_W} Z_\mu J_{NC}^\mu \right\}$$

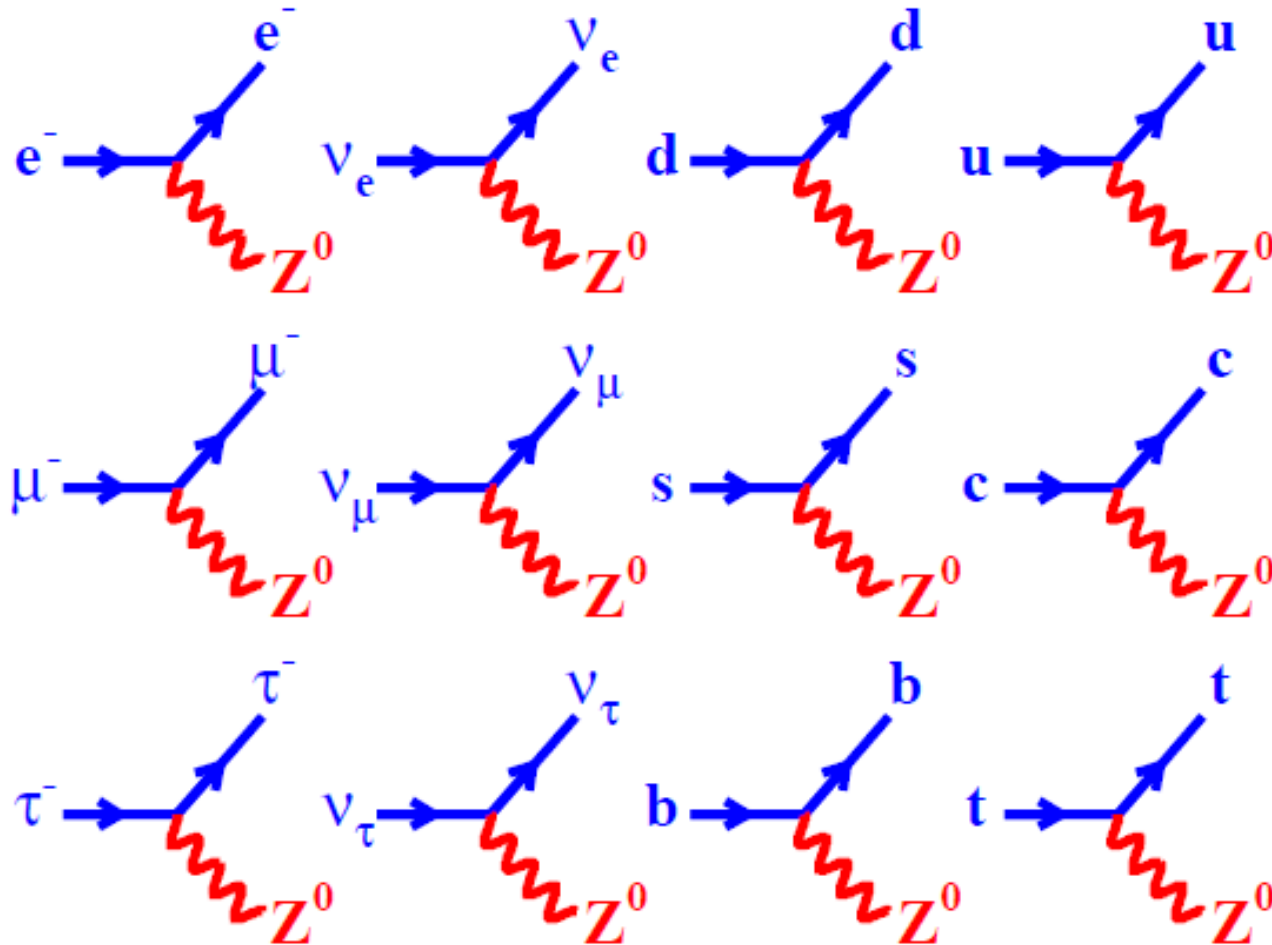
$$\sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

$$J_{em}^\mu = -\bar{e}_L \gamma^\mu e_L - \bar{e}_R \gamma^\mu e_R = -\bar{e} \gamma^\mu e$$

$$e = \frac{gg'}{\sqrt{g^2 + g'^2}} = g \sin \theta_W$$

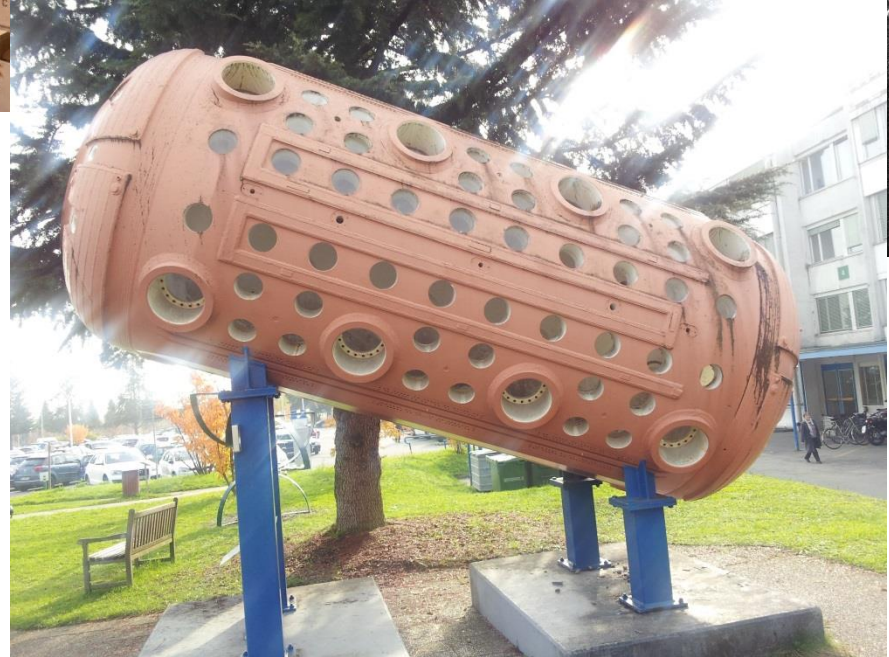
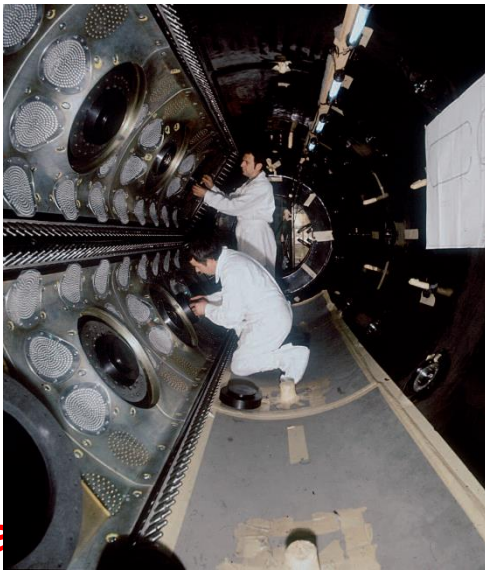
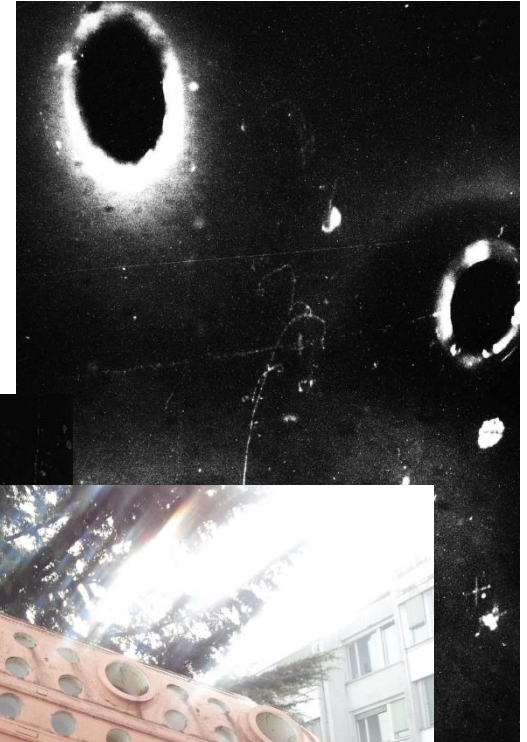
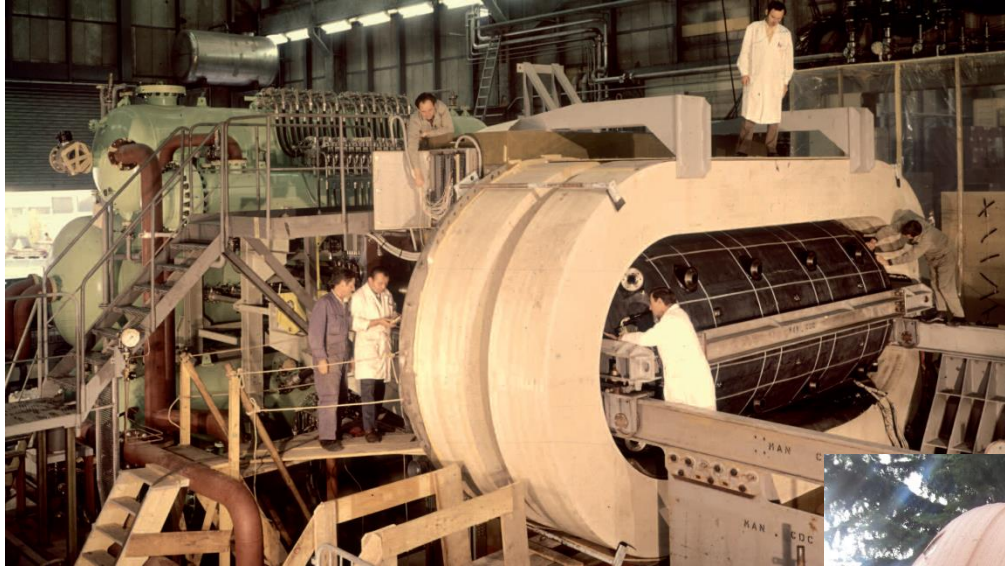
$$J_{NC}^\mu = \frac{1}{2} \bar{\nu}_{eL} \gamma^\mu \nu_{eL} - \frac{1}{2} \bar{e}_L \gamma^\mu e_L - \sin^2 \theta_W J_{em}^\mu$$

# Слаби неутрални токове



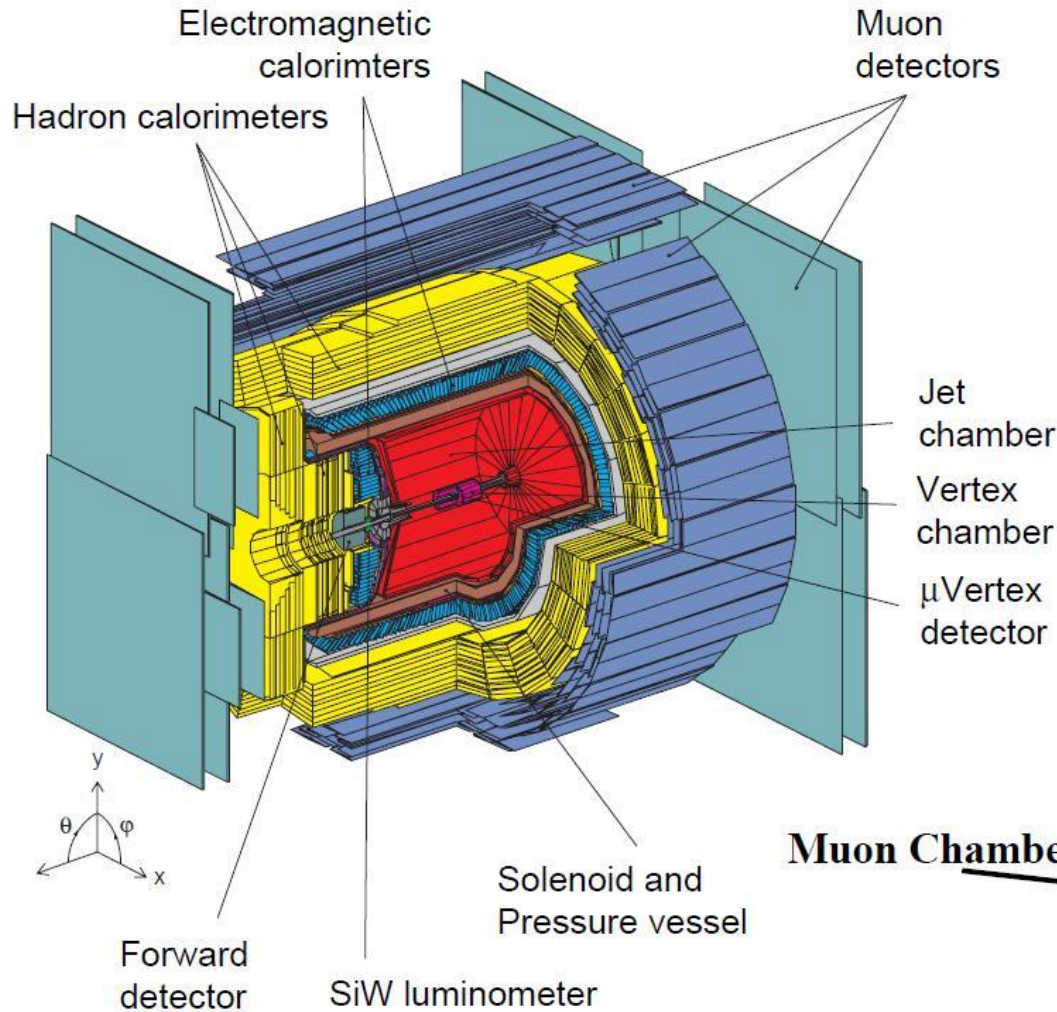
Не смесват ароматите

# Откриване на неутралните токове Gargamelle, 1973



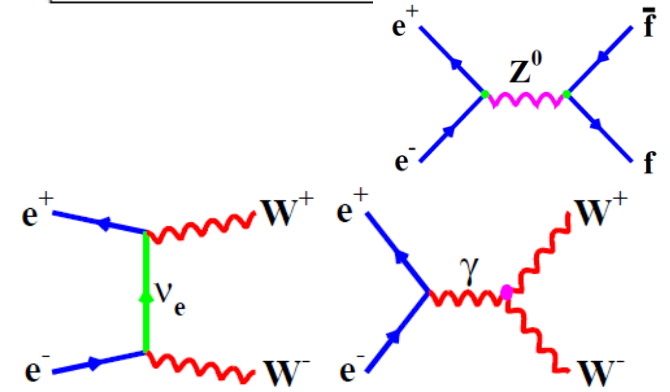
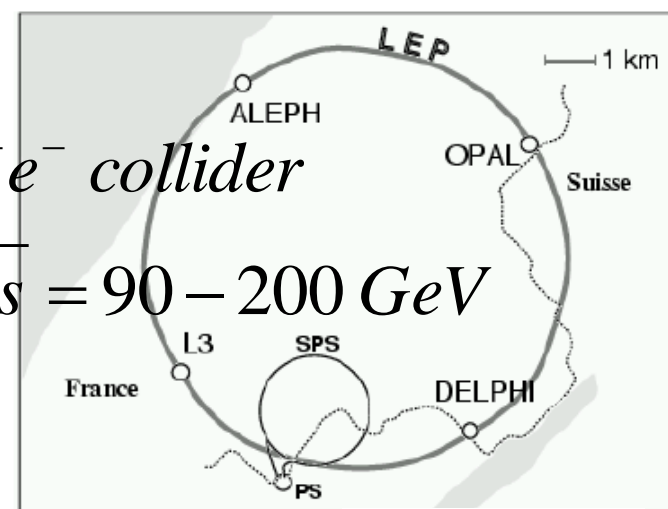


# A LEP Detector : OPAL



$e^+e^-$  collider

$$\sqrt{s} = 90 - 200 \text{ GeV}$$

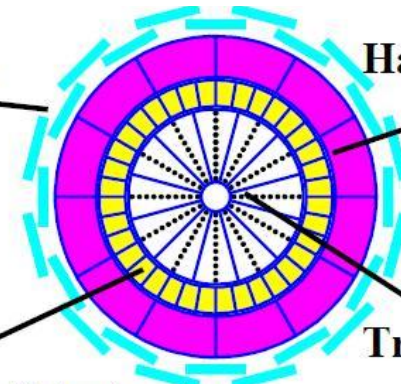


Muon Chambers

Hadron Calorimeter

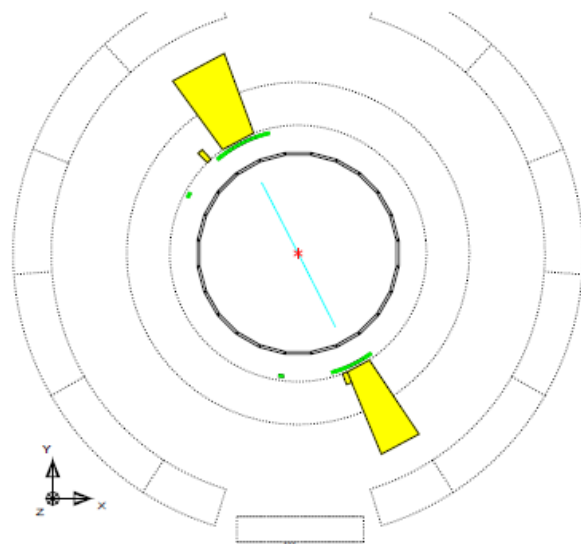
Electro-magnetic Calorimeter

Tracking Chambers

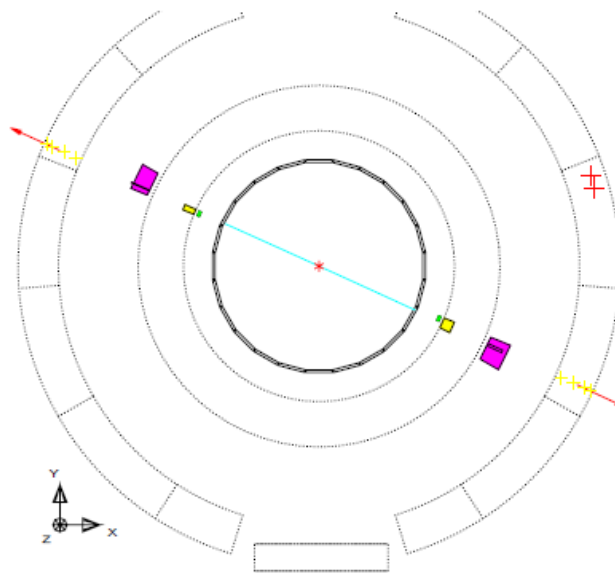




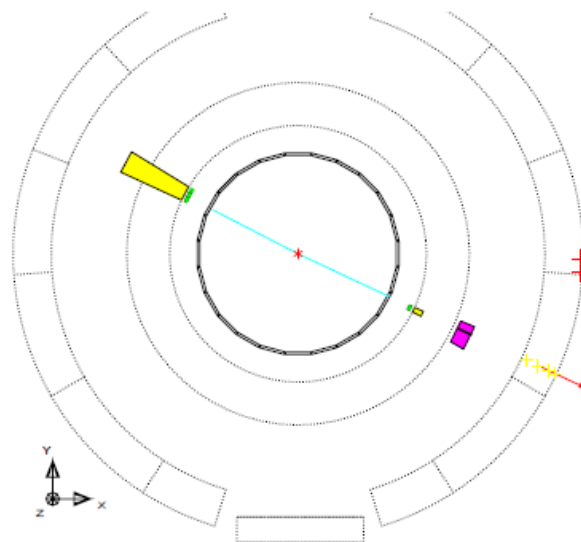
$$e^+e^- \rightarrow Z^0 \rightarrow e^+e^-$$



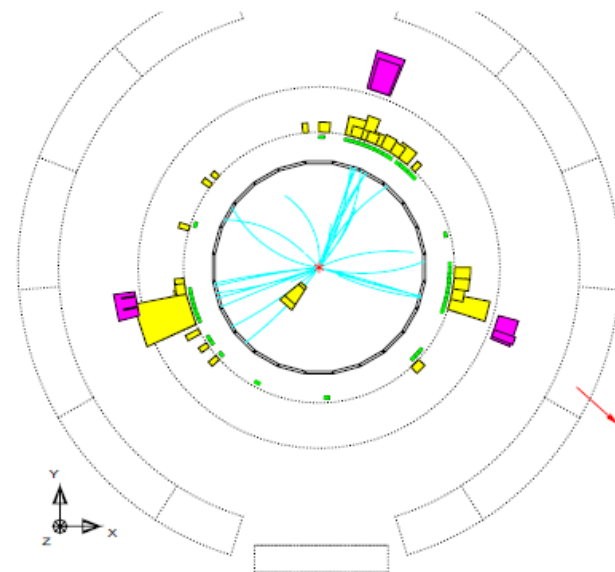
$$e^+e^- \rightarrow Z^0 \rightarrow \mu^+\mu^-$$



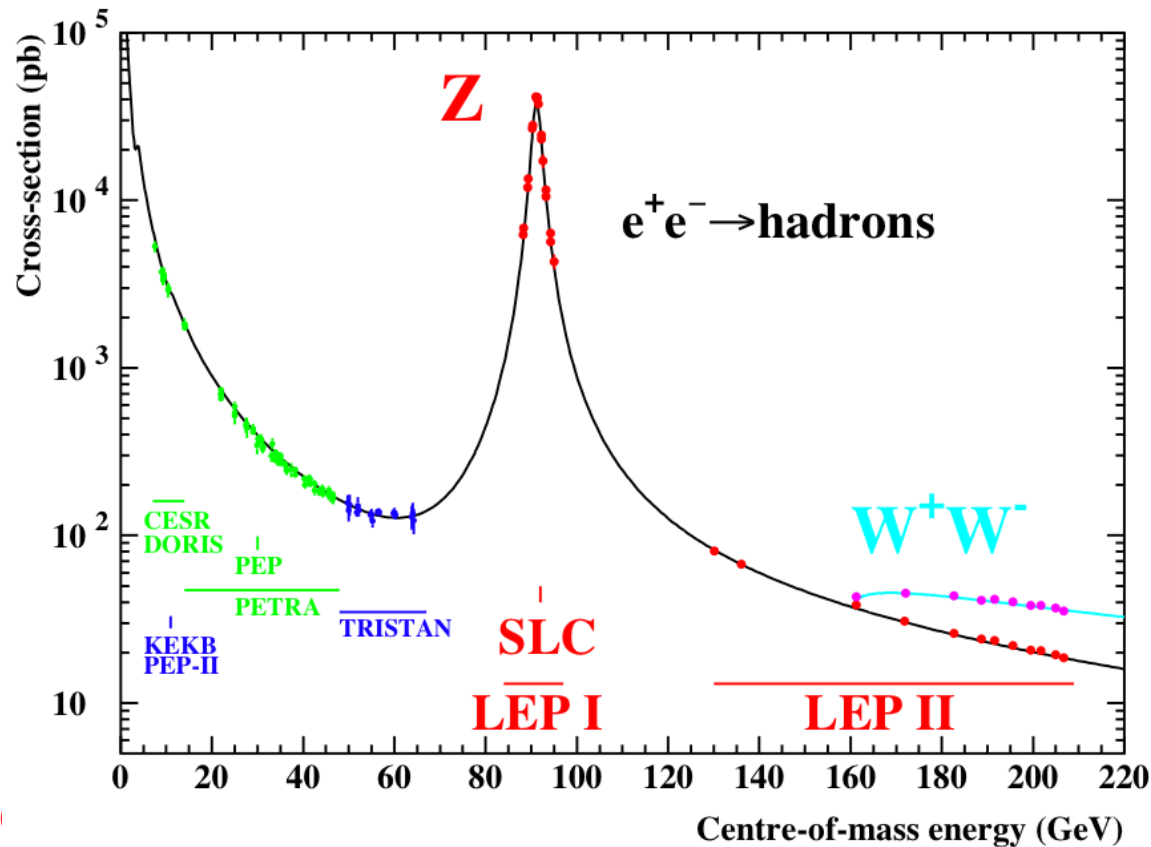
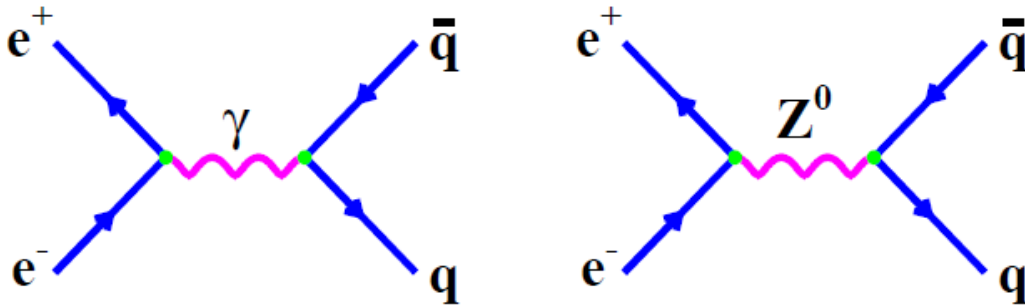
$$e^+e^- \rightarrow Z^0 \rightarrow \tau^+\tau^-$$



$$e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}$$



# $Z^0$ резонанс

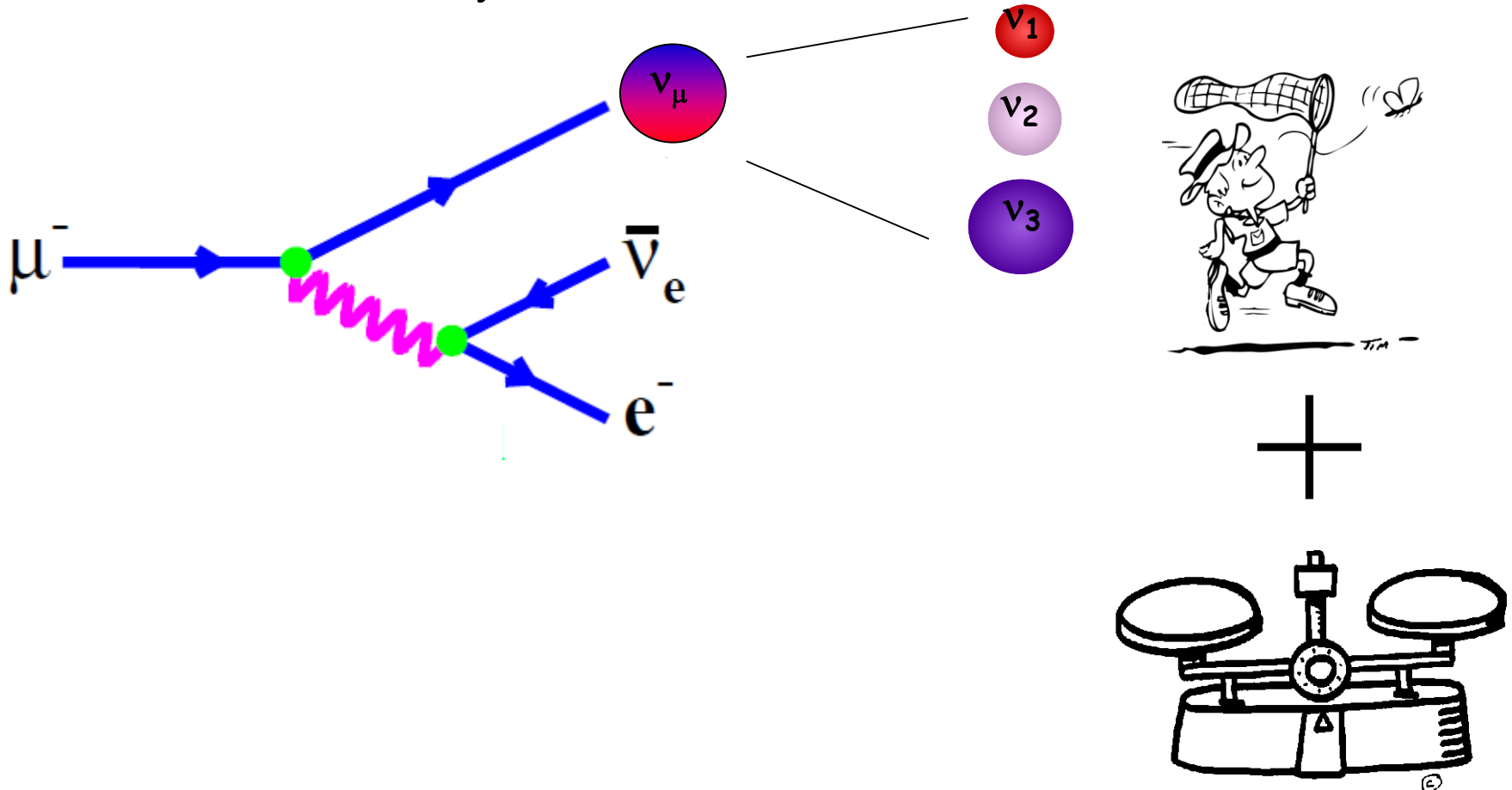


$$M_{W^\pm} = 80.385 \pm 0.015 \text{ GeV}/c^2$$

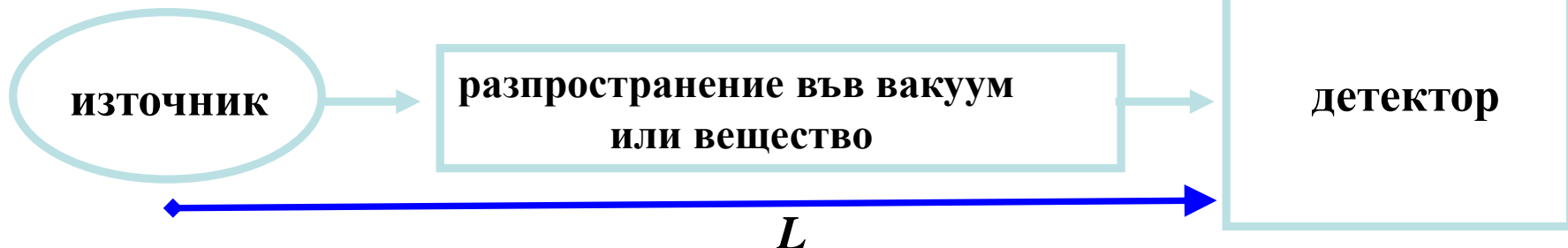
$$M_{Z^0} = 91.1876 \pm 0.0021 \text{ GeV}/c^2$$

# Обратно към лептоните

- А не съществува ли аналог на СКМ матрицата за лептонните слаби взаимодействия?
- Всъщност съществува.



# Осцилации на неутрината



раждат се състояния  
с определен аромат  
(напр. от  $\pi \rightarrow \mu\nu$ )

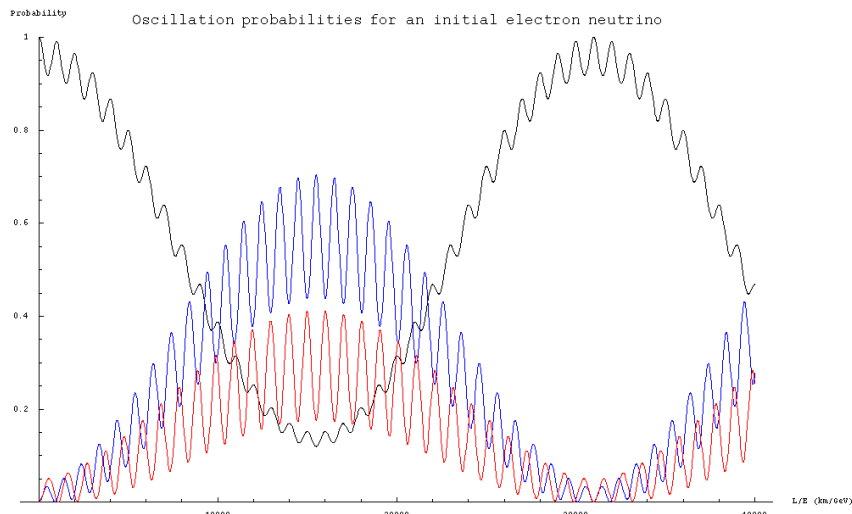
$$|\nu_\mu\rangle = \alpha |\nu_1\rangle + \beta |\nu_2\rangle + \gamma |\nu_3\rangle$$

$$t \sim L/E$$

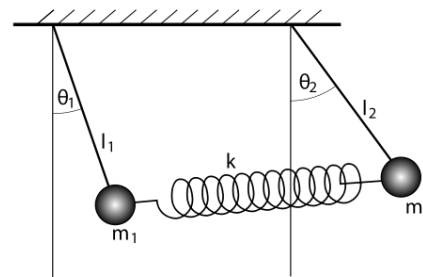
$$|\nu(t)\rangle = \alpha |\nu_1\rangle \exp(i E_1 t) + \beta |\nu_2\rangle \exp(i E_2 t) + \gamma |\nu_3\rangle \exp(i E_3 t)$$

слабо взаимодействие (СС)

$$\begin{aligned} \nu_\mu N &\rightarrow \mu^- X \\ \nu_e N &\rightarrow e^- X \\ \nu_\tau N &\rightarrow \tau^- X \end{aligned}$$



$$P(\mu \rightarrow \tau) = |\langle \nu_\tau | \nu(t) \rangle|^2$$



В изложението са използвани материали от:

- М.А. Thomson - Particle Physics (лекции)  
<http://www.hep.phy.cam.ac.uk/~thomson/particles/>
- J. Terning - Standard Model (лекции)  
<http://indico.cern.ch/conferenceDisplay.py?confId=91719>
- H. Murayama - The Standard Model (лекции)  
<http://indico.cern.ch/conferenceDisplay.py?confId=57516>
- A. Pich - The Standard Model (лекции)  
<http://indico.cern.ch/conferenceDisplay.py?confId=a07165>
- [http://en.wikipedia.org/wiki/Main\\_Page](http://en.wikipedia.org/wiki/Main_Page)