

Rozdział 5

**System neutralnych kaonów,
oscylacje dziwności,
regeneracja składowej krótkożyciowej.
Niezachowanie parzystości CP.
Odkrycie asymetrii kierunku czasu.
Oscylacje neutralnych mezonów B**

Oscylacje dziwności

$$\Psi(t) = \Psi(0) e^{-i\omega t} e^{-t/2\tau} = \Psi_0 e^{-i\frac{E}{\hbar}t} e^{-\frac{\Gamma t}{2\hbar}} = \Psi_0 e^{-imt} e^{-t/2\tau}$$

$$\hbar = 1, \quad \Gamma/\hbar = 1/\tau$$

Zaczynamy od stanu neutralnego kaonu o ustalonej dziwności

$$|\Psi(t=0)\rangle \equiv |K^0\rangle = \frac{1}{\sqrt{2}} \left(|K_1^0\rangle + |K_2^0\rangle \right)$$

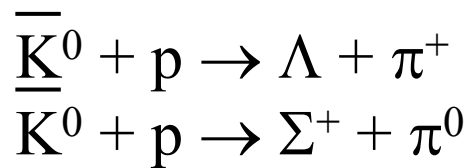
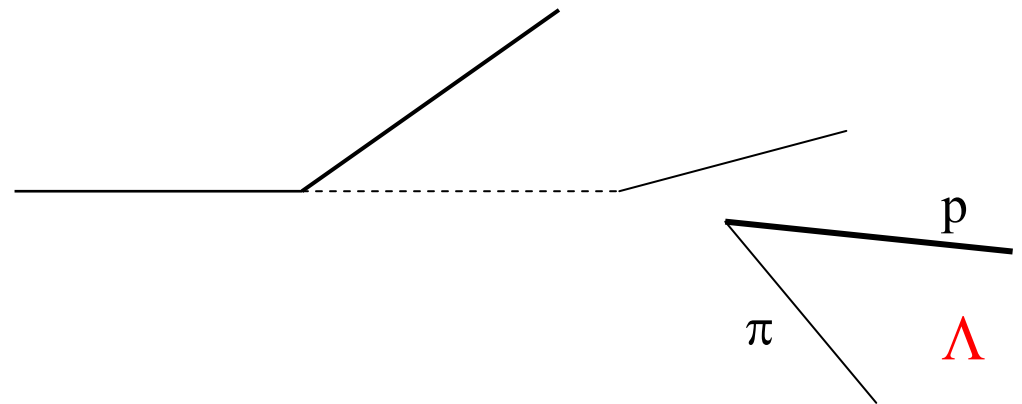
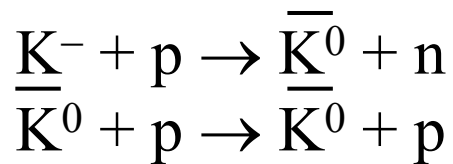
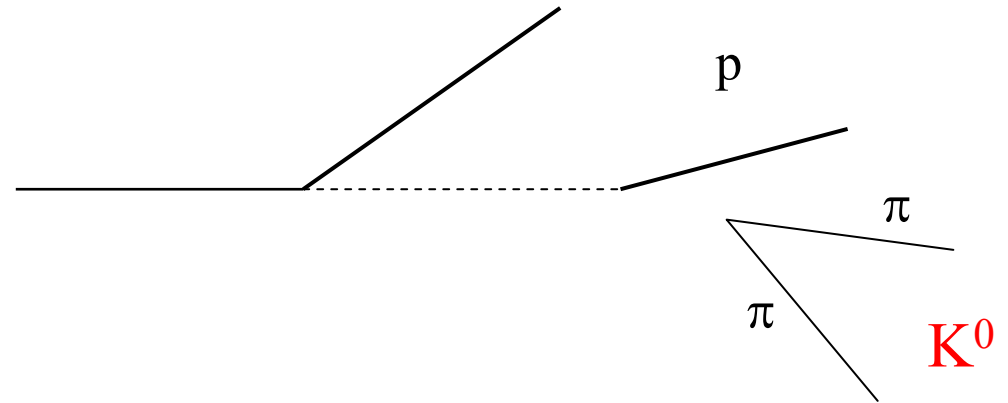
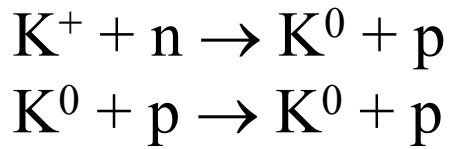
$$|\Psi(t)\rangle = \frac{1}{\sqrt{2}} \left[e^{-im_1 t - t/2\tau_1} |K_1^0\rangle + e^{-im_2 t - t/2\tau_2} |K_2^0\rangle \right]$$
$$\underbrace{\frac{1}{\sqrt{2}} \left(|K^0\rangle - |\overline{K}^0\rangle \right)}_{\text{CP-odd}} \quad \underbrace{\frac{1}{\sqrt{2}} \left(|K^0\rangle + |\overline{K}^0\rangle \right)}_{\text{CP-even}}$$

$$|\Psi(t)\rangle = \frac{1}{2} \left\{ \left[e^{-im_1 t - t/2\tau_1} + e^{-im_2 t - t/2\tau_2} \right] |K^0\rangle + \left[e^{-im_2 t - t/2\tau_2} - e^{-im_1 t - t/2\tau_1} \right] |\bar{K}^0\rangle \right\}$$

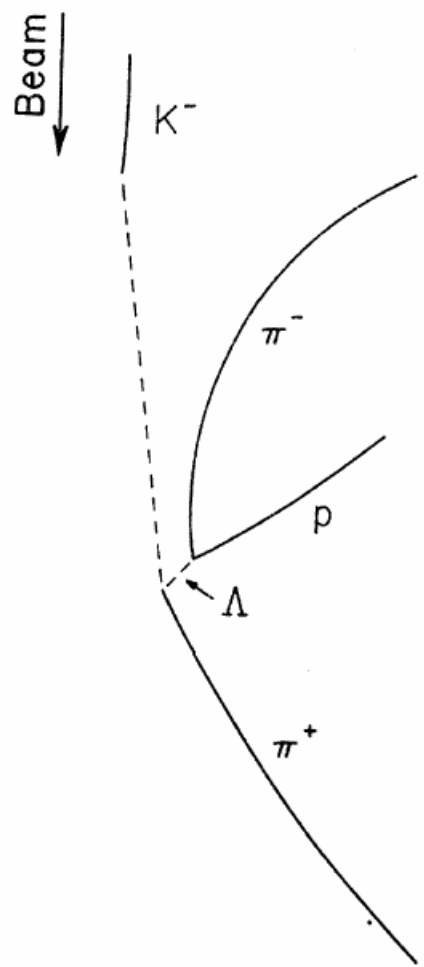
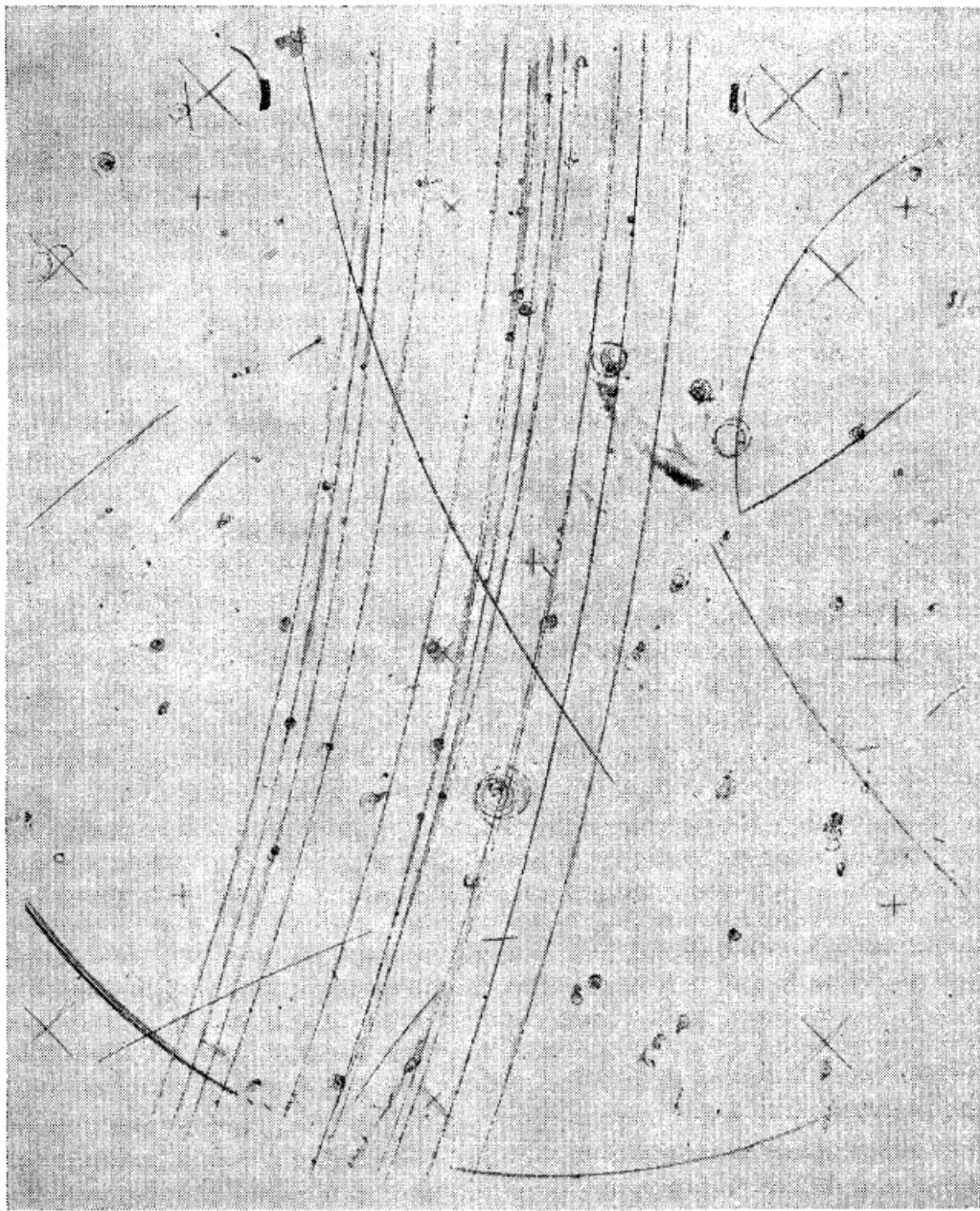
Prawdopodobieństwo obserwacji $P(K^0, t) = \left| \langle K^0 | \Psi(t) \rangle \right| =$

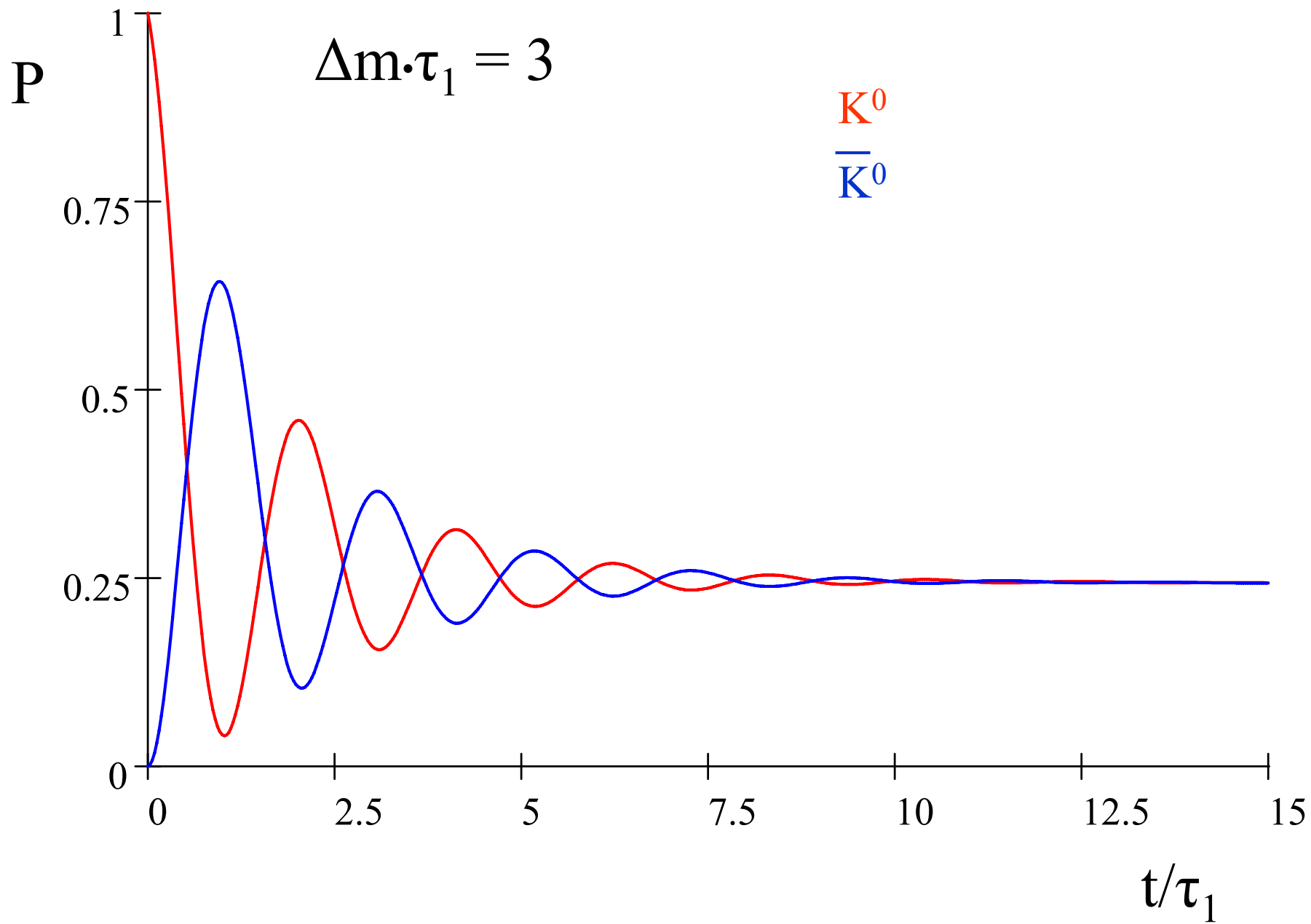
$$= \frac{1}{4} \left(e^{-t/\tau_1} + e^{-t/\tau_2} + 2e^{-\left(\frac{t}{2\tau_1} + \frac{t}{2\tau_2}\right)} \cos(\Delta m \cdot t) \right)$$

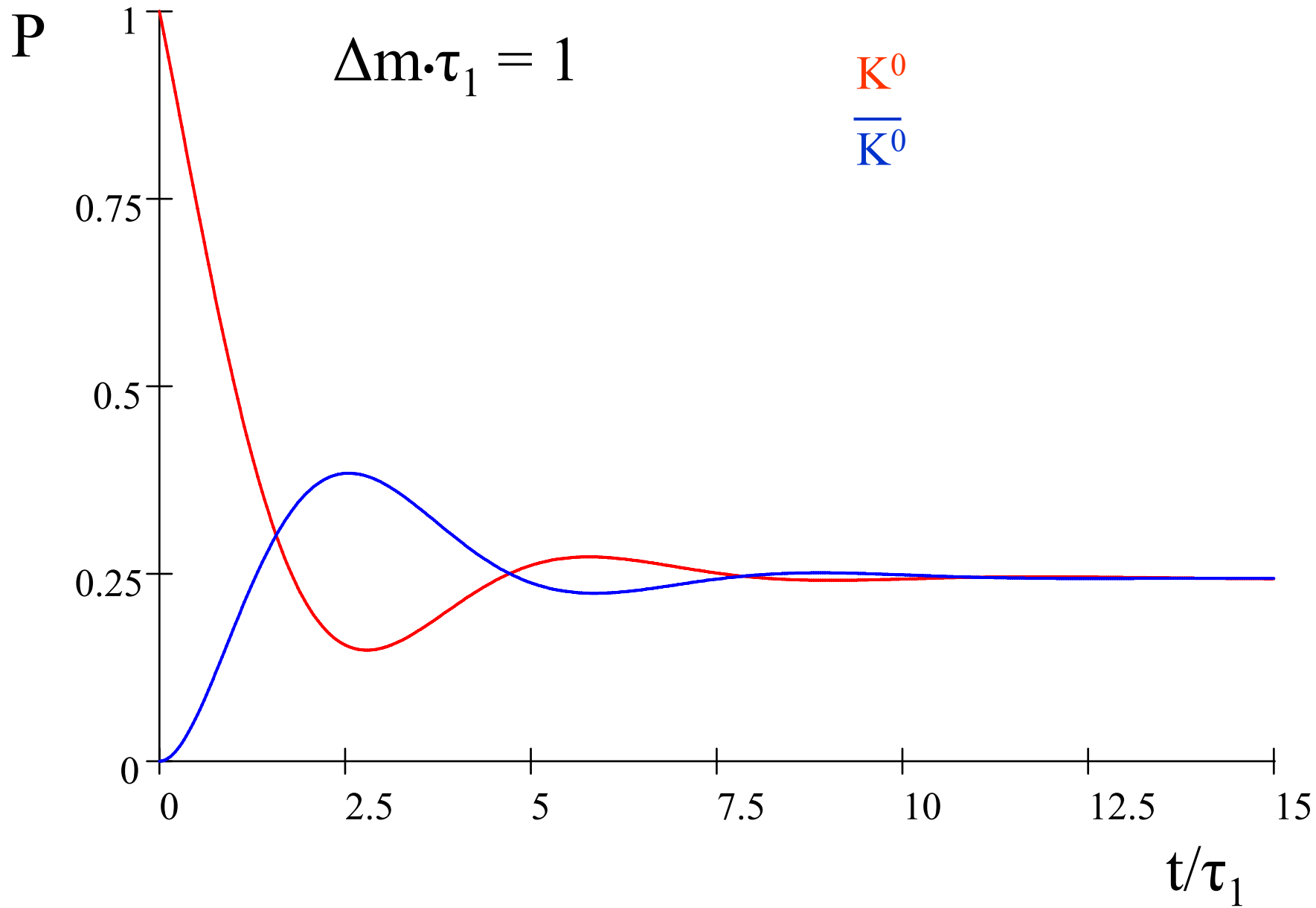
$$P(\bar{K}^0, t) = \frac{1}{4} \left(e^{-t/\tau_1} + e^{-t/\tau_2} - 2e^{-\left(\frac{t}{2\tau_1} + \frac{t}{2\tau_2}\right)} \cos(\Delta m \cdot t) \right)$$

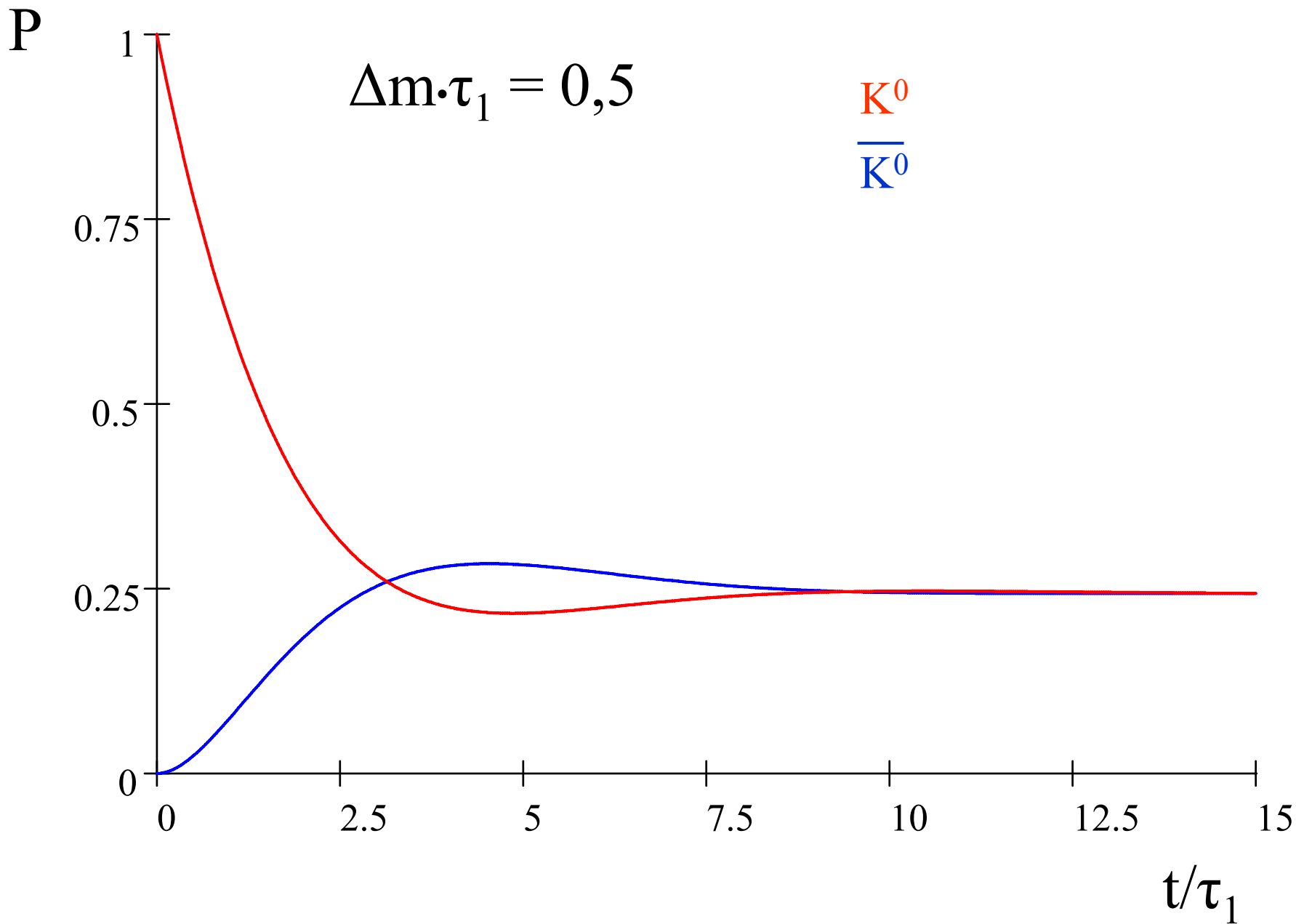


Obserwacja produkcji hiperonów pozwala wykryć obecność dziwności o przeciwnym znaku

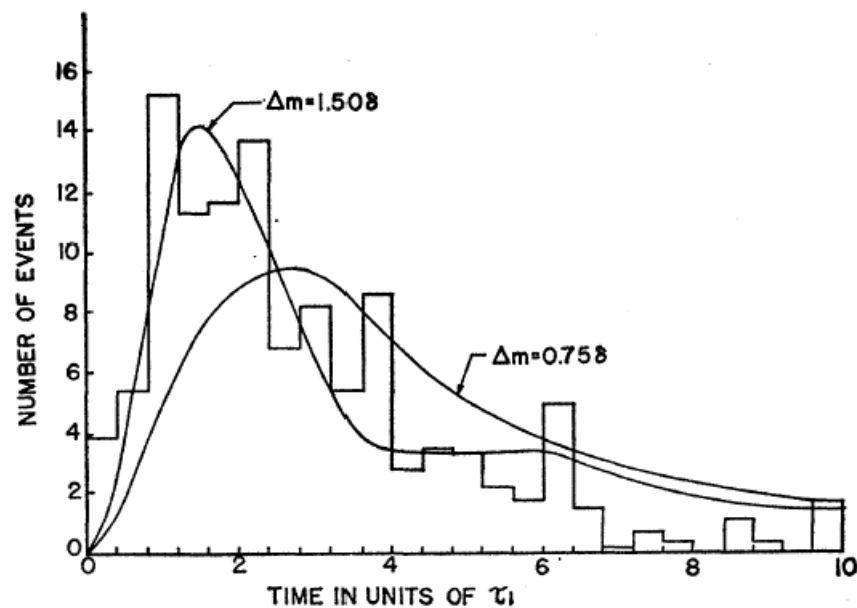
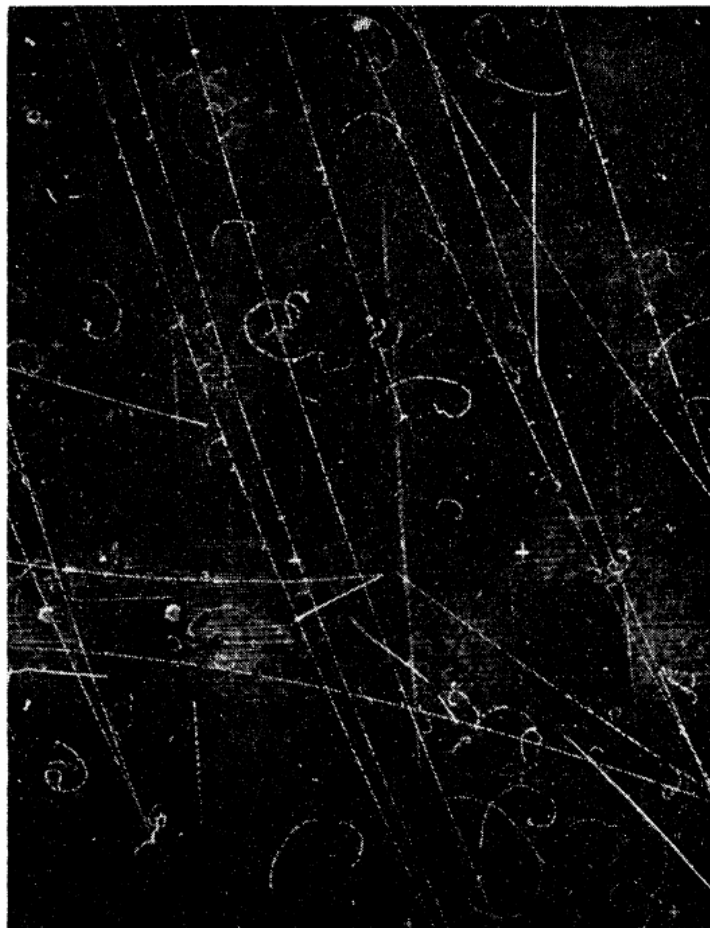








Jeden z pierwszych eksperymentów, w których wyznaczano Δm
U. Camerini et al., Phys. Rev. **128**, 362 (1962)



rozkład oddziaływań \bar{K}^0
z produkcją hiperonów Λ

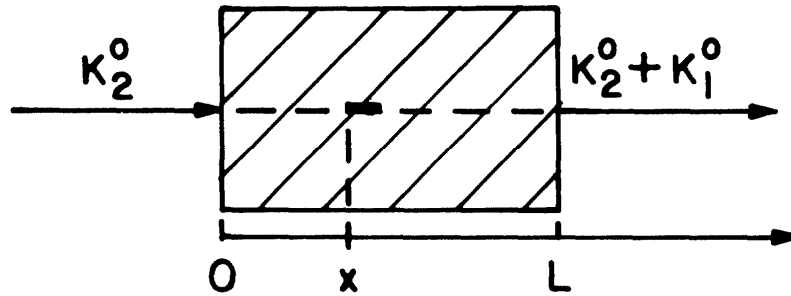
$$\begin{aligned}\Delta m &= m_2 - m_1 = (0,5292 \pm 0,0009)10^{10} \hbar s^{-1} = \\ &\approx 0,529210^{10} \times 6,582 \times 10^{-22} \text{MeV} \cdot s \cdot s^{-1} = \\ &= 3,483 \times 10^{-12} \text{MeV} = 3,483 \times 10^{-6} \text{eV}\end{aligned}$$

$$\tau_1 = (0,8958 \pm 0,0005) \times 10^{-10} \text{s}$$

PDG 2008

$$\Delta m \cdot \tau_1 \approx 0,5292 \times 0,8958 \hbar \approx 0,474$$

Regeneracja koherentna kaonów



$$A_2(x) = \exp(ip_2x)$$

(zaniedbujemy rozpad K_2)

Amplituda konwersji $K_2^0 \rightarrow K_1^0$ $dA_1(x) \sim (f - \bar{f})A_2(x)dx$

Uwzględnienie τ_1 $\Lambda = \gamma_1 v_1 \tau_1$

$$dA_1(L) = e^{ip_1(L-x) - (L-x)/2\Lambda} dA_1(x)$$

$$A_1(L) = \int_0^L dA_1(L) = \text{const} \cdot (f - \bar{f}) e^{-p_1 L - L/2\Lambda} \int_0^L dx e^{i(p_2 - p_1)x} e^{x/2\Lambda}$$

$$|\mathbf{K}_2^0\rangle = \frac{1}{\sqrt{2}} \left(|\mathbf{K}^0\rangle + |\overline{\mathbf{K}}^0\rangle \right)$$

$$\begin{aligned} |\text{reg}\rangle &= \frac{1}{\sqrt{2}} \left(f |\mathbf{K}^0\rangle + \bar{f} |\overline{\mathbf{K}}^0\rangle \right) = \frac{1}{\sqrt{2}} \left(\frac{f}{2} |\mathbf{K}^0\rangle + \frac{\bar{f}}{2} |\overline{\mathbf{K}}^0\rangle + \frac{f}{2} |\mathbf{K}^0\rangle + \frac{\bar{f}}{2} |\overline{\mathbf{K}}^0\rangle \right) = \\ &= \frac{f + \bar{f}}{2\sqrt{2}} \left(|\mathbf{K}^0\rangle + |\overline{\mathbf{K}}^0\rangle \right) + \frac{f - \bar{f}}{2\sqrt{2}} \left(|\mathbf{K}^0\rangle - |\overline{\mathbf{K}}^0\rangle \right) = \\ &= \frac{1}{2} (f + \bar{f}) |\mathbf{K}_2^0\rangle + \frac{1}{2} (f - \bar{f}) |\mathbf{K}_1^0\rangle \end{aligned}$$

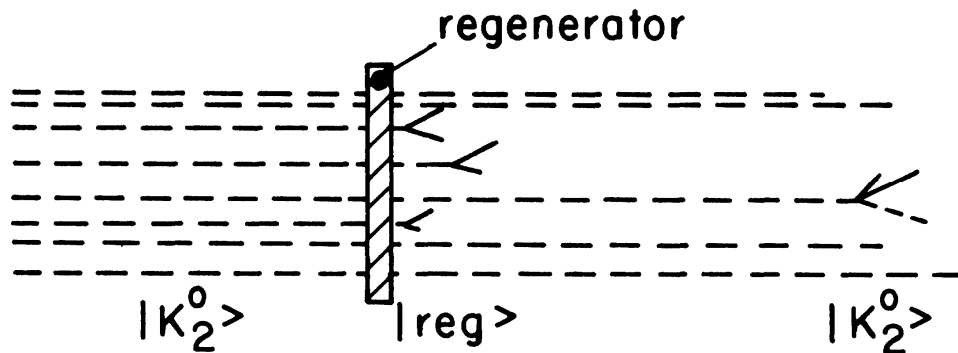
$$|\mathbf{K}_2^0\rangle = \frac{1}{\sqrt{2}} \left(|\mathbf{K}^0\rangle - |\overline{\mathbf{K}}^0\rangle \right)$$

$$\begin{aligned} |\text{reg}\rangle &= \frac{f + \bar{f}}{2\sqrt{2}} \left(|\mathbf{K}^0\rangle - |\overline{\mathbf{K}}^0\rangle \right) + \frac{f - \bar{f}}{2\sqrt{2}} \left(|\mathbf{K}^0\rangle + |\overline{\mathbf{K}}^0\rangle \right) = \\ &= \frac{1}{2} (f + \bar{f}) |\mathbf{K}_2^0\rangle + \frac{1}{2} (f - \bar{f}) |\mathbf{K}_1^0\rangle \end{aligned}$$

wynik nie zależy od konwencji zapisu

Regeneracja koherentna kaonów

Przy rozpraszaniu do przodu



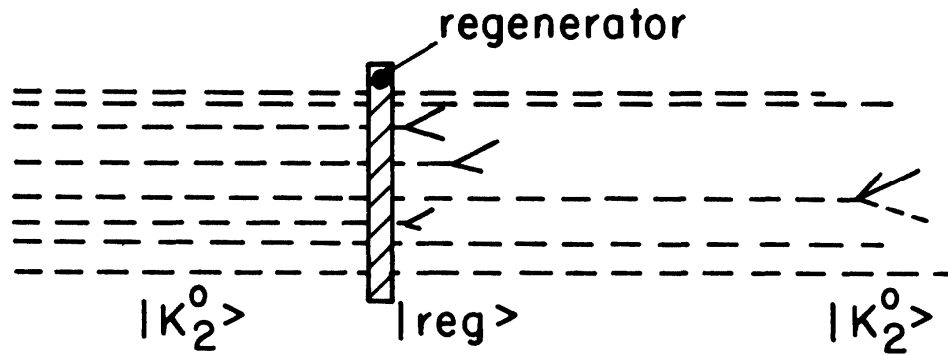
$$p_1^2 + m_1^2 = p_2^2 + m_2^2$$

$$p_2^2 - p_1^2 = (p_2 + p_1)(p_2 - p_1) = (m_1 - m_2)(m_1 + m_2)$$

$$p_2 - p_1 = \frac{m}{p} \Delta m$$

Prawdopodobieństwo obserwacji K_1^0 po grubej płytce $L \gg \Lambda$

$$P(K_1^0, L) = P_0 \left[1 + e^{-L/2\Lambda} - 2e^{-L/2\Lambda} \cos\left(\frac{m}{p} \Delta m \cdot L\right) \right]$$



$$\lambda = \frac{2\pi\hbar}{p} \approx \frac{2\pi \cdot 2 \cdot 10^{-11} \text{ MeV} \cdot \text{cm}}{10^3 \text{ MeV}} \approx 1,2 \cdot 10^{-13} \text{ cm}$$

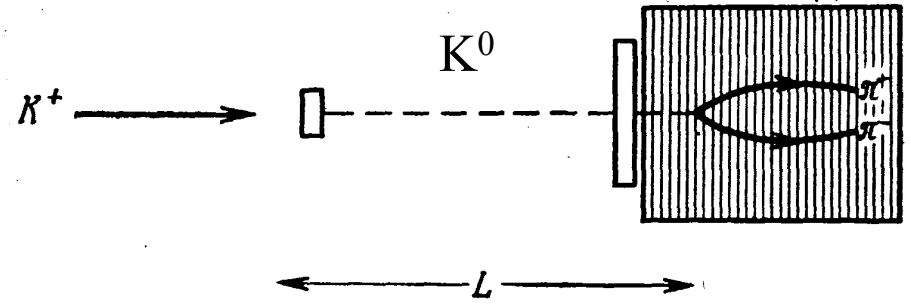
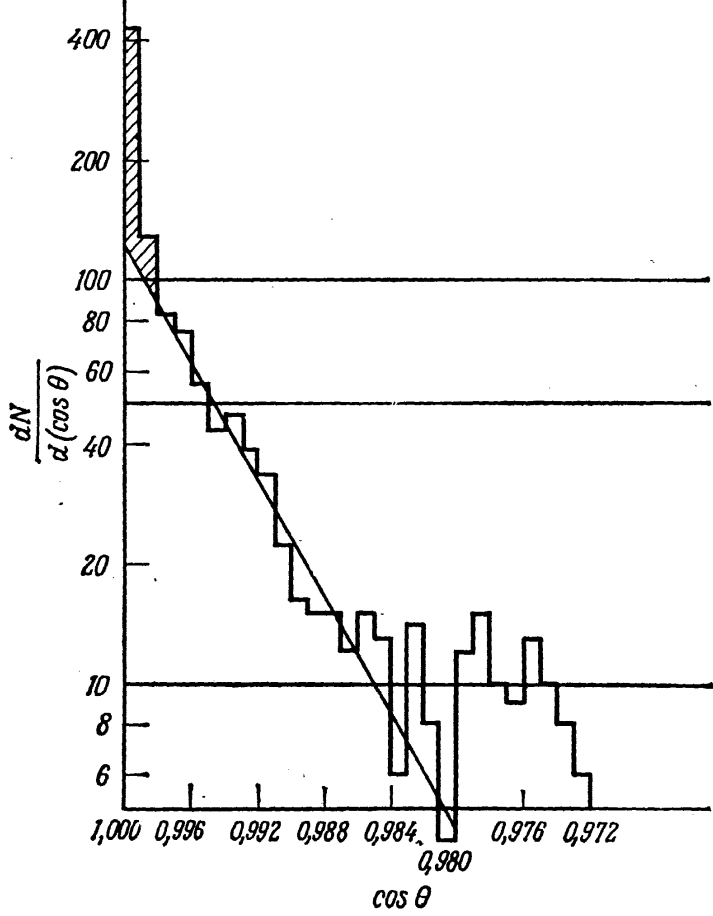
$$\Delta\theta = \frac{\lambda}{d} \approx \frac{1,2 \cdot 10^{-13} \text{ cm}}{20 \text{ cm}} \approx 10^{-14}$$

dla płytki

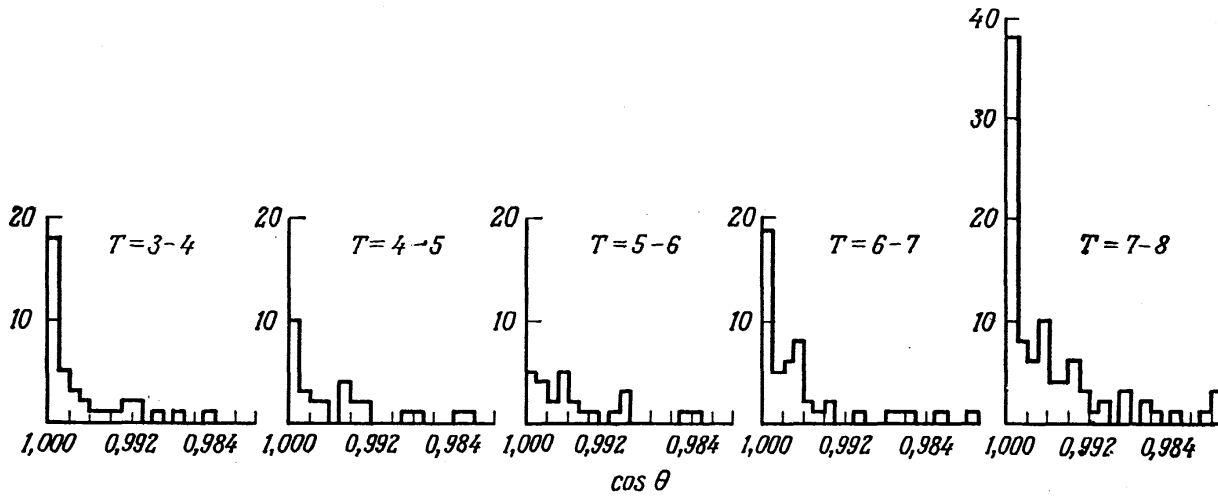
$$\Delta\theta = \frac{\lambda}{d} \approx \frac{1,2 \cdot 10^{-13} \text{ cm}}{10^{-13} \text{ cm}} \approx 1$$

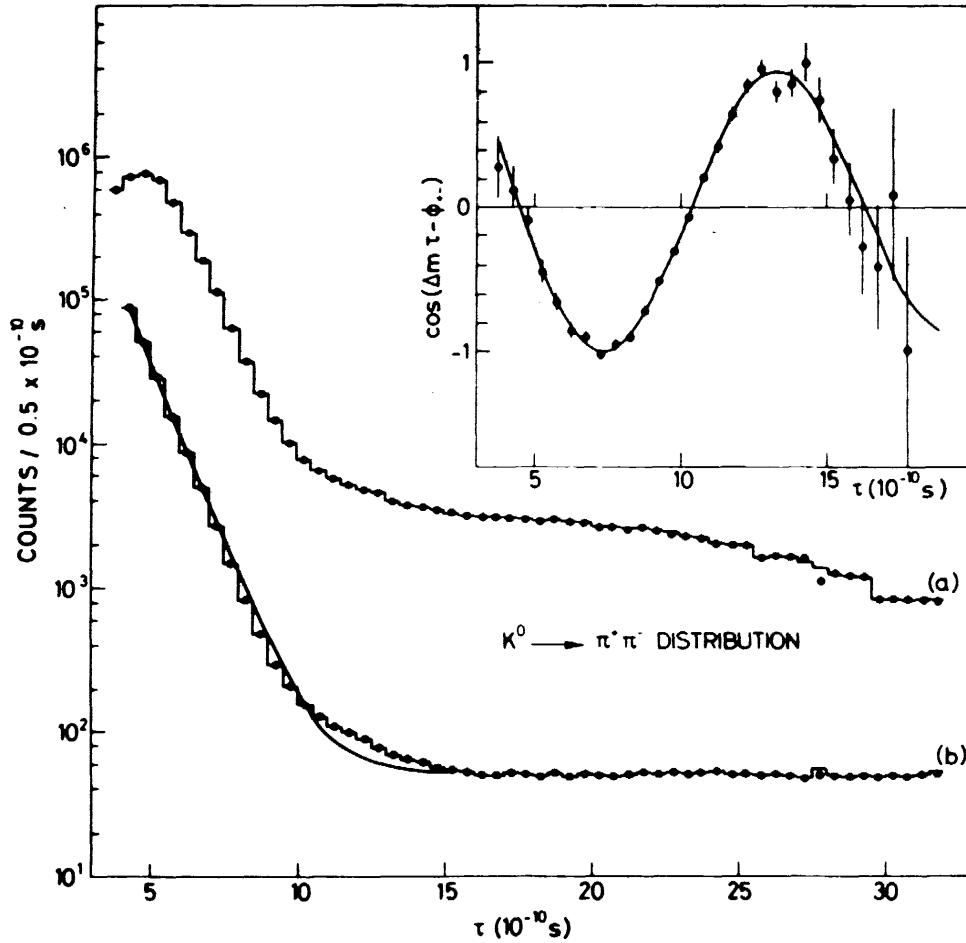
dla jąder atomowych

Interferencja składowej regenerowanej i składowej wprost



$$T = L/\Lambda$$

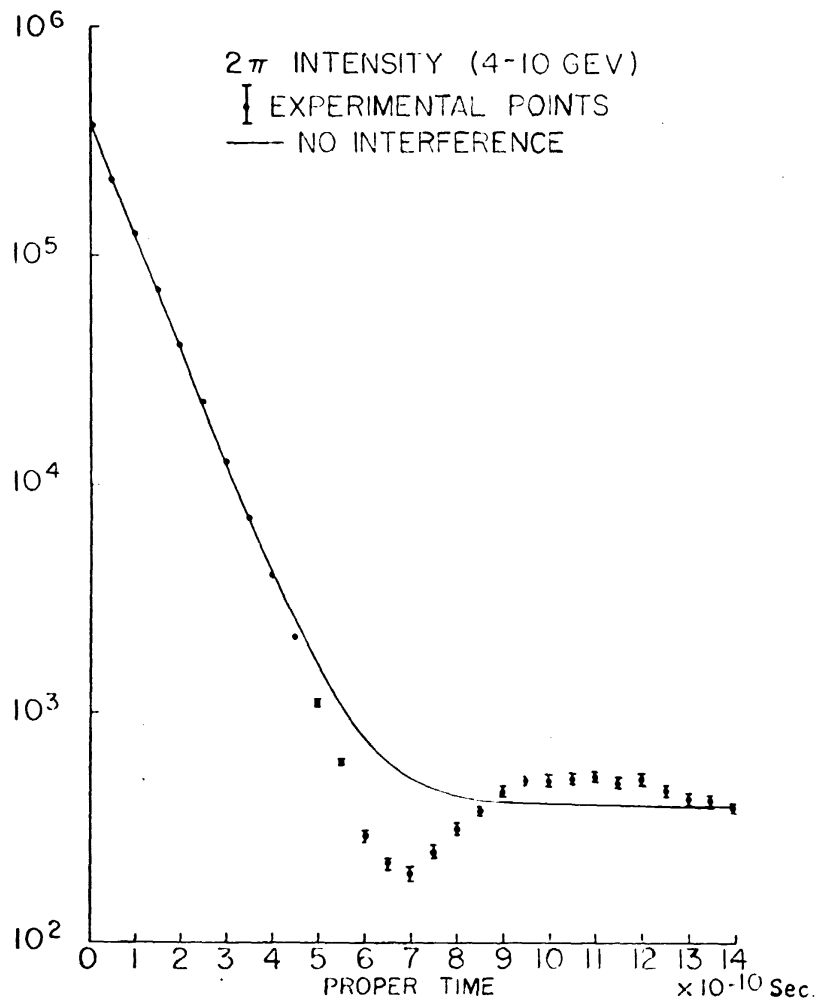




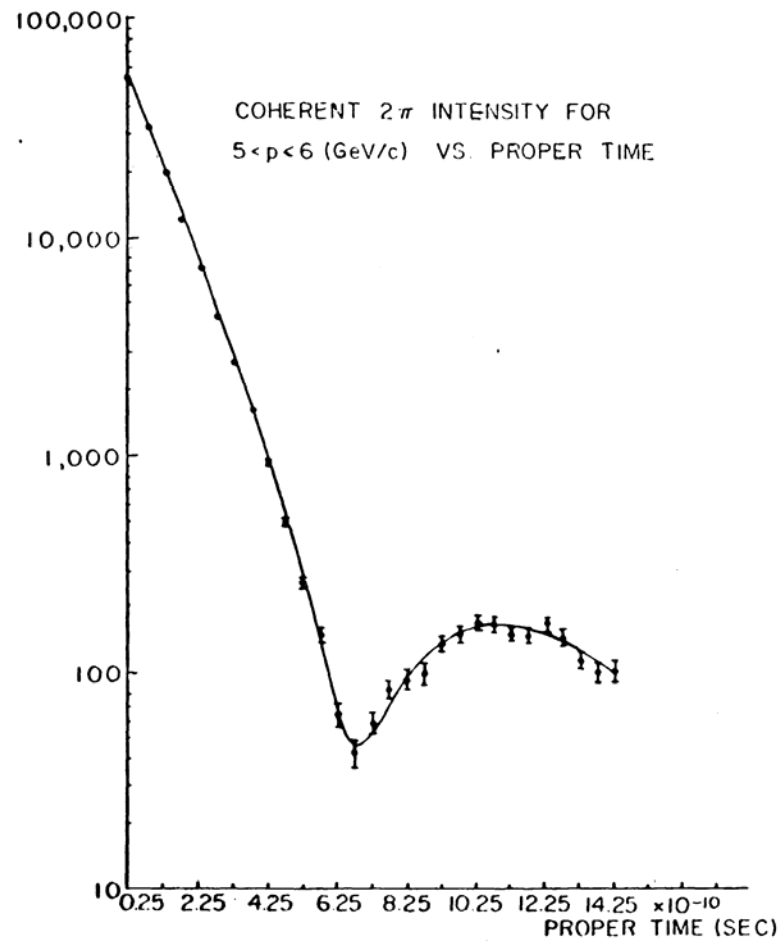
Time distribution of $K \rightarrow \pi^+ \pi^-$ events in the vacuum interference experiment

- (a) Events (histogram) and fitted distribution (dots).
- (b) Events corrected for efficiency (histogram), fitted distribution with interference term (dots) and without interference term (full line); scale arbitrary. Insert: Interference term as extracted from data (dots) and fitted term (line).

$$I_{2\pi}(t) = I_{2\pi}(0) \left[e^{-\Gamma_S t} + |\eta_{+-}| e^{-\Gamma_L t} + 2|\eta_{+-}| e^{[(\Gamma_S + \Gamma_L)/2]t} \cos(\Delta m \cdot t + \Phi_{+-}) \right]$$



Time dependence of $K \rightarrow \pi^+ \pi^-$ intensity behind a regenerator. Curve indicates fit without interference term.



Time dependence of $K_{L,S} \rightarrow \pi^+ \pi^-$ intensity from ref. 78 for the kaon momentum bin $5 < p < 6$ GeV/c. Curve shows result of fit.

Odkrycie niezachowania CP

Odkrycie niezachowania CP



V.L.Fitch

R.Turlay

J.W.Cronin

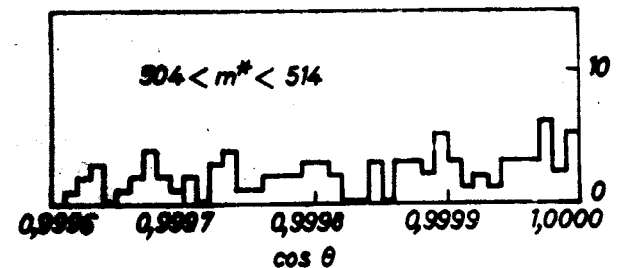
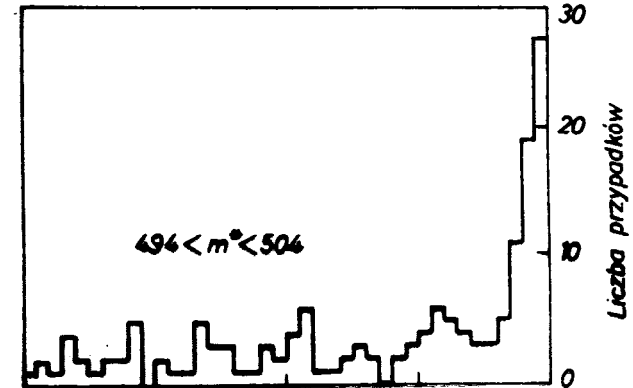
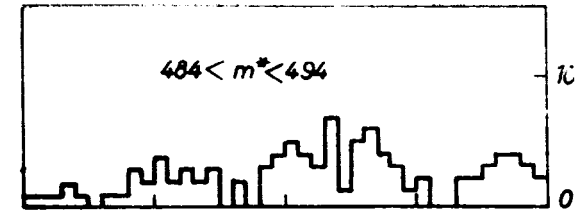
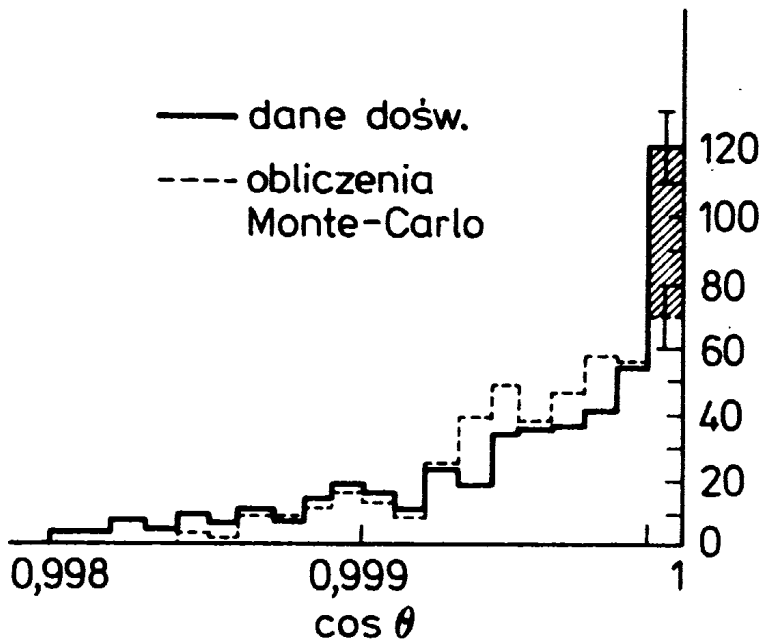
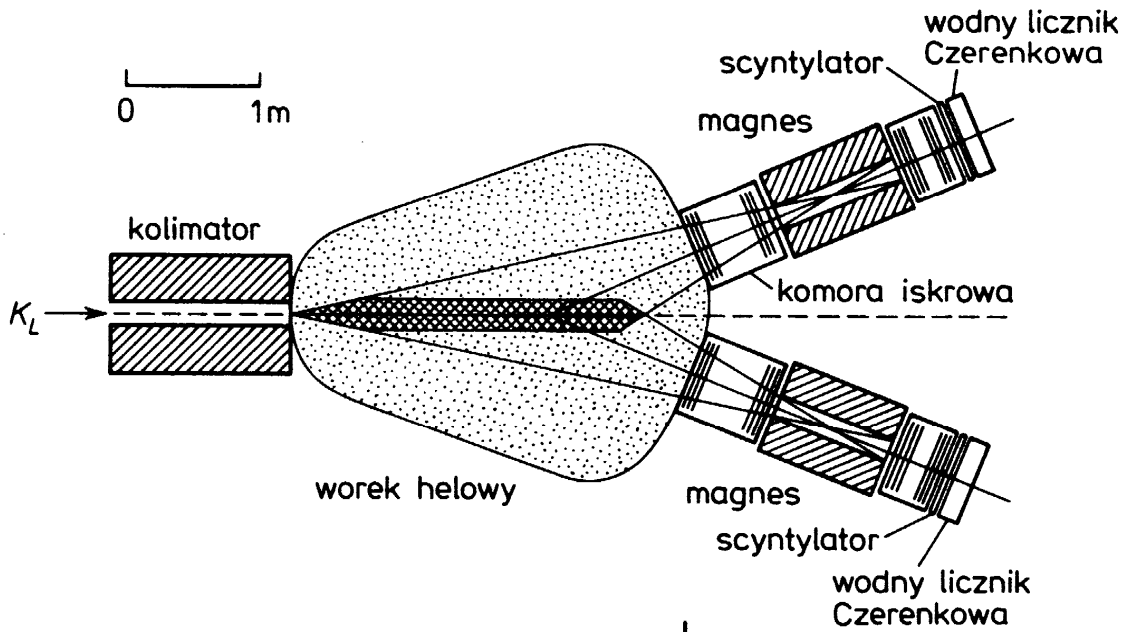
J.H.Christenson

J. H. Christenson,
J. Cronin,
V. Fitch,
R. Turlay,
Phys. Rev. Lett. **13**, 138 (1964)

$$(\mathbf{K}_2^0 \rightarrow \pi\pi) \approx 0,2\%$$

Odkrycie niezachowania CP

J. H. Christenson, J. Cronin,
V. Fitch, R. Turley,
Phys. Rev. Lett. **13**, 138 (1964)



Rozpady neutralnych mezonów K

$$\begin{aligned}
 M^2 &= (\sum E)^2 - (\sum \bar{p})^2 = (E_1 + E_2)^2 - (\bar{p}_1 + \bar{p}_2)^2 = \\
 &= (E_1^2 + E_2^2 + 2E_1E_2) - (p_1^2 + p_2^2 + 2p_1p_2 \cos \theta) = \\
 &= m_1^2 + p_1^2 + m_2^2 + p_2^2 + 2(m_1^2 + p_1^2)^{\frac{1}{2}}(m_2^2 + p_2^2)^{\frac{1}{2}} - (p_1^2 + p_2^2 + 2p_1p_2 \cos \theta) = \\
 &= m_1^2 + m_2^2 + 2(m_1^2 + p_1^2)^{\frac{1}{2}}(m_2^2 + p_2^2)^{\frac{1}{2}} - 2p_1p_2 \cos \theta
 \end{aligned}$$

Rozpad K_L	%	pęd w MeV/c
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$\pi^\pm e^\mp \nu_e$	40,6	229
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$\pi^\pm \mu^\mp \nu_\mu$	27,0	216
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$\pi^+ \pi^- \pi^0$	12,5	133
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$3\pi^0$	19,5	139
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$\pi^+ \pi^-$	0,2	206
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$K_L \approx K_2$

$$\eta_{+-} = |\eta_{+-}| e^{i\Phi_{+-}} = \frac{A(K_L^0 \rightarrow \pi^+ \pi^-)}{A(K_S^0 \rightarrow \pi^+ \pi^-)}$$

$$|\eta_{+-}| = (2,233 \pm 0,012) \cdot 10^{-3}$$

$$|\eta_{00}| = (2,222 \pm 0,012) \cdot 10^{-3}$$

$$\eta_{00} = |\eta_{00}| e^{i\Phi_{00}} = \frac{A(K_L^0 \rightarrow \pi^0 \pi^0)}{A(K_S^0 \rightarrow \pi^0 \pi^0)}$$

$$\Phi_{+-} = (43,4 \pm 0,8)^\circ$$

$$\Phi_{00} = (43,7 \pm 0,7)^\circ$$

$$|\eta_{+-0}|^2 = \frac{\Gamma(K_S^0 \rightarrow \pi^+ \pi^- \pi^0)}{\Gamma(K_L^0 \rightarrow \pi^+ \pi^- \pi^0)}$$

$$< 0,12$$

$$\text{Im}(\eta_{+-0}) = -0,002 \pm 0,009$$

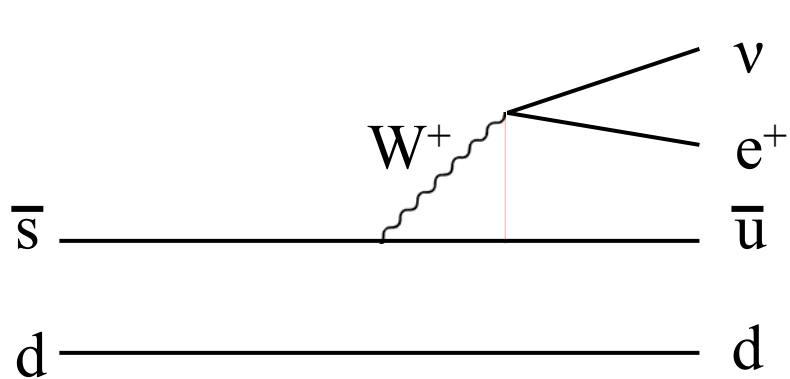
$$|\eta_{000}|^2 = \frac{\Gamma(K_S^0 \rightarrow \pi^0 \pi^0 \pi^0)}{\Gamma(K_L^0 \rightarrow \pi^0 \pi^0 \pi^0)}$$

$$< 0,018$$

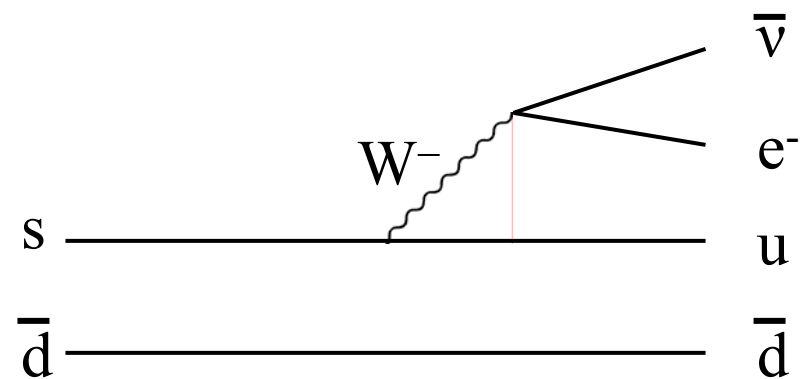
$$\delta = \frac{\Gamma(K_L^0 \rightarrow \pi^- 1^+ \nu) - \Gamma(K_L^0 \rightarrow \pi^+ 1^- \nu)}{\Gamma(K_L^0 \rightarrow \pi^- 1^+ \nu) + \Gamma(K_L^0 \rightarrow \pi^+ 1^- \nu)}$$

$$= (0,332 \pm 0,006) \cdot 10^{-2}$$

$$\begin{aligned}
|K_L\rangle &= \frac{1}{\sqrt{(1-\varepsilon^2)}} \left[|K_2^0\rangle + \varepsilon |K_1^0\rangle \right] = \\
&= \frac{1}{\sqrt{(1-\varepsilon^2)}} \left[\frac{1}{\sqrt{2}} \left(|K^0\rangle + |\bar{K}^0\rangle \right) + \frac{\varepsilon}{\sqrt{2}} \left(|K^0\rangle - |\bar{K}^0\rangle \right) \right] = \\
&= \frac{1}{\sqrt{2(1-\varepsilon^2)}} \left[(1+\varepsilon) |K^0\rangle + (1-\varepsilon) |\bar{K}^0\rangle \right] \\
|K_S\rangle &= \frac{1}{\sqrt{2(1-\varepsilon^2)}} \left[(1+\varepsilon) |K^0\rangle - (1-\varepsilon) |\bar{K}^0\rangle \right]
\end{aligned}$$



$$K^0(\bar{s}d) \rightarrow \pi^-(\bar{u}d)e^+ \nu$$



$$\bar{K}^0(s\bar{d}) \rightarrow \pi^+(u\bar{d})e^- \bar{\nu}$$

Izospin $K = 1/2$

Izospin ($\pi\pi$) = 0, ~~1~~, 2
(ponieważ $l = 0$)

$$|\pi^+\pi^-\rangle = \sqrt{\frac{2}{3}}|0\rangle + \sqrt{\frac{1}{3}}|2\rangle$$

$$|\pi^0\pi^0\rangle = -\sqrt{\frac{1}{3}}|0\rangle + \sqrt{\frac{2}{3}}|2\rangle$$

$$\varepsilon_0 = \frac{\langle 0 | H_w | K_L \rangle}{\langle 0 | H_w | K_S \rangle}, \quad \varepsilon_2 = \frac{\langle 2 | H_w | K_L \rangle}{\sqrt{2} \langle 0 | H_w | K_S \rangle}, \quad \omega = \frac{\langle 2 | H_w | K_S \rangle}{\langle 0 | H_w | K_S \rangle}$$

$$\begin{aligned} \eta_{+-} \left(1 + \frac{\omega}{\sqrt{2}}\right) &= \varepsilon_0 + \varepsilon_2 \\ \eta_{00} \left(1 - 2\sqrt{\omega}\right) &= \varepsilon_0 - 2\varepsilon_2 \end{aligned} \quad \xrightarrow{|\omega| \ll 1} \quad \begin{cases} \eta_{+-} = \varepsilon_0 + \varepsilon_2 \\ \eta_{00} = \varepsilon_0 - 2\varepsilon_2 \end{cases}$$

$$\eta_{+-} = \varepsilon + \varepsilon', \quad \eta_{00} = \varepsilon - 2\varepsilon', \quad \delta = 2\text{Re } \varepsilon$$

$$\varepsilon' = \frac{i}{\sqrt{2}} \frac{\text{Im } A_2}{\text{Re } A_0} e^{-i(\delta_2 - \delta_0)}$$

$$R = \frac{|\eta_{+-}|^2}{|\eta_{00}|^2} = \frac{\Gamma(\text{K}_L \rightarrow \pi^+ \pi^-) / \Gamma(\text{K}_S \rightarrow \pi^+ \pi^-)}{\Gamma(\text{K}_L \rightarrow \pi^0 \pi^0) / \Gamma(\text{K}_S \rightarrow \pi^0 \pi^0)} \cong 1 + 6 \text{Re} \left(\frac{\varepsilon'}{\varepsilon} \right)$$

Gdyby reguła $\Delta I = 1/2$ była ścisła, to $A_2 = 0$, $|\eta_{+-}| = |\eta_{00}|$,
 $\Phi_{+-} = \Phi_{00}$, $\varepsilon' = 0$

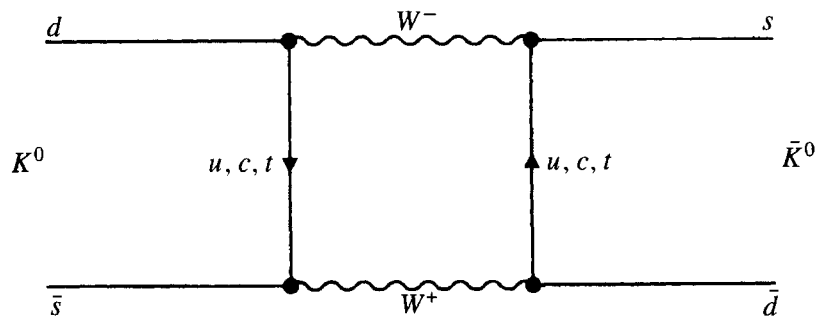
$$\text{Re} (\varepsilon'/\varepsilon) = (1,5 \pm 0,8) \cdot 10^{-3} \quad \text{PDG 1998}$$

$$= (2,1 \pm 0,5) \cdot 10^{-3} \quad \text{PDG 2000}$$

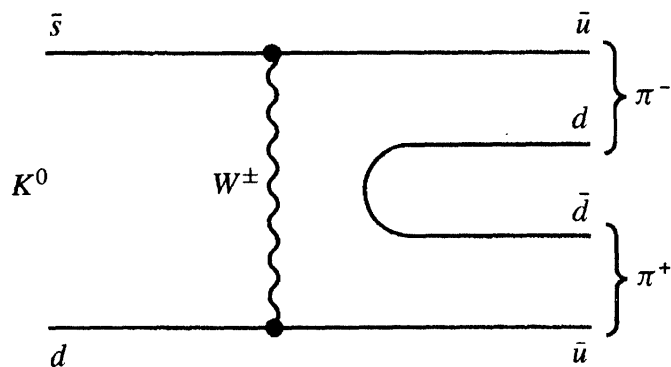
$$= (1,8 \pm 0,4) \cdot 10^{-3} \quad \text{PDG 2002}$$

$$= (1,66 \pm 0,26) \cdot 10^{-3} \quad \text{PDG 2006}$$

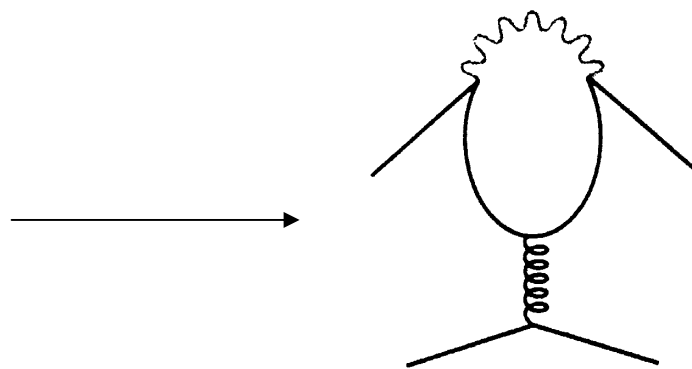
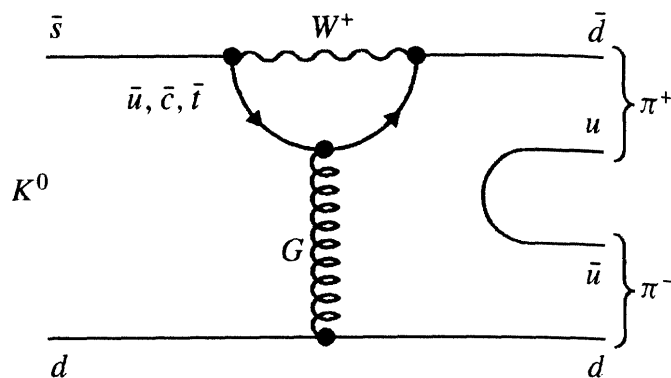
$$= (1,65 \pm 0,26) \cdot 10^{-3} \quad \text{PDG 2008}$$



„indirect” CP violation
 (K_S, K_L mają domieszkę
 „złej” CP)



„direct” CP violation
 (interferencja diagramów
 „tree” i „penguin”)



„penguin diagram”

Odkrycie asymetrii kierunku czasu
(CERN, grudzień 1998)



ELSEVIER

17 December 1998

PHYSICS LETTERS B

Physics Letters B 444 (1998) 43–51

First direct observation of time-reversal non-invariance in the neutral-kaon system

CPLEAR Collaboration

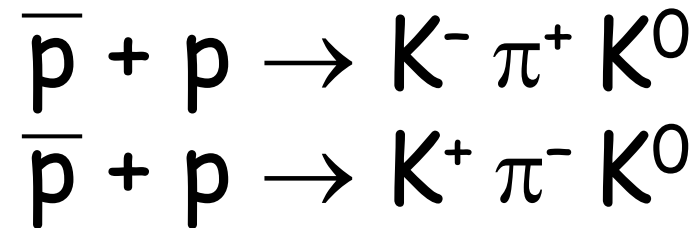
A. Angelopoulos^a, A. Apostolakis^a, E. Aslanides^k, G. Backenstoss^b, P. Bargassa^m,
O. Behnke^q, A. Benelli^b, V. Bertin^k, F. Blanc^{g,m}, P. Bloch^d, P. Carlson^o,
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H.-J. Gerber^q, A. Go^d, A. Haseldenⁱ, P.J. Haymanⁱ, F. Henry-Couannier^k,
R.W. Hollander^f, K. Jon-And^o, P.-R. Kettle^m, P. Kokkas^d, R. Kreuger^f,
R. Le Gac^k, F. Leimgruber^b, I. Mandić^j, N. Manthos^h, G. Marelⁿ, M. Mikuž^j,
J. Miller^c, F. Montanet^k, A. Mullerⁿ, T. Nakada^m, B. Pagels^q,
I. Papadopoulos^p, P. Pavlopoulos^b, A. Policarpo^e, G. Polivka^b, R. Rickenbach^b,
B.L. Roberts^c, T. Ruf^d, C. Santoni^b, M. Schäfer^q, L.A. Schaller^g,
T. Schietinger^b, A. Schopper^d, L. Tauscher^b, C. Thibault^l, F. Touchard^k,
C. Touramanisⁱ, C.W.E. Van Eijk^f, S. Vlachos^b, P. Weber^q, O. Wigger^m,
M. Wolter^q, D. Zavrtnik^j, D. Zimmerman^c

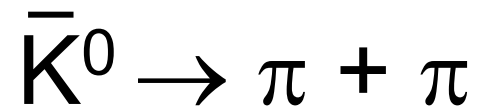
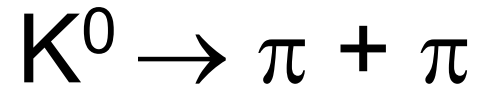
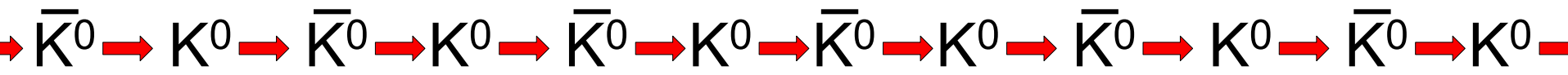
Odkrycie asymetrii kierunku czasu

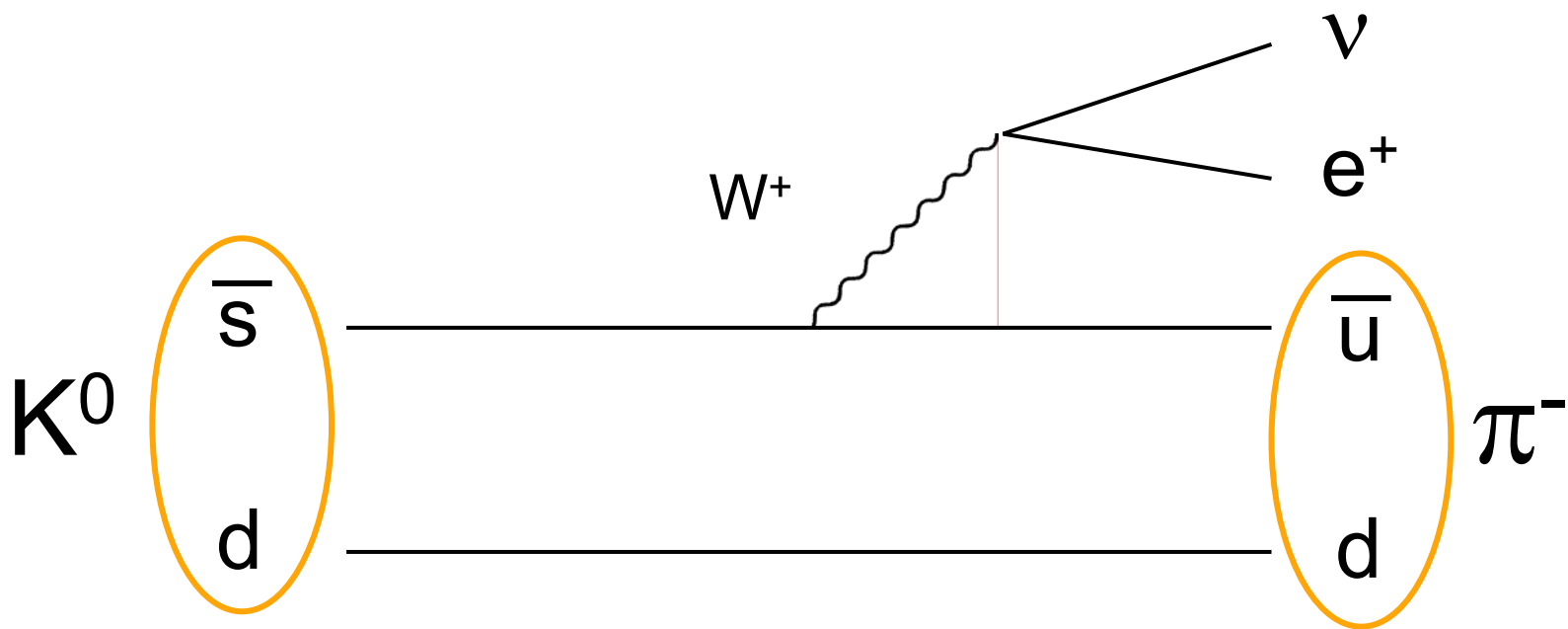
Pomiar różnicy

$$P\left(\overline{K}^0 \rightarrow K^0\right) - P\left(K^0 \rightarrow \overline{K}^0\right)$$

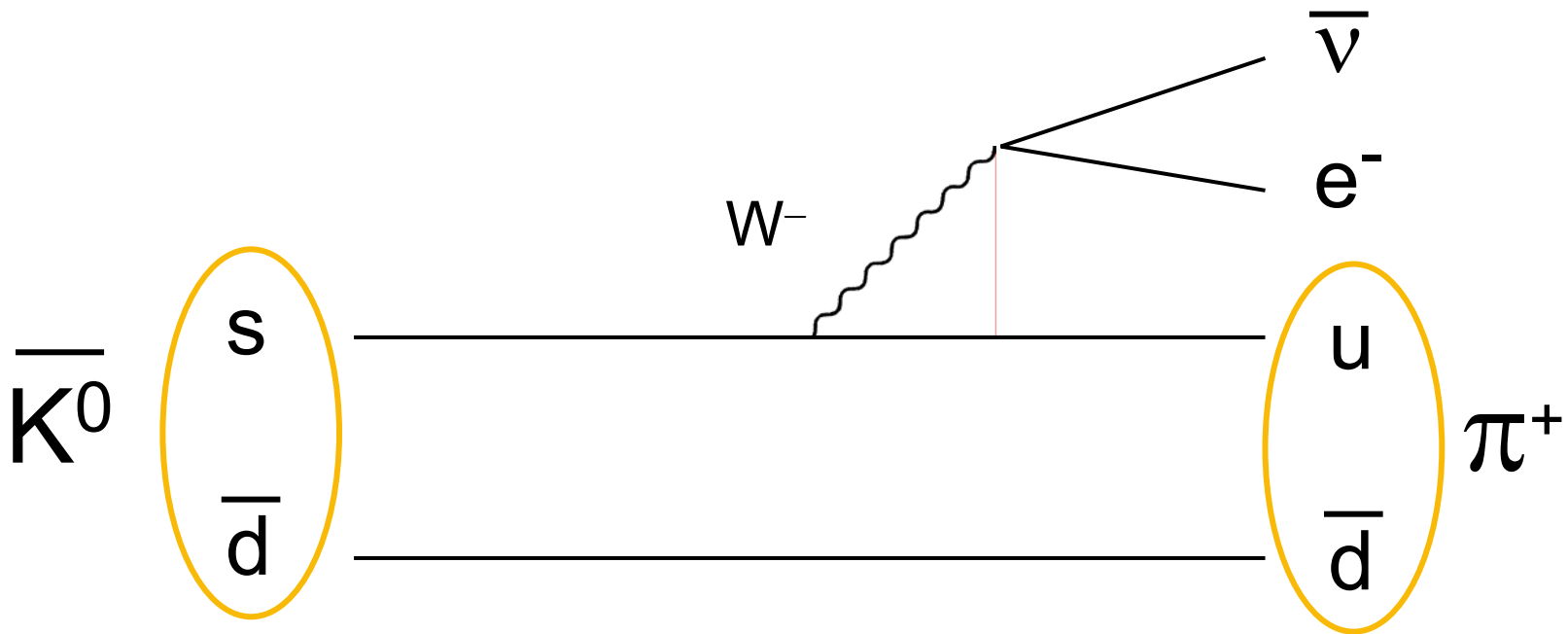
badane reakcje





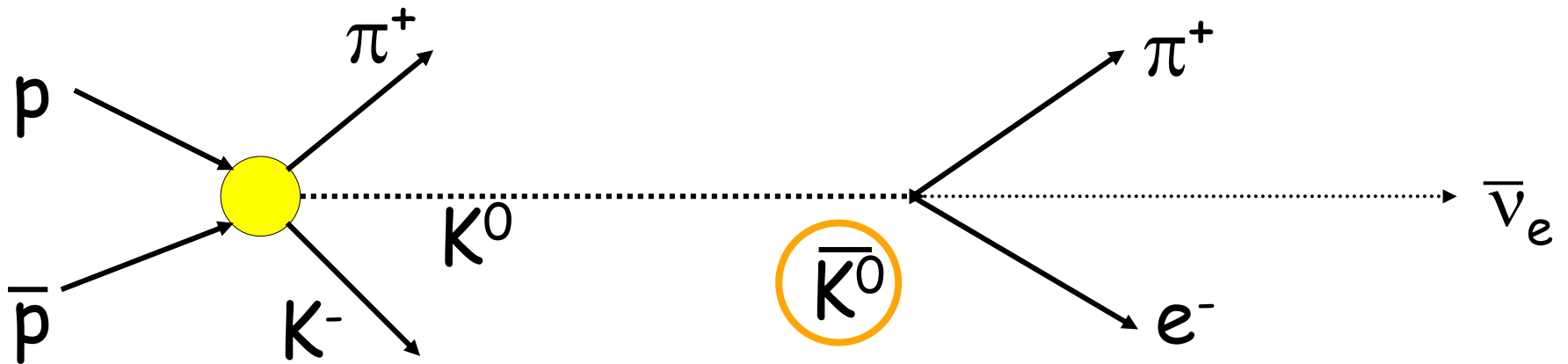
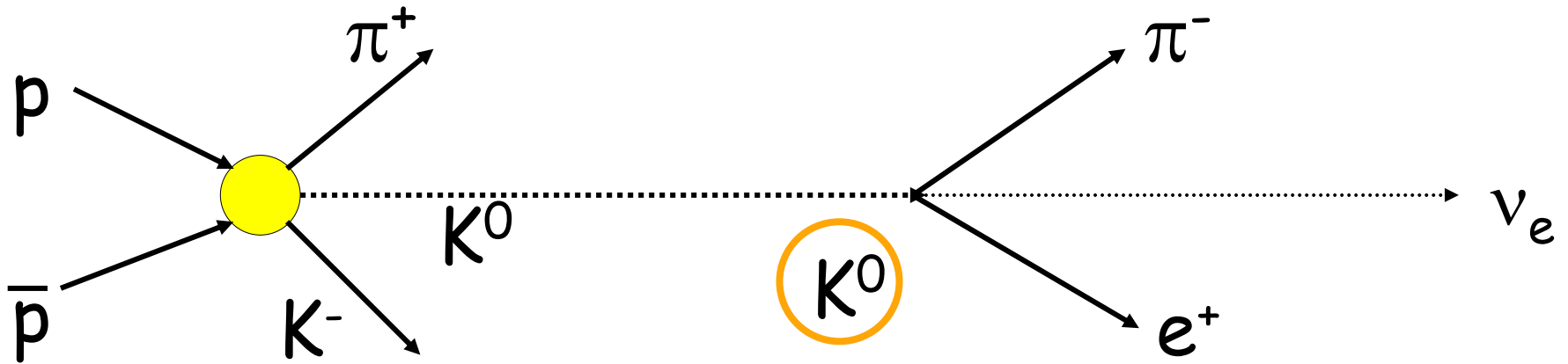


Stan końcowy $\pi^- e^+ \nu$ odpowiada rozpadowi K^0

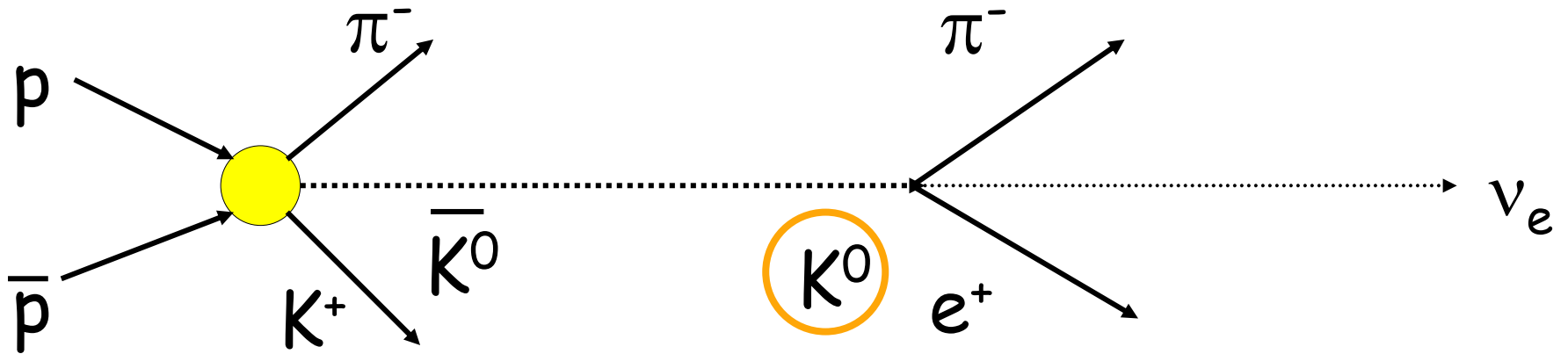
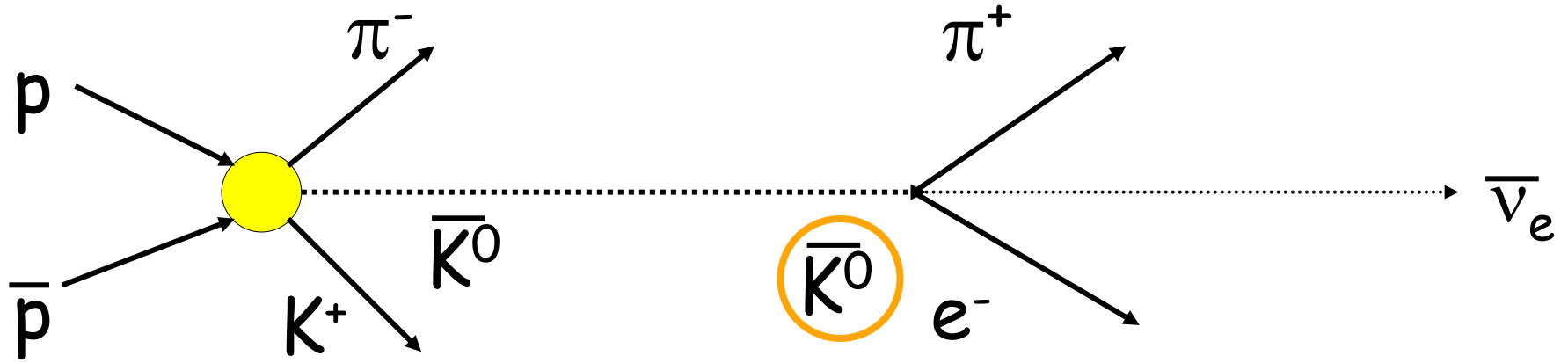


Stan końcowy $\pi^+ e^- \bar{\nu}$ odpowiada rozpadowi \bar{K}^0

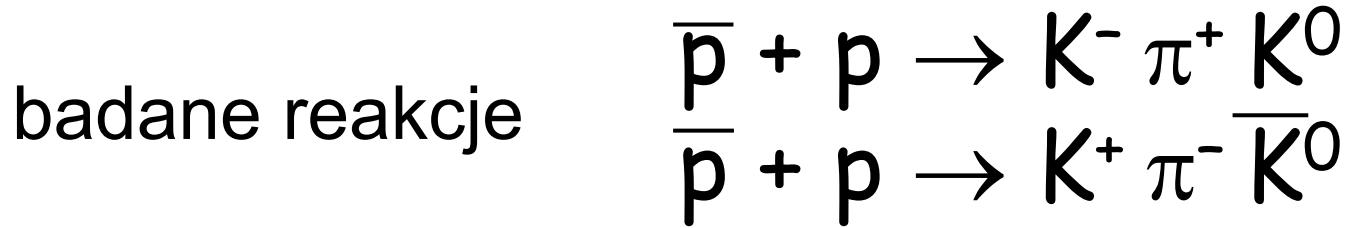
Odkrycie asymetrii kierunku czasu



Odkrycie asymetrii kierunku czasu



Low Energy Antiproton Ring (LEAR) w CERN antyprotony 200 MeV/c

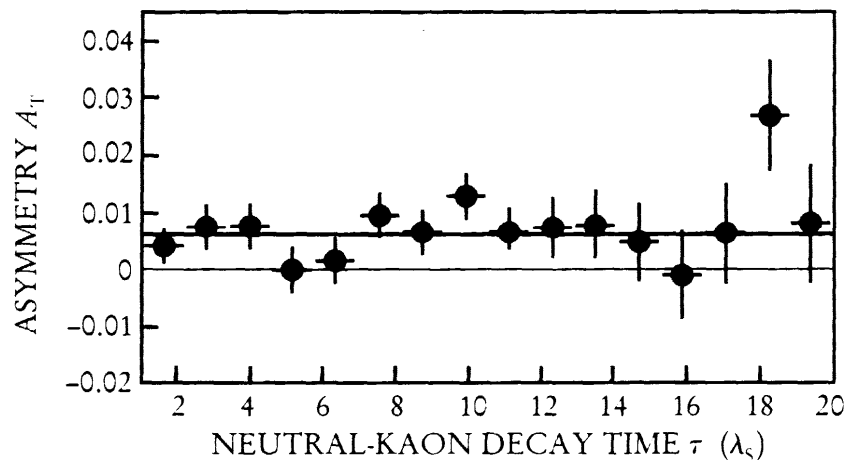


wyznaczanie asymetrii rozpadu w funkcji czasu

$$\frac{P(\bar{K}^0_{t=0} \rightarrow e^+ \pi^- \nu_{t=\tau}) - P(K^0_{t=0} \rightarrow e^- \pi^+ \nu_{t=\tau})}{P(\bar{K}^0_{t=0} \rightarrow e^+ \pi^- \nu_{t=\tau}) + P(K^0_{t=0} \rightarrow e^- \pi^+ \nu_{t=\tau})}$$

Naruszenie „zasady odwrócenia czasu” w rozpadach kaonów

$$A_T = \frac{P(\bar{K}^0 \rightarrow K^0) - P(K^0 \rightarrow \bar{K}^0)}{P(\bar{K}^0 \rightarrow K^0) + P(K^0 \rightarrow \bar{K}^0)}$$



$$A_T = (6,6 \pm 1,3_{\text{stat}} \pm 1,0_{\text{syst}}) \cdot 10^{-3}$$

Dodatek: Dlaczego nie widzimy we wszechświecie symetrii materia-antymateria?



- materia i antymateria zajmują rozdzielne obszary wszechświata

Oscar Klein



Hannes Alfvén

- symetria istniejąca w najwcześniejszym etapie historii wszechświata została naruszona



Andriy Sacharow



НАРУШЕНИЕ CP -ИНВАРИАНТНОСТИ, C -АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует принять, что в природе отсутствуют тела из антивещества, т.е. Вселенная асимметрична в отношении числа частиц и античастиц (C -асимметрия). В частности, отсутствие антибарионов и предполагаемое отсутствие неизвестных барионных нейтрино означает отличие от нуля барионного заряда (барионная асимметрия). Мы хотим указать на возможное объяснение C -асимметрии в горячей модели расширяющейся Вселенной (см. [1]) с привлечением эффектов нарушения CP -инвариантности (см. [2]). Для объяснения барионной асимметрии дополнительно предполагаем приближенный характер закона сохранения барионов.

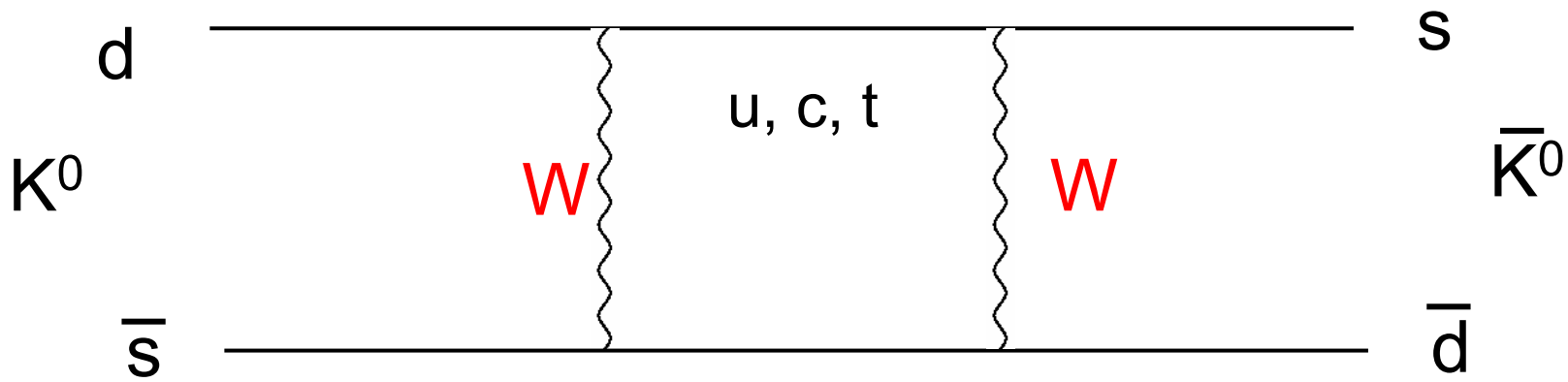
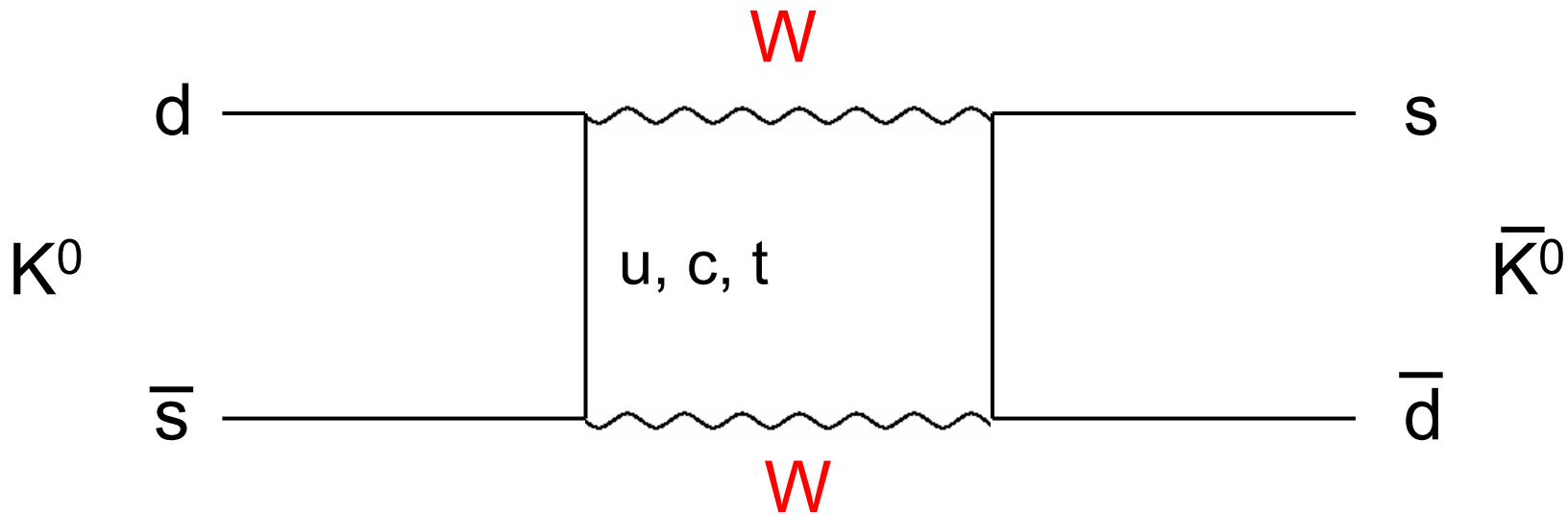
Принимаем, что законы сохранения барионов и мюонов не являются абсолютными и должны быть объединены в закон сохранения "комбинированного" барион-мюонного заряда $n_K = 3n_B - n_\mu$. Положено:

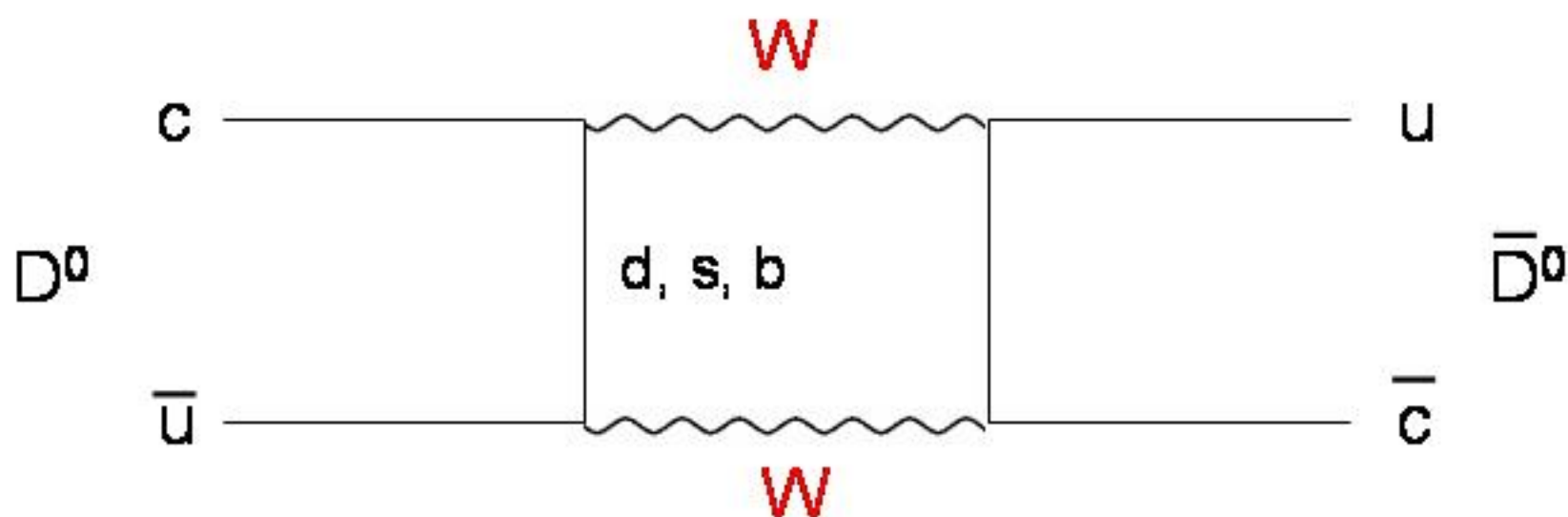
32

Trzy warunki Sacharowa (1967)

- etap nierównowagi termicznej wszechświata
- niezachowanie CP i C
- oddziaływanie niezachowujące liczbę barionową B

Oscylacje mezonów B





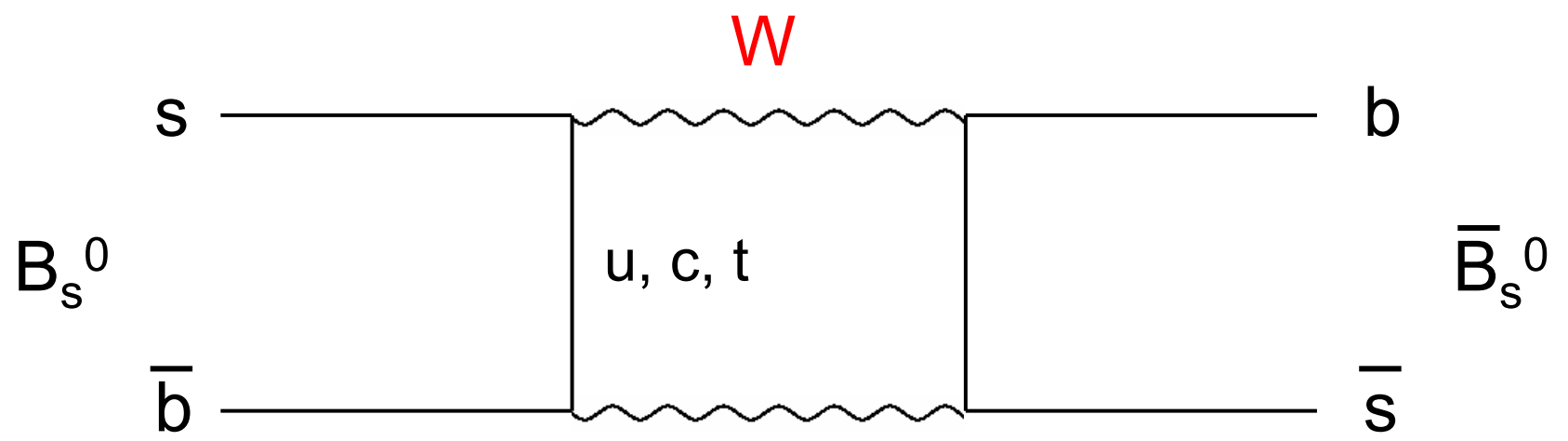
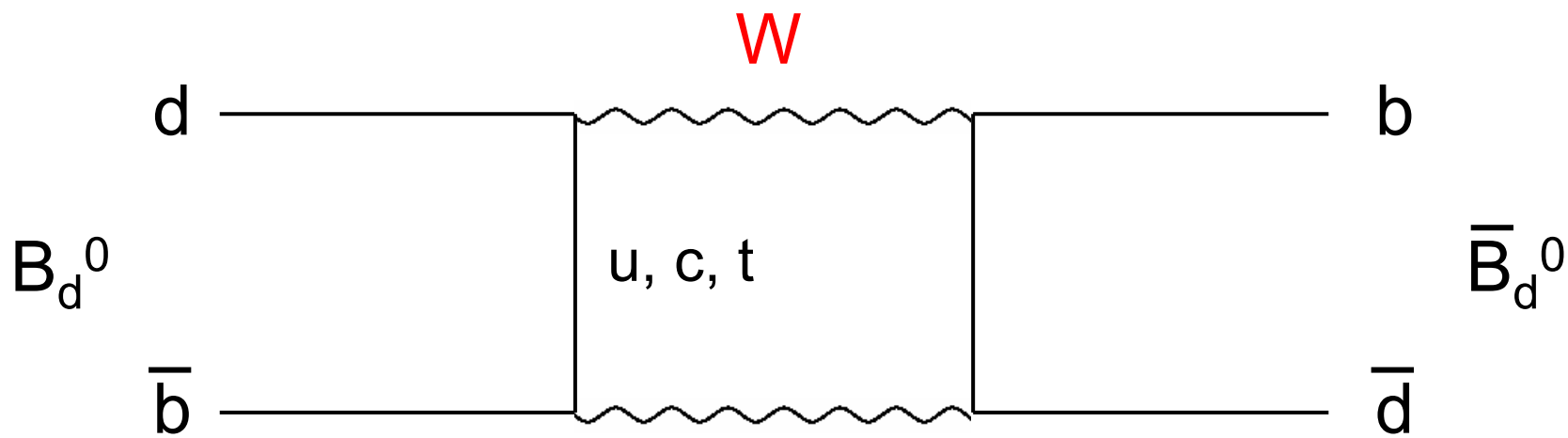
Efekt bardzo mały ze względu na małą wartość iloczynu $V_{cb} V_{ub}$

$$m_{D_1^0} - m_{D_2^0} < 7 \times 10^{10} \hbar s^{-1} \quad \text{PDG 2006}$$

$$m_{D_1^0} - m_{D_2^0} = (2,37^{+0,66}_{-0,71}) \times 10^{10} \hbar s^{-1} \quad \text{PDG 2008}$$

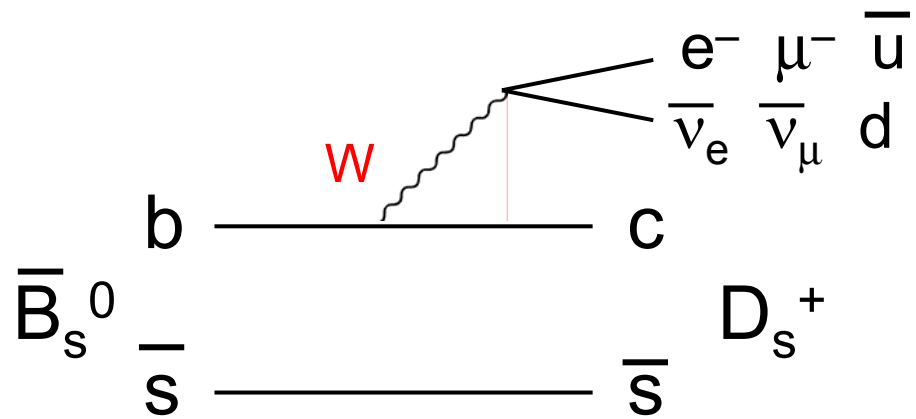
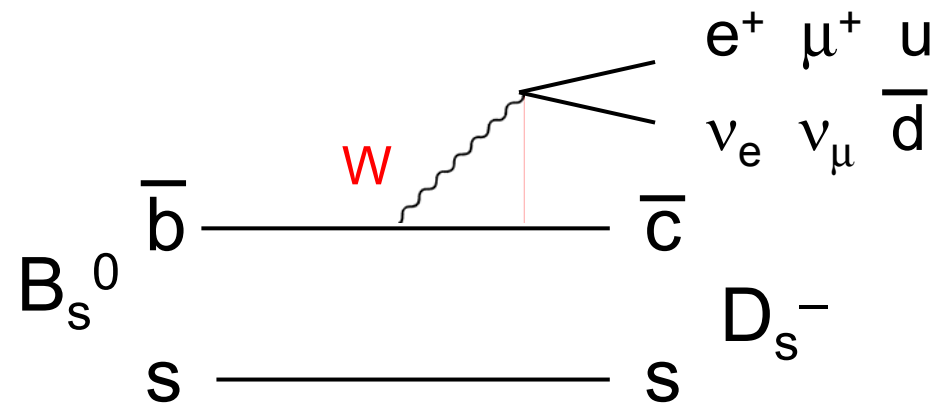
$$m_{D_1^0} - m_{D_2^0} = (2,39^{+0,59}_{-0,63}) \times 10^{10} \hbar s^{-1} \quad \text{PDG 2010}$$

Pierwsze eksperymentalne potwierdzenie oscylacji mezonów D
 BaBar Collaboration, Phys. Rev. Lett. **98**, 211802 (25 May 2007)
 Belle Collaboration, Phys. Rev. Lett. **98**, 211803 (25 May 2007)

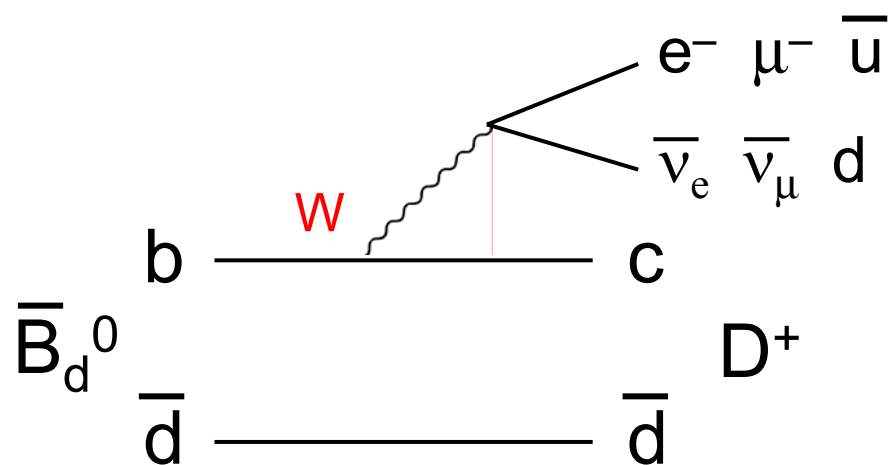
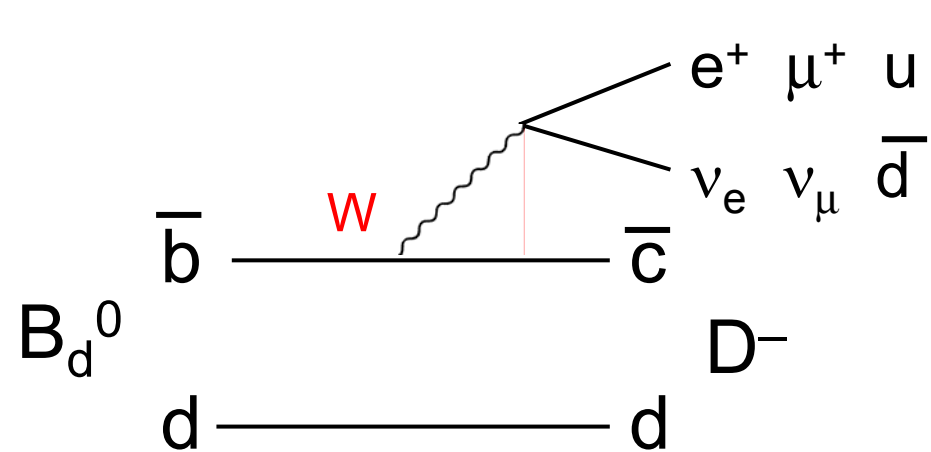


$$\frac{\Delta m_s}{\Delta m_d} \sim \frac{m_{Bs}}{m_{Bd}} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

$|V_{ts}| \gg |V_{td}| \Rightarrow \Delta m_s \gg \Delta m_d$
 \Rightarrow obserwacje oscylacji w zakresie THz



$$D_s^- \rightarrow \phi\pi^-, K^{*0}K^-, \pi^+\pi^-\pi^-$$



Formalizm podobny do stosowanego dla neutralnych kaonów

$$|B^0_1\rangle = (1/2)^{1/2} [|B^0_q\rangle - |\bar{B}^0_q\rangle]$$

$q \equiv d \text{ lub } b$

$$|B^0_2\rangle = (1/2)^{1/2} [|B^0_q\rangle + |\bar{B}^0_q\rangle]$$

$$\Delta m_{B^0} = \Delta m = \Delta m_{B^0_d} = m_{B^0_H} - m_{B^0_L}$$

$$\Delta m_s = \Delta m_{B^0_s} = m_{B^0_{sH}} - m_{B^0_{sL}}$$

PDG 2010

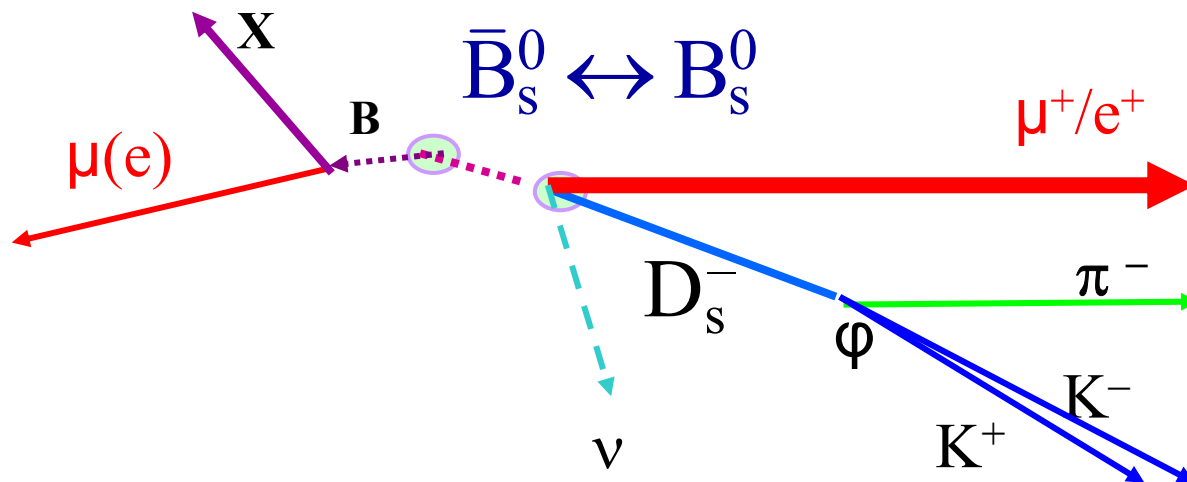
$$\begin{aligned} \Delta m &= (0,507 \pm 0,005) \cdot 10^{12} \hbar \text{ s}^{-1} = (0,507 \pm 0,005) \text{ ps}^{-1} = \\ &= (3,337 \pm 0,033) \cdot 10^{-10} \text{ MeV} \end{aligned}$$

Przypomnienie: wzory dla neutralnych kaonów

$$P(K^0, t) = \frac{1}{4} \left(e^{-t/\tau_1} + e^{-t/\tau_2} + 2e^{-\left(\frac{t}{2\tau_1} + \frac{t}{2\tau_2}\right)} \cos(\Delta m \cdot t) \right)$$
$$P(\bar{K}^0, t) = \frac{1}{4} \left(e^{-t/\tau_1} + e^{-t/\tau_2} - 2e^{-\left(\frac{t}{2\tau_1} + \frac{t}{2\tau_2}\right)} \cos(\Delta m \cdot t) \right)$$

Dla neutralnych mezonów B (także D) $\tau_1 \cong \tau_2 = \tau$

$$P(B^0 \rightarrow B^0, t) = \frac{1}{4} \left(e^{-\Gamma t} + e^{-\Gamma t} + 2e^{-\left(\frac{\Gamma t}{2} + \frac{\Gamma t}{2}\right)} \cos(\Delta m_B \cdot t) \right) = \frac{1}{2} e^{-\Gamma t} (1 + \cos \Delta m \cdot t)$$
$$P(B^0 \rightarrow \bar{B}^0, t) = \frac{1}{4} \left(e^{-\Gamma t} + e^{-\Gamma t} - 2e^{-\left(\frac{\Gamma t}{2} + \frac{\Gamma t}{2}\right)} \cos(\Delta m_B \cdot t) \right) = \frac{1}{2} e^{-\Gamma t} (1 - \cos \Delta m \cdot t)$$



$$B_d^0$$

$$\tau = 1,53 \cdot 10^{-12} \text{ s}$$

$$c\tau = 459 \mu\text{m}$$

$$B_s^0$$

$$\tau = 1,47 \cdot 10^{-12} \text{ s}$$

$$c\tau = 439 \mu\text{m}$$

Dla porównania K_S^0 $c\tau = 2,68 \text{ cm}$ K_L^0 $c\tau = 15,3 \text{ m}$

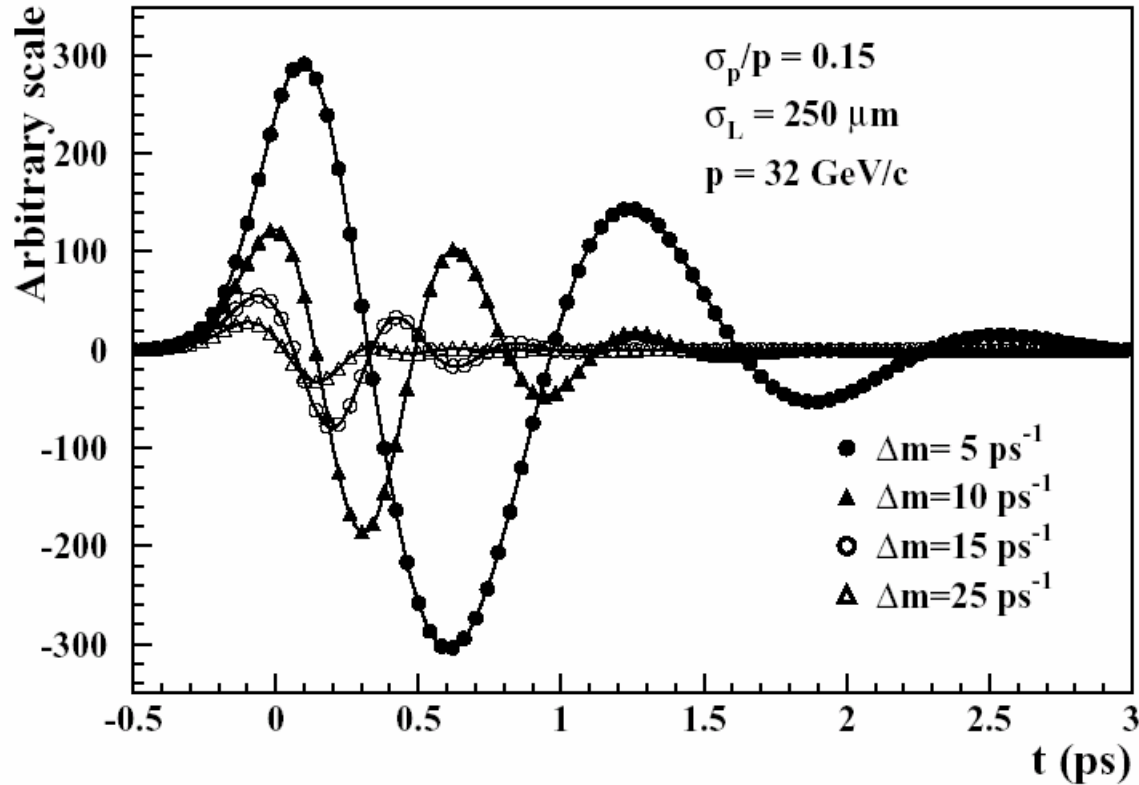
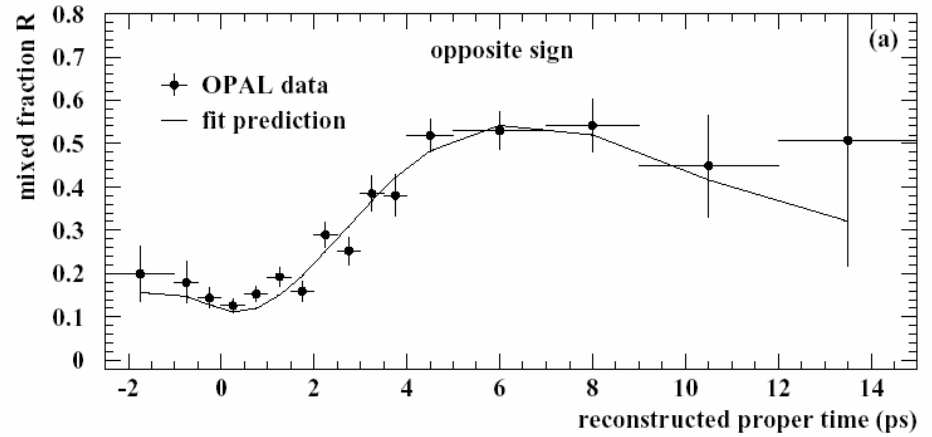
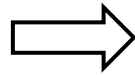


Figure 2: *Difference in the proper time distributions of unmixed and mixed decays for monochromatic B mesons, fixed decay length and momentum resolutions, and different values of the oscillation frequency.*

Przykłady analizy

OPAL



BaBar

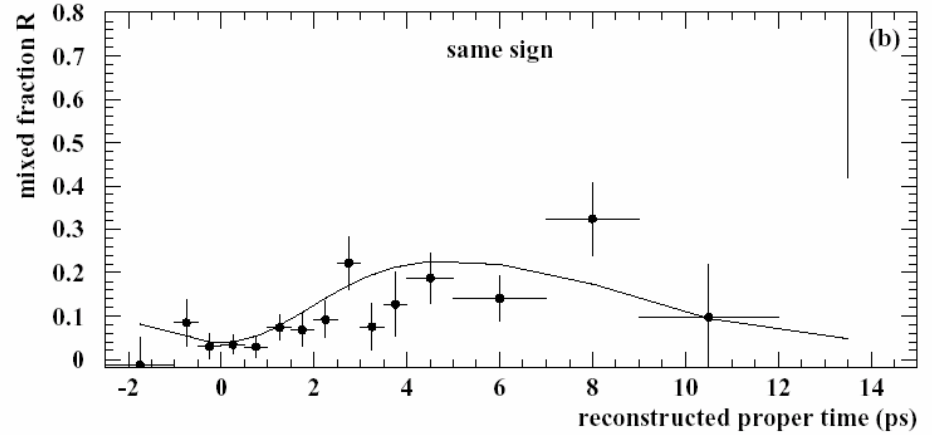
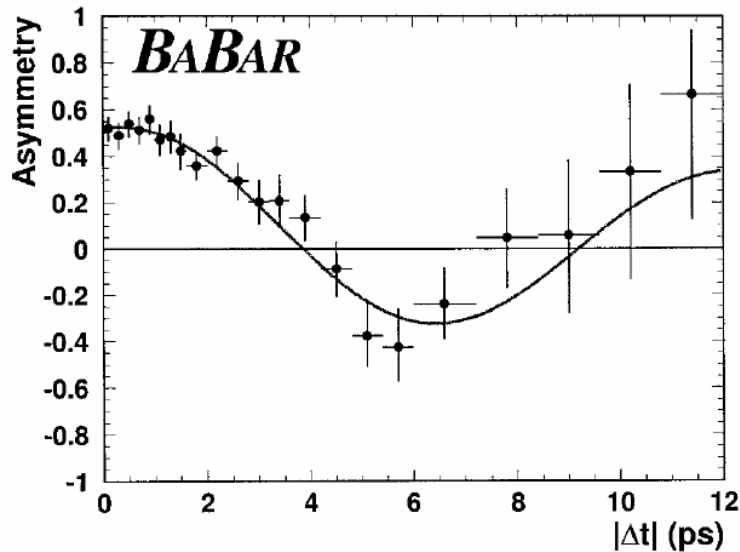
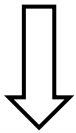


Figure 5: Fraction of events tagged as mixed as a function of the reconstructed proper time, for the correct (a) and wrong (b) charge combinations. Superimposed is the curve predicted for the fitted value of Δm_d .

Bezpośrednie „zobaczenie” oscylacji neutralnych B_s jest bardzo trudne

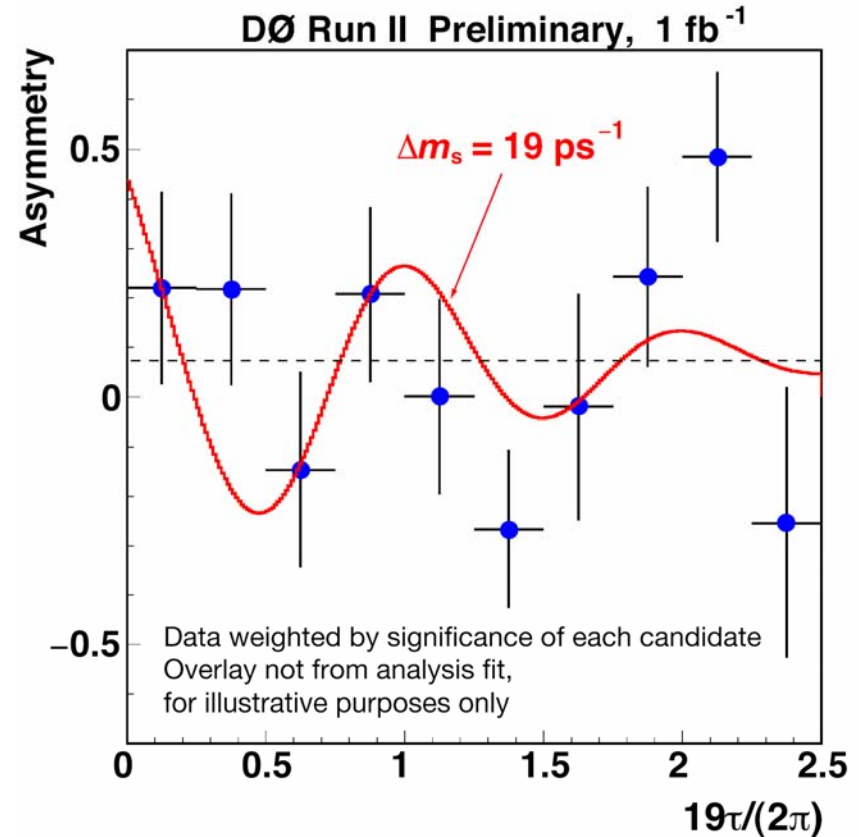
T. Moulik (D0 Collaboration)
ICHEP 2006 (Moskwa)

$$\text{Asymmetry } A(t) = \frac{N_{OS} - N_{SS}}{N_{OS} + N_{SS}}$$

(OS – *opposite sign*, SS – *same sign*)

$17 < \Delta m_s < 21 \text{ ps}^{-1}$ (90% CL)

Most probable value of $\Delta m_s = 19 \text{ ps}^{-1}$

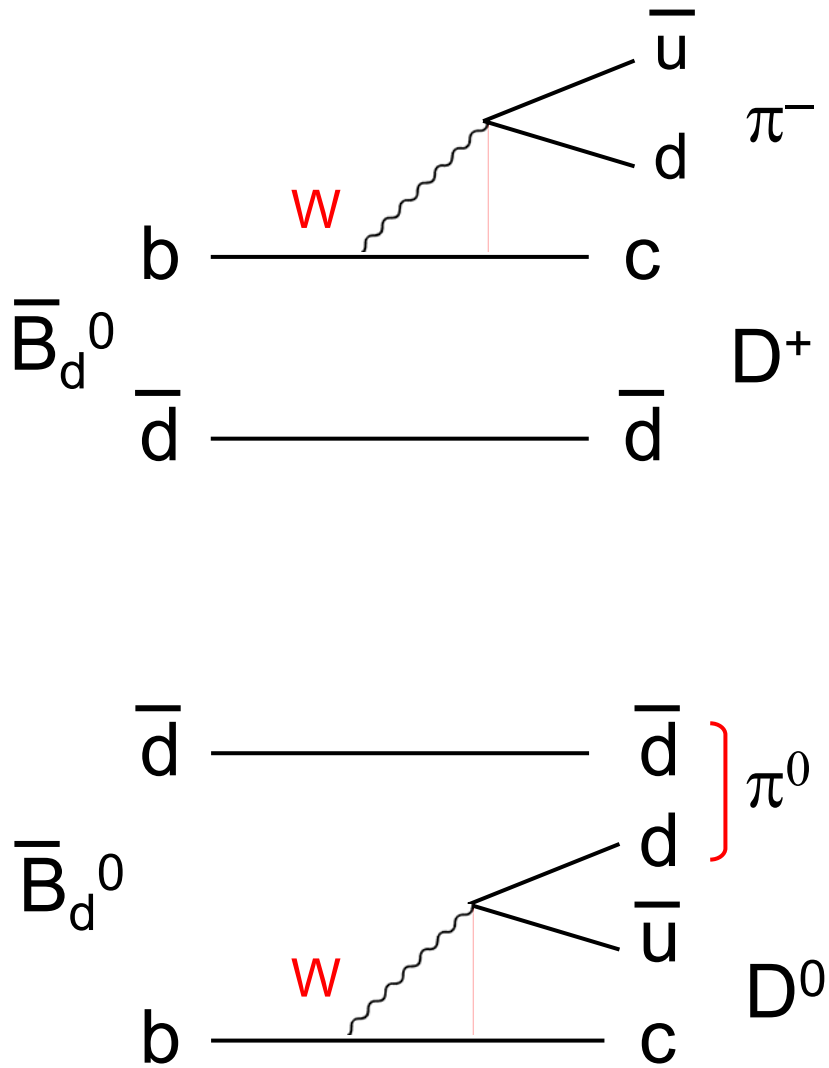


CDF Collaboration (2006) $\Delta m_s = 17,31^{+0.33}_{-0.18} \text{ (stat.)} \pm 0,07 \text{ (syst.) } \text{ps}^{-1}$

PDG 2008

$$\Delta m_s = (17,77 \pm 0,12) \times 10^{12} \hbar s^{-1} = (117,0 \pm 0,8) \times 10^{-10} \text{ MeV}$$

Dodatek: „colour suppression”



Wyniki pomiarów znacząco różnią się od przewidywań teoretycznych
[Belle Collaboration,
Phys. Rev. D74, 092002 (2006)]