Precision studies of neutron decay and physics of fundamental interactions

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MOSCOW STATE UNIVERSITY

Part 1

1. *Experimental data on neutron decay*
2. *Increasing measurement accuracy over the past 30 years*
3. *Deviations from the Standard Model*

Part 2

1. *The decay of a neutron within the model of mixing left and right vector bosons can be successfully described*
2. *CP violation in baryons and mesons*
3. *Baryon and lepton asymmetry of the Universe*

Part 3

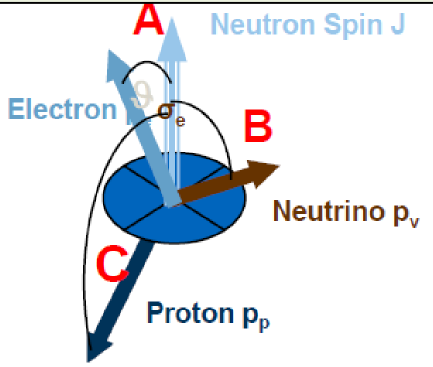
Prospects of the experiment

Precision studies of neutron decay and the search for deviations from the Standard Model

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{2(2\pi)^5} G_F^2 |V_{ud}|^2 \left(1+3|\lambda|^2\right) p_e E_e \left(E_0 - E_e\right)^2$$

$$\times\left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \frac{\langle\vec{\sigma}_n\rangle}{\vec{\sigma}_n}\cdot\left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_e E_\nu}\right)\right]$$

Jackson, Treiman, Wyld, Nucl. Phys. 4, 1957



$$A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}$$ **-0.11958(21) 0.17%**

$$B = 2\frac{\lambda^2-\lambda}{1+3\lambda^2}$$ **0.9807(30) 0.3%**

$\lambda = g_A/g_V$ **-1.2757(5) 0.04%**

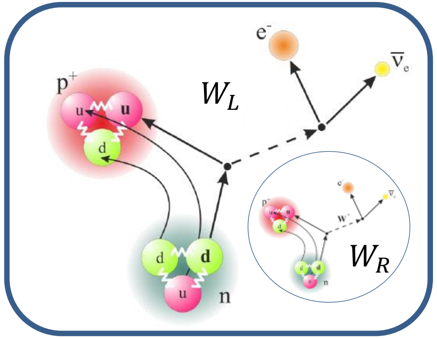
$$a = \frac{(1-\lambda^2)}{(1+3\lambda^2)}$$ **-0.10402(82) 1.3%**

$$D = 2\cdot\frac{\mathrm{Im}(\lambda)}{1+3|\lambda|^2}$$ **$-1.2\ (2.0)\times 10^{-4}$**

Neutron lifetime

$$\tau^{-1} = G_F^2|V_{ud}|^2(1+3\lambda^2)\frac{f^R m_e^5 c^4}{2\pi^3\hbar^7}$$

877.75 ± 0.35s 0.04%



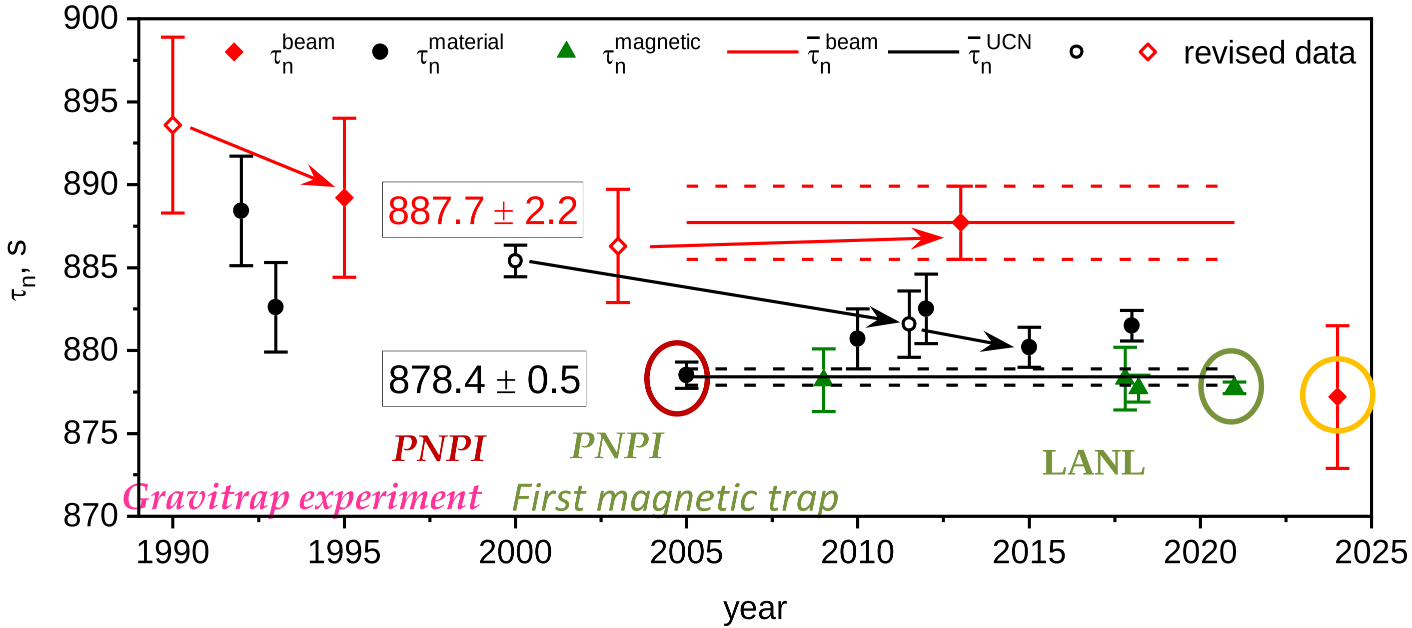
Unitarity CKM

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

$$V_{ud}^{unit} = \sqrt{1 - V_{us}^2 - V_{ub}^2} = 0.97452(18).$$

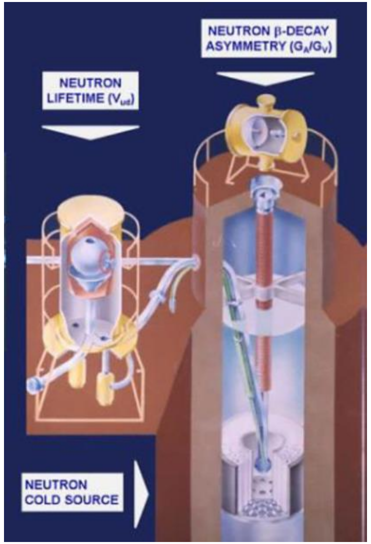
Improving the accuracy of measurements and trends in the neutron lifetime

Neutron lifetime



Experimental results for the neutron lifetime since 1990 from [8], discrepancy between 2005 [9] and 2000 [10] data, new magnetic trap results (marked in green) which are decisive [11-14]. New beam experiment [15].

Реактор ВВР-М 1986-1996
ПИЯФ-ОИЯИ, Гатчина



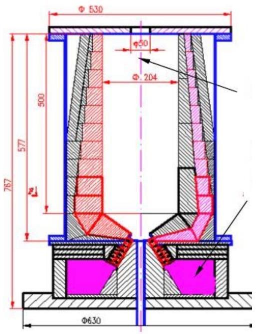
Gravitrap experiment

A.Serebrov et al. , Phys Lett B 605, (2005) 72-78 : 878.5 ± 0.8 s

2002-2004 (PNPI-JINR-ILL), ILL reactor, Grenoble

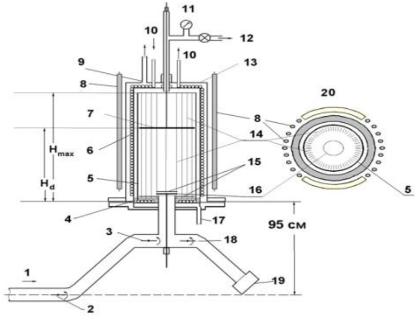
First trap of permanent magnets

τ_n = **878.3±1.9 s**



Technical Physics Letters. 2001. T. 27. C. 1055.

V. F. Ezhov

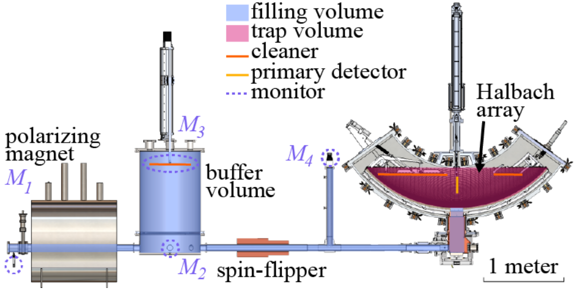


The result of experiment:

τ = (880.2 ± 1.2) s

Phys. Lett. B. 745 (2015) 79-89

V.I. Morozov 2015



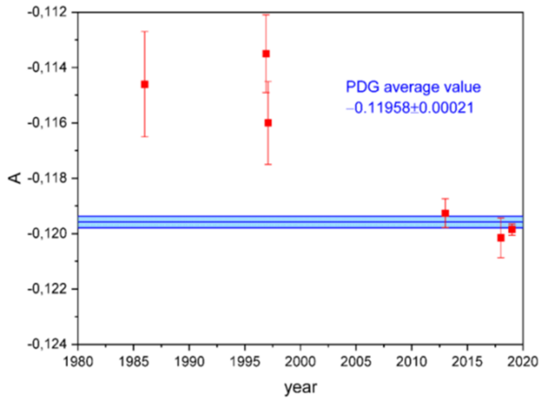
877.75 ± 0.35

Phys. Rev. Lett. 2021. V. 127. P. 162501.

877.82± 0.30

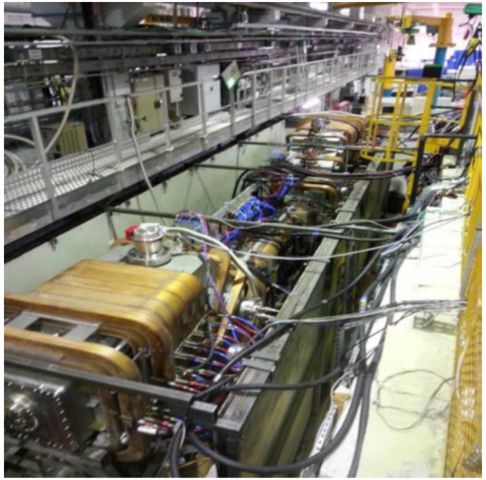
PRC 111, 045501

Measurement of electron asymmetry of neutron decay - A



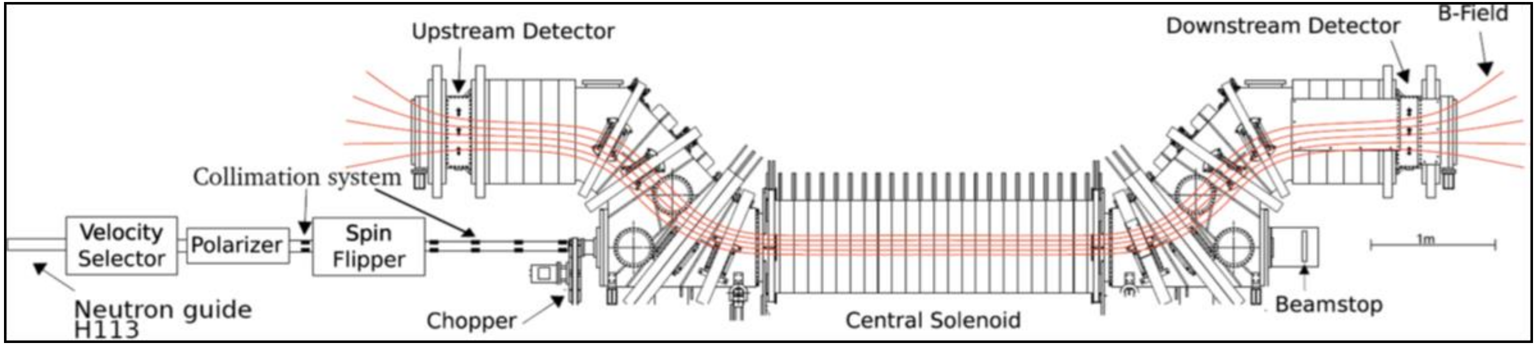
Measurement of the Weak Axial-Vector Coupling Constant in the Decay of Free Neutrons Using a Pulsed Cold Neutron Beam

B. Märkisch,1,2,* H. Mest,2 H. Saul,1,3,4 X. Wang,1,3 H. Abele,1,2,3,† D**. Dubbers,2** M. Klopf,3 A. Petoukhov,5 C. Roick,1,2 T. Soldner,5 and D. Werder2

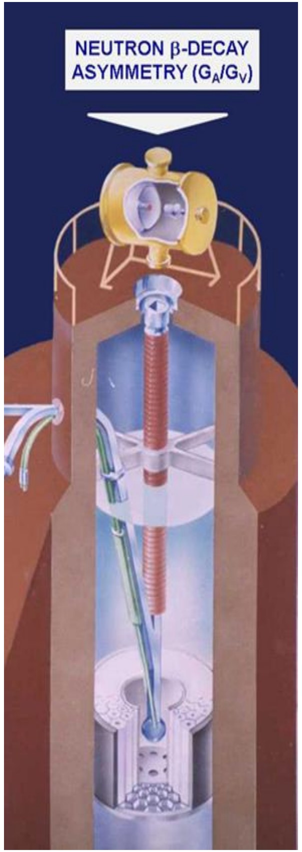


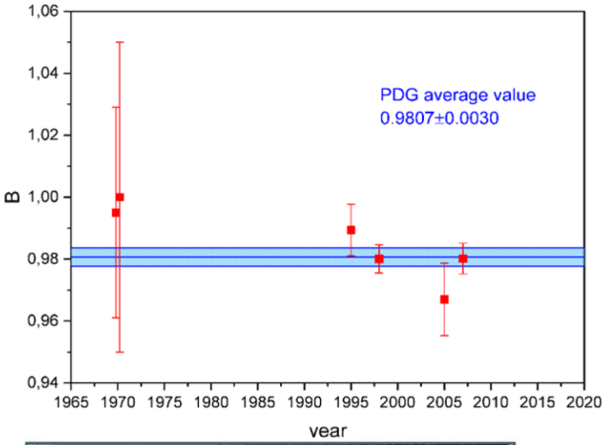
$$A_{exp} = -0.11958(21)$$

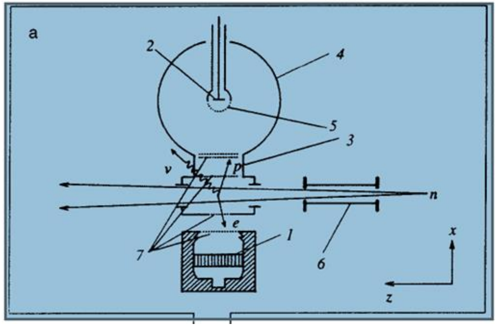
λ= - 1.2757(5)



Experimental results of neutrino asymmetry of neutron decay *B*







B.G. Yerozolimsky's installation, brought from the Kurchatov Institute

Measurement of the antineutrino escape asymmetry with respect to the spin of the decaying neutron

A. P. Serebrov, I. A. Kuznetsov, I. V. Stepanenko, A. V. Aldushchenkov, and M. S. Lasakov

St. Petersburg Nuclear Physics Institute, Russian Academy of Sciences, 188350 Gatchina, Russia

VALUE	DOCUMENT ID	
0.9807±0.0030 OUR AVERAGE	See the ideogram below	
0.9802±0.0034±0.0036	SCHUMANN	07
0.967 ±0.006 ±0.010	KREUZ	05
0.9801±0.0046	SEREBROV	98
0.9894±0.0083	KUZNETSOV	95
1.00 ±0.05	CHRISTENSEN	70
0.995 ±0.034	EROZOLIM...	70C

Accuracy of the polarization measurements was at the 0.25% level

Electron-neutrino asymmetry of neutron decay - a

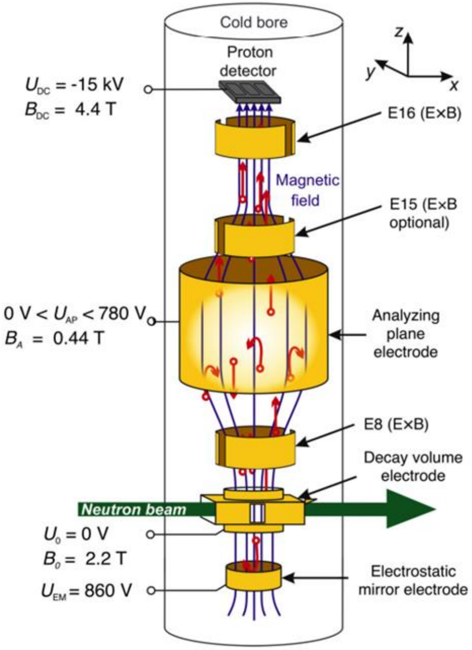
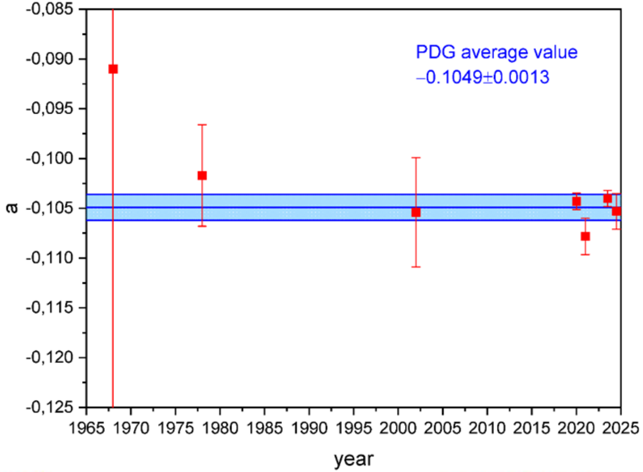


FIG. 2. Schematic of *a*SPECT. Only the most important electrodes are shown. The magnetic field is oriented in vertical direction (blue lines). The whole setup is under ultrahigh vacuum conditions.



VALUE		DOCUMENT ID	
−0.1049 ±0.0013 OUR AVERAGE		Error includes scale	
−0.10782±0.00124±0.00133	[1]	HASSAN	21
−0.10430±0.00084		BECK	20
−0.1054 ±0.0055		BYRNE	02
−0.1017 ±0.0051		STRATOWA	78
−0.091 ±0.039		GRIGOREV	68

$$a_{\mathrm{exp}} = -0.10402(82)$$

Improved determination of the β-$\bar{\nu}_e$ angular correlation coefficient *a* in free neutron decay with the *a*SPECT spectrometer

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F. Glück
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(Received 14 August 2019; revised manuscript received 19 December 2019; accepted 17 March 2020; published 26 May 2020)

We report on a precise measurement of the electron-antineutrino angular correlation (*a* coefficient) in free neutron beta decay from the *a*SPECT experiment. The *a* coefficient is inferred from the recoil energy spectrum of the protons which are detected in 4π by the *a*SPECT spectrometer using magnetic adiabatic collimation with an electrostatic filter. Data are presented from a 100-day run at the Institut Laue Langevin in 2013. The sources of systematic errors are considered and included in the final result. We obtain $a = -0.104\,30(84)$ which is the most precise measurement of the neutron *a* coefficient to date. From this, the ratio of axial vector to vector coupling constants is derived giving $|\lambda| = 1.2677(28)$.

The description of experimental results within the framework of the V-A version of the theory turns out to be unsatisfactory, since it cannot be represented by a single value of the parameter $\lambda = G_A / G_V$

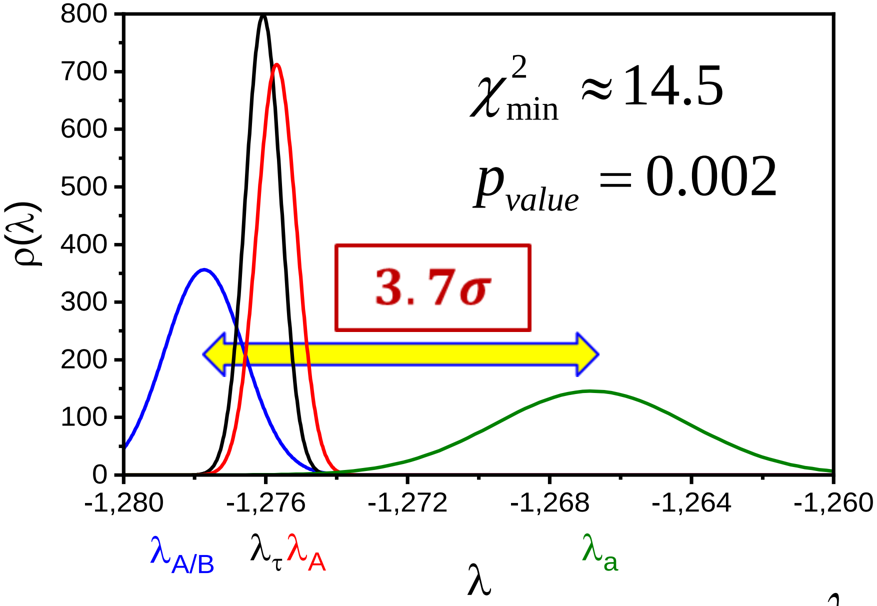
$$\tau_{exp} = \frac{4905,7}{V_{ud}^2 (1+3\lambda^2)}$$

$$a_{exp} = \frac{(1-\lambda^2)}{(1+3\lambda^2)}$$

$$A_{exp} = -\frac{2\lambda(\lambda+1)}{1+3\lambda^2}$$

$$B_{exp} = \frac{2\lambda(\lambda-1)}{1+3\lambda^2}$$

$$\tau_{exp} = 877.75(35)$$
$$a_{exp} = -0.10402(82)$$
$$A_{exp} = -0.11958(21)$$
$$B_{exp} = 0.9807(30)$$
$$V_{ud}^n = 0.97477(37)$$



Deviation from Standard Model is 3.7 sigma

Results of calculating the parameter value $\lambda = G_A / G_V$ within the V-A version of the weak interaction theory, the experiments for a, A, B and τ cannot be represented by a single value.

The observed discrepancy can be analyzed within the framework of a model taking into account right-handed currents. In the simplest left-right manifesto of the model, mixing of left W_L and right W_R vector bosons is considered, and for flavor states , and mass states W_1 W_2 , we can write:

$$\begin{pmatrix} W_L^{\pm} \\ W_R^{\pm} \end{pmatrix} = \begin{pmatrix} \cos\zeta & +\sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^{\pm} \\ W_2^{\pm} \end{pmatrix}$$

where ζ is the mixing angle of the current states W_L and W_R , and δ is the ratio of the squares of the masses of the states W_1 and W_2 .

$$\delta = (M_1/M_2)^2$$

[3] M. A. B. Beg, R. V. Budny, R.N. Mohapatra, and A. Sirlin, Phys. Rev. Lett. 38, 1252 (**1977**),
[4] B. R. Holstein and S. B. Treiman, Phys. Rev. D **16**, 2369 (**1977**),
[5] P. Herczeg, Phys. Rev. D **34**, 3449 (**1986**),
[6] P. Herczeg, Prog. Part. Nucl. Phys. **46**, 413 (**2001**)

N. Severijns, M. Beck and O. Naviliat-Cuncic, Rev. Mod. Phys. **78**, 991 (2006)]

V-A variant of the theory

$$\tau_{\exp} = \frac{4905,7}{V_{ud}^2(1+3\lambda^2)}$$

$$a_{\exp} = \frac{(1-\lambda^2)}{(1+3\lambda^2)}$$

$$A_{\exp} = -\frac{2\lambda(\lambda+1)}{1+3\lambda^2}$$

$$B_{\exp} = \frac{2\lambda(\lambda-1)}{1+3\lambda^2}$$

left-right model

$$\tau_{\exp} \pm \Delta\tau_{\exp} = \frac{4905,7}{V_{ud}^2[1+x^2+3\lambda^2(1+y^2)]}$$

$$a_{\exp} \pm \Delta a_{\exp} = \frac{(1-\lambda^2)[1+(\delta+\zeta)^2]-4\delta\zeta}{(1+3\lambda^2)[1+(\delta+\zeta)^2]-4\delta\zeta}$$

$$A_{\exp} \pm \Delta A_{\exp} = -\frac{2\lambda[\lambda(1-y^2)+(1-xy)]}{1+x^2+3\lambda^2(1+y^2)}$$

$$B_{\exp} \pm \Delta B_{\exp} = \frac{2\lambda[\lambda(1-y^2)-(1-xy)]}{1+x^2+3\lambda^2(1+y^2)}$$

где $x = \delta - \zeta, \quad y = \delta + \zeta.$

Expansion in δ and ζ of order no higher than two can be represented by the following expressions

$$\tau_{\exp} \pm \Delta\tau_{\exp} = \frac{4905,7}{V_{ud}^2[1 + x^2 + 3\lambda^2(1 + y^2)]}$$

$$a_{\exp} \pm \Delta a_{\exp} = \frac{(1-\lambda^2)[1+(\delta+\zeta)^2] - 4\delta\zeta}{(1+3\lambda^2)[1+(\delta+\zeta)^2] - 4\delta\zeta}$$

$$A_{\exp} \pm \Delta A_{\exp} = -\frac{2\lambda[\lambda(1-y^2) + (1-xy)]}{1 + x^2 + 3\lambda^2(1+y^2)}$$

$$B_{\exp} \pm \Delta B_{\exp} = \frac{2\lambda[\lambda(1-y^2) - (1-xy)]}{1 + x^2 + 3\lambda^2(1+y^2)}$$

$$\frac{\tau_{\exp} \pm \Delta\tau_{\exp} - \tau_{V-A}}{\tau_{V-A}} \simeq -\left[\delta^2 + \zeta^2 + 2\frac{(3\lambda^2 - 1)}{(3\lambda^2 + 1)}\delta\zeta\right]$$

$$\frac{a_{\exp} \pm \Delta a_{\exp} - a_{V-A}}{a_{V-A}} \simeq -\frac{16}{(1-\lambda^2)(1+3\lambda^2)}\delta\zeta$$

$$\frac{A_{\exp} \pm \Delta A_{\exp} - A_{V-A}}{A_{V-A}} \simeq -2\delta^2 - 2\delta\zeta\frac{[6\lambda^3 + 3\lambda^2 - 1]}{(\lambda+1)(1+3\lambda^2)} - 2\frac{\lambda}{\lambda+1}\zeta^2$$

$$\frac{B_{\exp} \pm \Delta B_{\exp} - B_{V-A}}{B_{V-A}} \simeq -2\delta^2 - 2\delta\zeta\frac{[6\lambda^3 - 3\lambda^2 + 1]}{(\lambda-1)(1+3\lambda^2)} - 2\frac{\lambda}{\lambda-1}\zeta^2$$

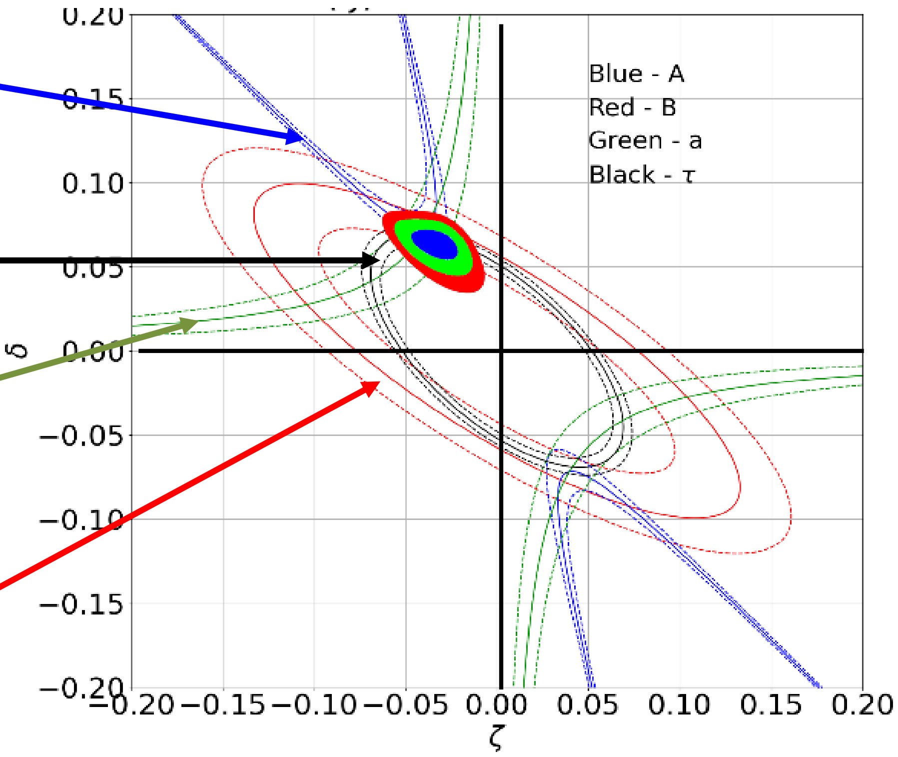
The decay of a neutron within the model of mixing left and right vector bosons can be successfully described

$$\frac{A_{\exp} \pm \Delta A_{\exp} - A_{V-A}}{A_{V-A}} \simeq -2\delta^2 - 2\delta\zeta \frac{\left[6\lambda^3 + 3\lambda^2 - 1\right]}{(\lambda+1)\left(1+3\lambda^2\right)} - 2\frac{\lambda}{\lambda+1}\zeta^2$$

$$\frac{\tau_{\exp} \pm \Delta\tau_{\exp} - \tau_{V-A}}{\tau_{V-A}} \simeq -\left[\delta^2 + \zeta^2 + 2\frac{\left(3\lambda^2 - 1\right)}{\left(3\lambda^2 + 1\right)}\delta\zeta\right]$$

$$\frac{a_{\exp} \pm \Delta a_{\exp} - a_{V-A}}{a_{V-A}} \simeq -\frac{16}{\left(1-\lambda^2\right)\left(1+3\lambda^2\right)}\delta\zeta$$

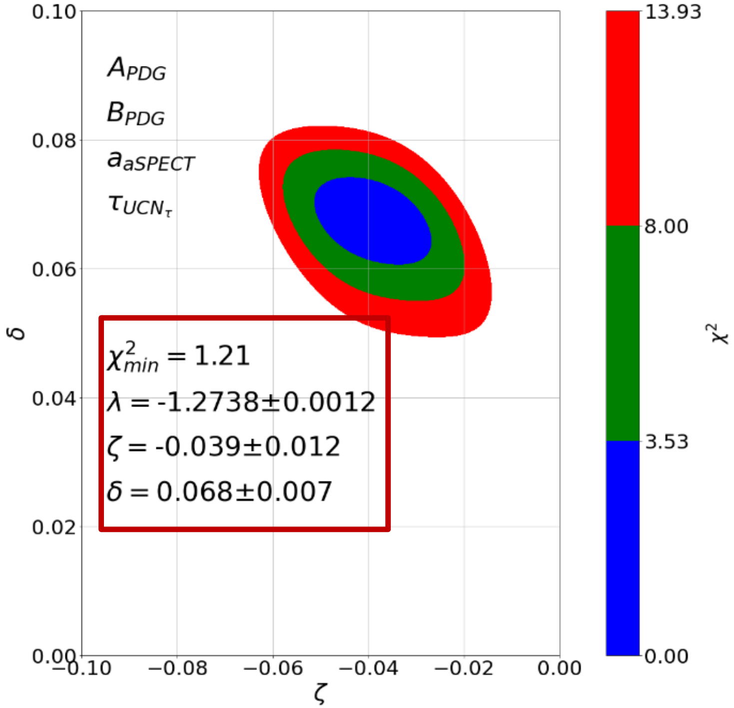
$$\frac{B_{\exp} \pm \Delta B_{\exp} - B_{V-A}}{B_{V-A}} \simeq -2\delta^2 - 2\delta\zeta \frac{\left[6\lambda^3 - 3\lambda^2 + 1\right]}{(\lambda-1)\left(1+3\lambda^2\right)} - 2\frac{\lambda}{\lambda-1}\zeta^2$$



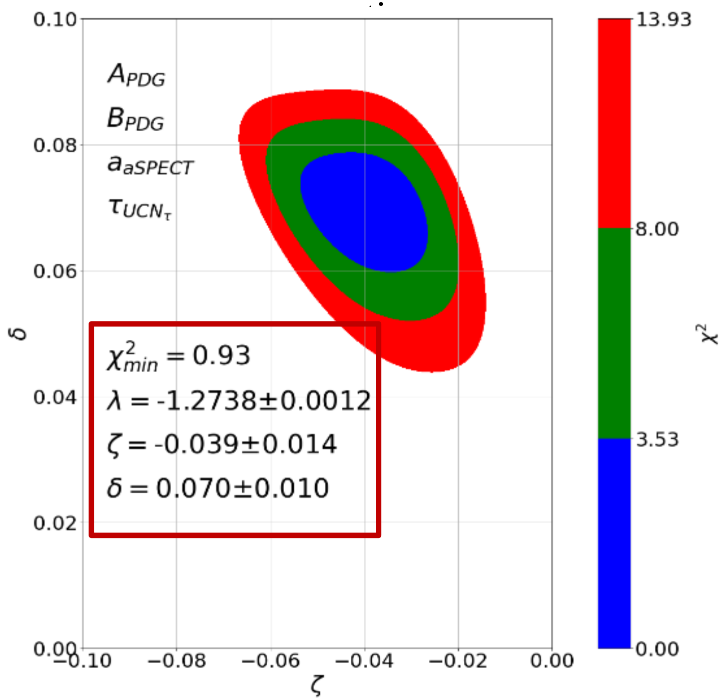
Optimal values of the parameters δ and ζ obtained by the χ2 method using experimental neutron decay data for a, A, B and τ

$$\chi^2_{\min} = 1.21$$

for the most accurate experimental data



for the most accurate experimental data taking into account radiation



Final result of the analysis

As a result of the analysis, it was found that there are indications of the existence of a right vector boson with mass and mixing angle

Письма в ЭЧАЯ. 2024. Т. 22, № 1(258). С. 134–145

ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА 2025. Т. 56, вып. 3. С. 1405–1426

$$M_{W_R} = 304^{+24}_{-20}\ \text{GeV}$$

$$\zeta = -0.039 \pm 0.014$$

$$\delta = 0.070 \pm 0.010$$

АНАЛИЗ ЭКСПЕРИМЕНТАЛЬНЫХ ДАННЫХ РАСПАДА НЕЙТРОНА НА ВОЗМОЖНОСТЬ СУЩЕСТВОВАНИЯ ПРАВОГО ВЕКТОРНОГО БОЗОНА W_R

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Петербургский институт ядерной физики им. Б. П. Константинова Национального исследовательского центра «Курчатовский институт», Гатчина, Россия

Проведен анализ последних наиболее точных экспериментальных данных распада нейтрона на возможность существования правого векторного бозона W_R. В результате анализа обнаружено, что имеется указание на существование правого векторного бозона W_R с массой $M_{W_R} \approx 319^{+26}_{-20}$ ГэВ и углом смешивания с W_L: $\zeta = -0{,}034 \pm 0{,}013$. Этот результат, с одной стороны, следует рассматривать как вызов к экспериментальной физике на коллайдерах, где верхний предел на массу правого векторного бозона W_R значительно выше, а с другой — он указывает на необходимость проведения еще более точных измерений распада нейтрона и его теоретического анализа.

Why resonance W_R

was not detected in collider experiments?

Why resonance W_R was not detected in collider experiments?

Calculation of the cross-section in the left-right model

$$\sigma(s) = \frac{\pi\alpha_W^2}{6} V_{ud}^2 \times \left[\frac{a_{ud}^{L^2} a_{lv}^{L^2} + a_{ud}^{R^2} a_{lv}^{R^2} + a_{ud}^{R^2} a_{lv}^{L^2} + a_{ud}^{L^2} a_{lv}^{R^2}}{(s - m_{W_L}^2)^2 + \gamma_{W_L}^2 m_{W_L}^2} + 2 a_{ud}^{L} a_{lv}^{L} \frac{(s - m_{W_L}^2)(s - M_{W_R}^2) + \gamma_{W_L}^2 \Gamma_{W_R}^2}{\left((s - m_{W_L}^2)^2 + \gamma_{W_L}^2 m_{W_L}^2\right)\left((s - M_{W_R}^2)^2 + \Gamma_{W_R}^2 M_{W_R}^2\right)} + \frac{a_{ud}^{L^2} a_{lv}^{L^2} + a_{ud}^{R^2} a_{lv}^{R^2} + a_{ud}^{R^2} a_{lv}^{L^2} + a_{ud}^{L^2} a_{lv}^{R^2}}{(s - M_{W_R}^2)^2 + \Gamma_{W_R}^2 M_{W_R}^2} \right]$$

$$\sigma(s) = \frac{\pi\alpha_W^2}{6} V_{ud}^2 * \left[\frac{1}{(s - m_{W_L}^2)^2 + \gamma_{W_L}^2 m_{W_L}^2} + \sin^2\zeta \frac{2\frac{\cos^4\zeta}{\sin^2\zeta}\delta^2 + (\delta - 1)^2 \cos^2\zeta \left(e^{2i\omega} + e^{-2i\omega}\right)}{(s - M_{W_R}^2)^2 + \Gamma_{W_R}^2 M_{W_R}^2} \right]$$

For left resonance

$$a_{ud}^{L^2} a_{lv}^{L^2} = (\cos^2\zeta + \delta \sin^2\zeta)^2$$
$$a_{ud}^{R^2} a_{lv}^{R^2} = (\sin^2\zeta + \delta \cos^2\zeta)^2$$
$$a_{ud}^{R^2} a_{lv}^{L^2} = (\delta - 1)^2 \sin^2\zeta \cos^2\zeta\, e^{2i\omega}$$
$$a_{ud}^{L^2} a_{lv}^{R^2} = (\delta - 1)^2 \sin^2\zeta \cos^2\zeta\, e^{-2i\omega}$$

For right resonance

$$a_{ud}^{L^2} a_{lv}^{L^2} = (\sin^2\zeta + \delta \cos^2\zeta)^2$$
$$a_{ud}^{R^2} a_{lv}^{R^2} = (\delta \cos^2\zeta + \sin^2\zeta)^2$$
$$a_{ud}^{R^2} a_{lv}^{L^2} = (\delta - 1)^2 \sin^2\zeta \cos^2\zeta\, e^{2i\omega}$$
$$a_{ud}^{L^2} a_{lv}^{R^2} = (\delta - 1)^2 \sin^2\zeta \cos^2\zeta\, e^{-2i\omega}$$

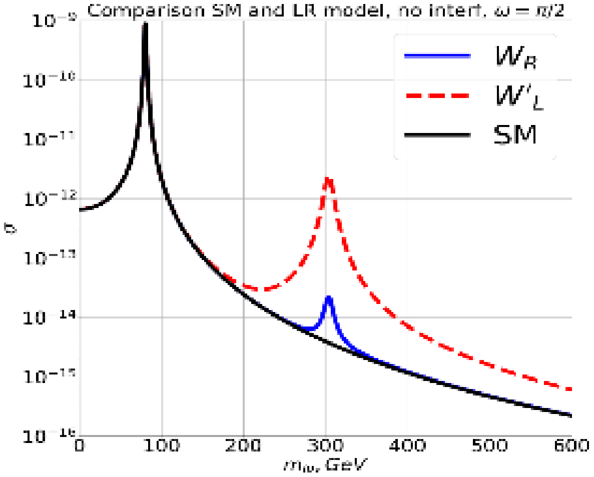
[5] P. Herczeg, Phys. Rev. D **34**, 3449 (1986),

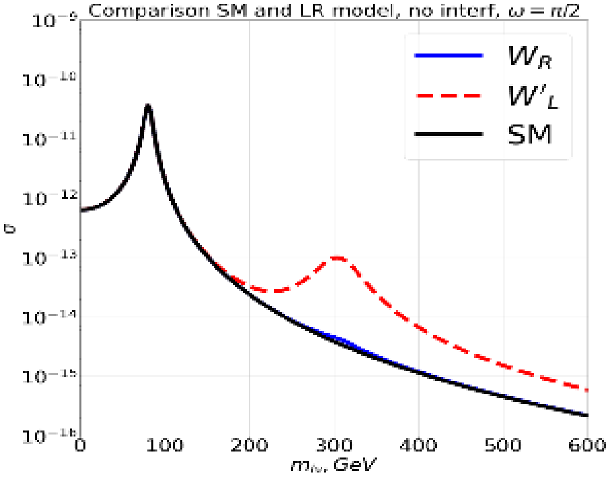
[44] E. Boos, V. Bunichev, L. Dudko, M. Perfilov, Phys. Lett. B **655**, 245 (2007)

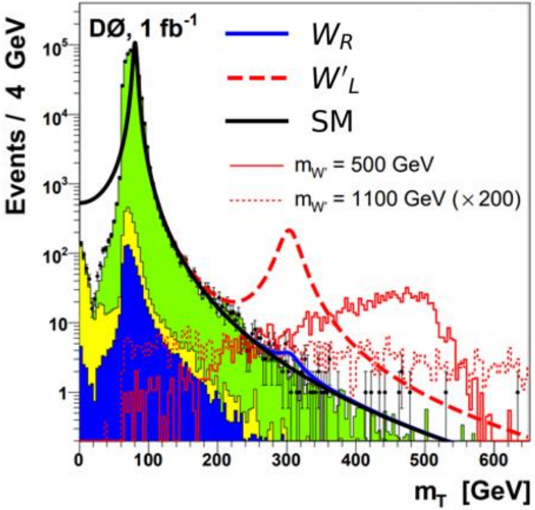
Why resonance W_R was not detected in collider experiments?

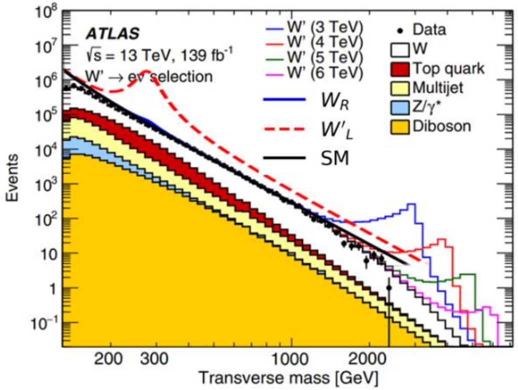
Calculation of the cross-section in the left-right model

accounting for hardware broadening



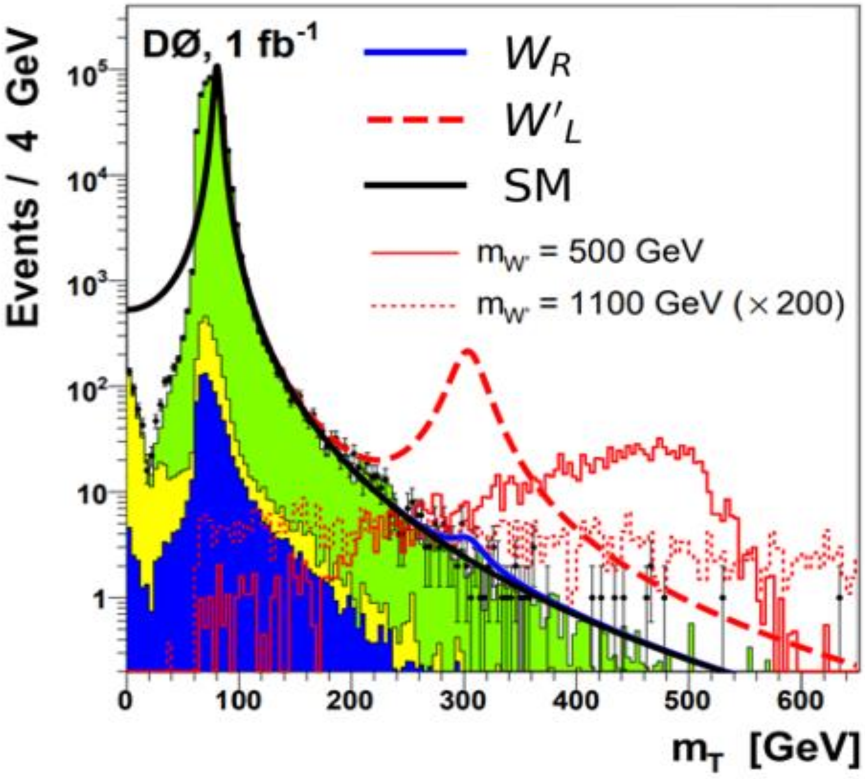


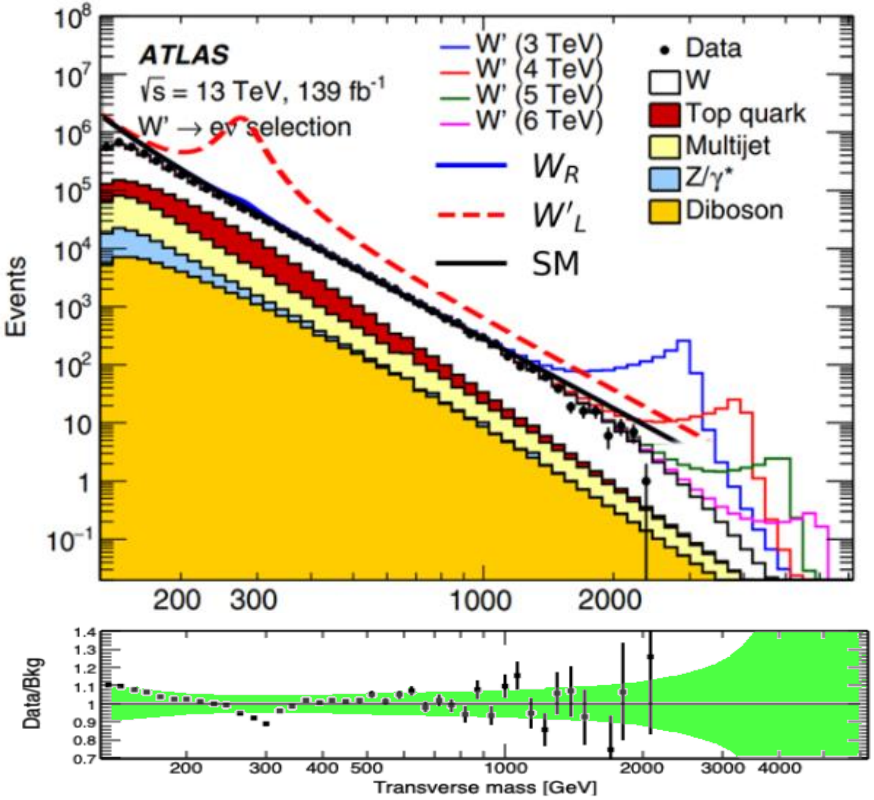




Why resonance W_R *was not detected in collider experiments?*

Comparison of the calculation results with experimental data for the Tevatron experiment at Fermilab from publication [45] and for the ATLAS experiment [46] at CERN.



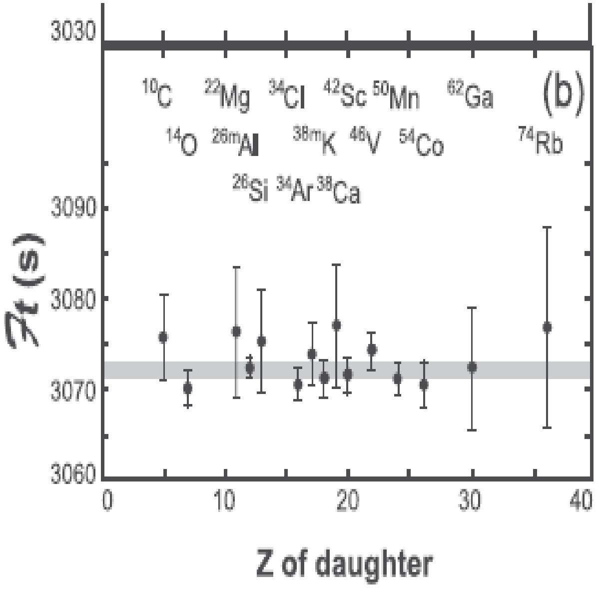


Data from experiments with nuclear superallowed 0+ - 0+ transitions allow us to determine the V_{ud} element of the CKM matrix independently

PROBLEM OF UNITARITY OF THE CKM MATRIX

Superallowed $0^+ \rightarrow 0^+$ nuclear β decays: 2020 critical survey, with implications for V_{ud} and CKM unitarity

J. C. Hardy* and I. S. Towner
Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA

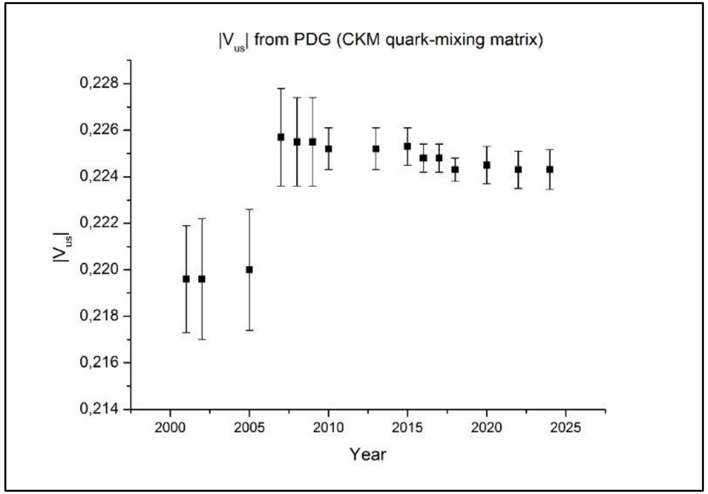


A new critical review of all half-life, decay energy, and branching ratio measurements associated with 23 superresolved 0+ → 0+ is presented. Their average Ft combined with the muon lifetime yields the up-down quark mixing element of the Cabibbo-Kobayashi-Maskawa matrix, Vud = 0.97373 ± 0.00031. This is one standard deviation lower than our 2015 result, and its uncertainty has increased by 50%. This is not a consequence of any shifts in the experimental data, but of new radiative correction calculations. The lower Vud now leads to a higher voltage in the top-row unitarity test in the CKM matrix.

This result is given in the last row of Table XVII: where the unitarity sum is |Vu|2 = 0.9985(6), indicating a violation of 2.4σ unitarity.

Data |Vus| from PDG

$V_{us} = 0.2243(8)$



The third element of the top row, |Vub|, is very small and has almost no effect on the unitarity test. Its value from the Particle Data Group (PDG) evaluation is:

|Vub| = (3.94 ± 0.36) × 10−3

V_{ud}^{unit} from the Unity of the CKM matrix

$$V_{ud}^{unit} = \sqrt{1 - V_{us}^2 - V_{ub}^2} = 0.97452(18).$$

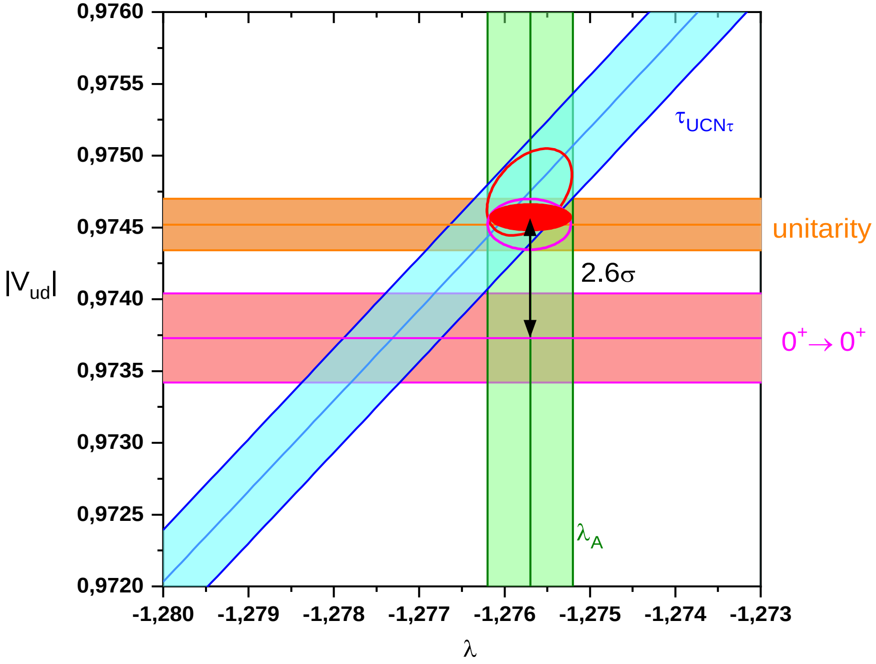
However, the matrix element V_ud^00 of 0^+−0^+ beta decays differs

$$V_{ud}^{00} = 0.97367(32)$$

$$\frac{V_{ud}^{unit} - V_{ud}^{00}}{V_{ud}^{00}} = 8.6 * 10^{-4} (2.4\,\sigma)$$

PROBLEM OF UNITARITY OF THE CKM MATRIX

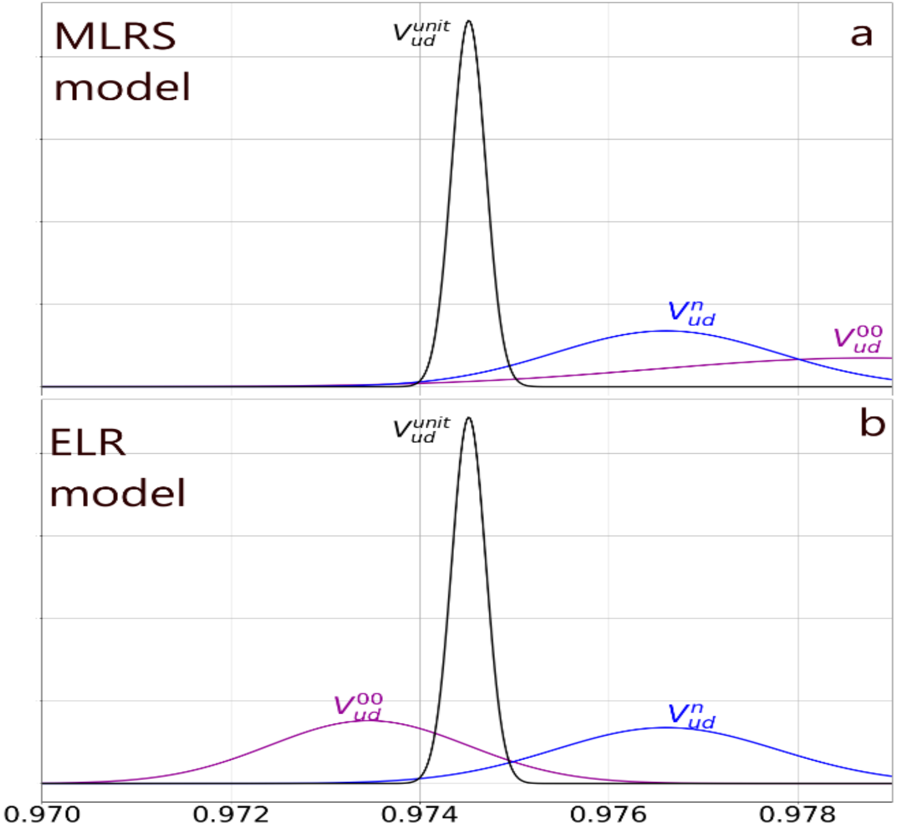
The difference Vud between the matching values from neutron decay and CKM unitarity and the Vud value from 0+-0+ transitions is 2.6 sigma



Dependence of the quark mixing matrix element Vud on λ, calculated using the SM formulas from neutron decay, from experiments with Fermi-superallowed nuclear transitions 0+ - 0+ and from the unitarity of the SCM matrix using Vus measurements [18].

$$\frac{\Delta V_{ud}}{V_{ud}} = 8.6 * 10^{-4}(2.6\ \sigma)$$

Comparison of the values of V_{ud} obtained from data on neutron decay, superallowed Fermi transitions, and the requirement of CKM matrix unitarity within the framework of two models.

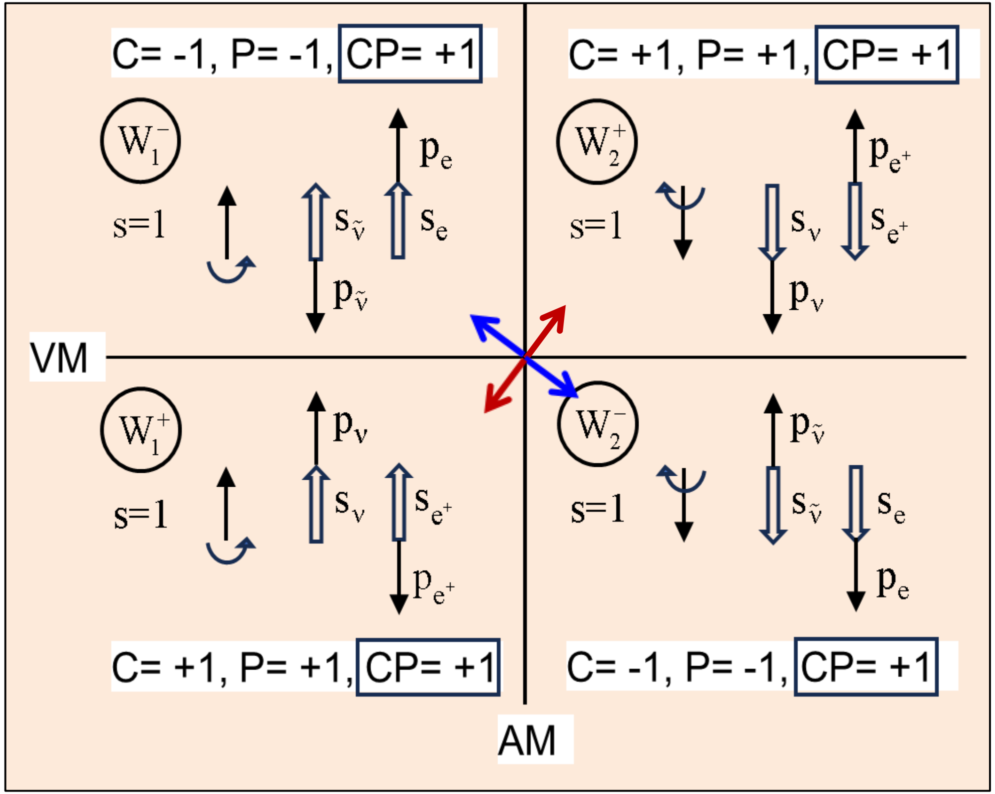


$$\begin{pmatrix} W_L^{\pm} \\ W_R^{\pm} \end{pmatrix} = \begin{pmatrix} \cos\zeta & +\sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^{\pm} \\ W_2^{\pm} \end{pmatrix}$$

$$\begin{pmatrix} W_L^{\pm} \\ W_R^{\pm} \end{pmatrix} = \begin{pmatrix} \cos\zeta & \mp\sin\zeta \\ \pm\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^{\pm} \\ W_2^{\pm} \end{pmatrix}$$

(a) The left-right manifest model as presented in work [5]. (b) The extended left-right model, introduced in this work.

The mixing scheme between left and right particles W_1^- and W_2^-, and between left and right antiparticles W_1^+ and W_2^+.



VM – vector mirror, AM – mirror of axial vectors.

W_1^-—left particle (C = -1, P=-1), CP=+1

W_2^- —right particle(C=-1, P=-1), CP=+1

W_1^+—left antiparticle (C=+1, P=+1), CP=+1

W_2^+—right antiparticle (C=+1, P=+1), CP=+1

$$\begin{pmatrix} W_L^{\pm} \\ W_R^{\pm} \end{pmatrix} = \begin{pmatrix} \cos\zeta & \mp\sin\zeta \\ \pm\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^{\pm} \\ W_2^{\pm} \end{pmatrix}$$

The observed discrepancy can be analyzed within the framework of a model taking into account right-handed currents. In the simplest left-right manifesto of the model, mixing of left W_L and right W_R vector bosons is considered, and for flavor states , and mass states W_1 W_2 , we can write:

$$\begin{pmatrix} W_L^{\pm} \\ W_R^{\pm} \end{pmatrix} = \begin{pmatrix} \cos\zeta & \mp\sin\zeta \\ \pm\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^{\pm} \\ W_2^{\pm} \end{pmatrix}$$

where $\boldsymbol{\zeta}$ is the mixing angle of the current states W_L and W_R , and δ is the ratio of the squares of the masses of the states W_1 and W_2.

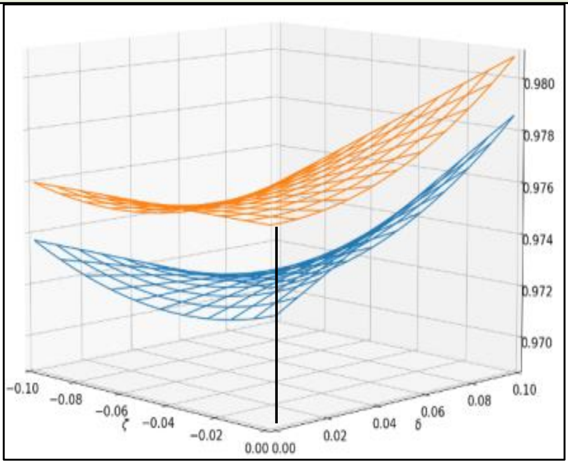
$$\delta = (M_1/M_2)^2$$

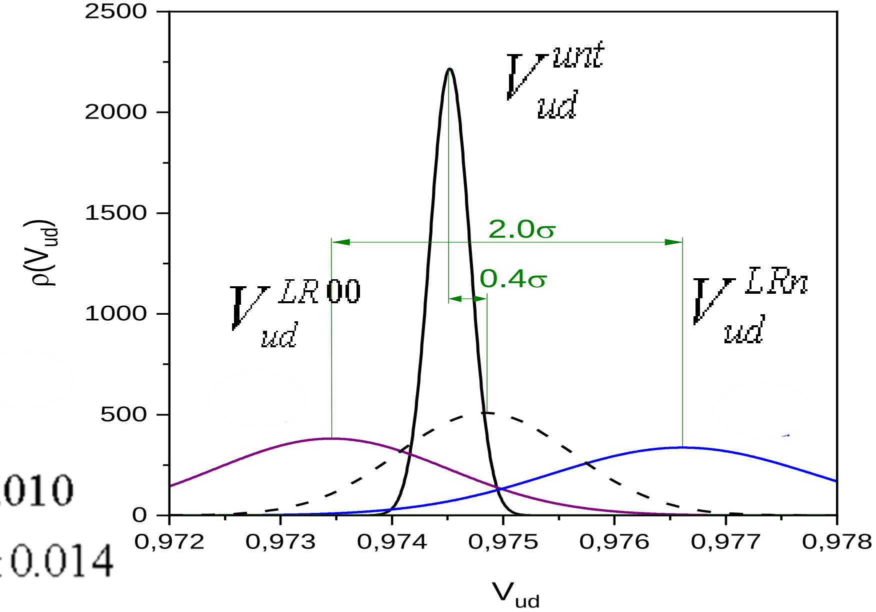
In this model, we consider W^- and W^+ as particle and antiparticle respectively, and as a consequence, the mixing matrices for negative and positive bosons are Hermitian conjugate, which explains the sign reversal of the sines.

Extended left-right model with CP-violation

In this scheme, we essentially introduce a difference in the interaction of (W^-) and (W^+), i.e. particles and antiparticles, which will lead to CP violation.

The mixing scheme between left and right particles W_1^- and W_2^-, and between left and right antiparticles W_1^+ and W_2^+.





$$V_{ud}^{00LR} = V_{ud}^{00(V)} \sqrt{\frac{[1+(\delta+\zeta)^2]}{1+\zeta^2}}$$

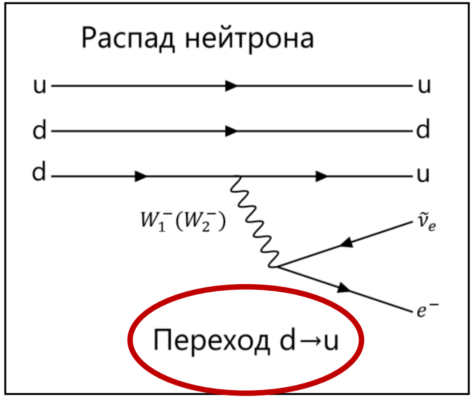
$$\delta = 0.070 \pm 0.010$$

$$\zeta = -0.039 \pm 0.014$$

$$V_{ud}^{nLR} = V_{ud}^{n(V-A)} \times \sqrt{\frac{1+3\lambda_{n,V-A}^2}{1+3\lambda_{\exp,LR}^2} \frac{[1+(\delta^2+\zeta^2)+2\frac{(3\lambda_{n,V-A}^2-1)}{(3\lambda_{n,V-A}^2+1)}\delta\zeta]}{(1+\zeta^2)}}$$

$$(V_{ud}^{LR})^2 = \frac{1}{2}[(V_{ud}^{LR}W^+)^2 + (V_{ud}^{LR}W^-)^2]$$

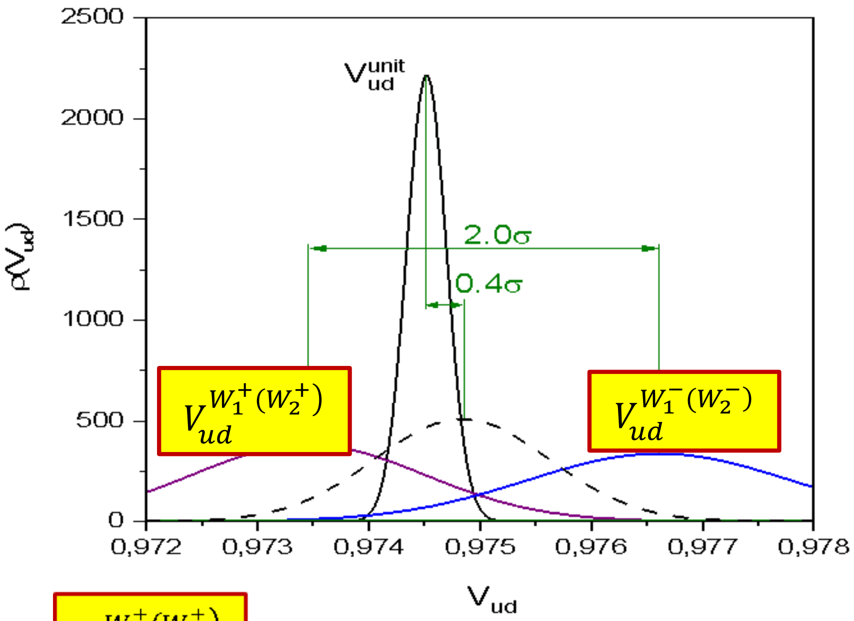
Violation of CP invariance in baryons



$$A_{p-n} = \frac{(V_{ud}^{00LR})^2 - (V_{ud}^{nLR})^2}{(V_{ud}^{00LR})^2 + (V_{ud}^{nLR})^2} = (-3.2 \pm 1.6) \cdot 10^{-3} (2.0\sigma)$$

$$V_{ud}^{nLR} \equiv V_{ud}^{W_1^-(W_2^-)}$$

$$V_{ud}^{00LR} \equiv V_{ud}^{W_1^+(W_2^+)}$$



The discrepancy between the values $V_{ud}^{W_1^-(W_2^-)}$ and $V_{ud}^{W_1^+(W_2^+)}$ within the left-right model is **2.0σ.** And the deviation of their average value from unitarity is **0.4σ.**

An important consequence within the left-right model is the difference in the strength of vector and axial-vector interactions due to CP violation

$$A_{p-n} = \frac{(V_{ud}^{00LR})^2 - (V_{ud}^{nLR})^2}{(V_{ud}^{00LR})^2 + (V_{ud}^{nLR})^2} = (-3.2 \pm 1.6)\cdot 10^{-3} (2.0\sigma)$$

$$p + \bar{\nu}_e \rightarrow n + e^+ \qquad \neq \qquad n + \nu_e \rightarrow p + e^-$$

The reason for baryon and lepton asymmetry in cosmology.

Violation of CP invariance in baryons has not yet been detected in laboratory conditions. However, it is necessary to explain the baryon asymmetry of the Universe, i.e. the excess of matter in it.

In 1967, A. D. Sakharov showed that for baryon asymmetry to appear in the Universe, three conditions must be met:

1. Violation of CP-invariance (asymmetry of the replacement of all particles with antiparticles).

2.Non-conservation of baryon (quark) number.

3.Violation of thermodynamic equilibrium in the early Universe.

The mechanism for violating CP-invariance has not yet been established.

Analysis of CP-violation processes in K-meson decays within the extended left-right model using the parameters δ and ζ

In connection with this circumstance, it is advisable to conduct an analysis of CP violation processes in K-meson decays within the framework of the extended left-right model, using the parameters δ and ζ.

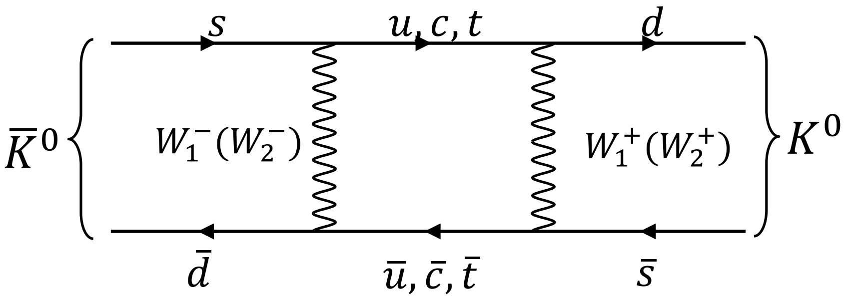
In the process of system oscillations K^0 $\bar{K}^0$ may decay into a state

$$e^- \pi^+ \bar{\nu}$$

or in a state

.

$$e^+ \pi^- \nu$$



The weak interaction Hamiltonian in the case where only vector currents are present can be represented in the same general form as for transitions $0^+ \leftrightarrow 0^+$.

However, K-mesons are pseudoscalar particles with spin and parity 0^-,
so transitions $K^0 \tilde{K}^0$ are transitions $0^- \leftrightarrow 0^-$

Therefore, there is a change in sign before ζ compared to transitions $0^+ \leftrightarrow 0^+$.

$$H_V^N = \bar{e}\gamma_\mu \left(C_A + C'_A\gamma_5\right)\nu \cdot \bar{\pi}\gamma_\mu K^0$$

where with decay $W_1^+(W_2^+)$ the relationship is related

$$\left|C_A\right|^2 + \left|C'_A\right|^2 = G_F^2 \left|V_{us}\right|^2 \left(1 + (\delta - \zeta)^2\right)$$

with decay $W_1^-(W_2^-)$ the relationship is related

$$\left|C_A\right|^2 + \left|C'_A\right|^2 = G_F^2 \left|V_{us}\right|^2 \left(1 + (\delta + \zeta)^2\right)$$

CP-violating asymmetry in K0 meson decays

$$A_T^{LR} = \frac{1+(\delta-\zeta)^2-\left(1+(\delta+\zeta)^2\right)}{2\left(1+\delta^2+\zeta^2\right)} \approx -2\delta\zeta$$

Using the values obtained earlier $\delta = 0.070(10)$ и $\zeta = -0.039(14)$

we obtain for the value A_T meaning:

$$A_T^{LR} = (5.5 \pm 2.1) \times 10^{-3} (2.6\sigma)$$

CL 99.1 % **Prediction of the left-right model with CP-violation**

$$A_T^{\exp} = \left(6.6 \pm 1.3 \pm 1.0\right) \times 10^{-3} (4\sigma)$$

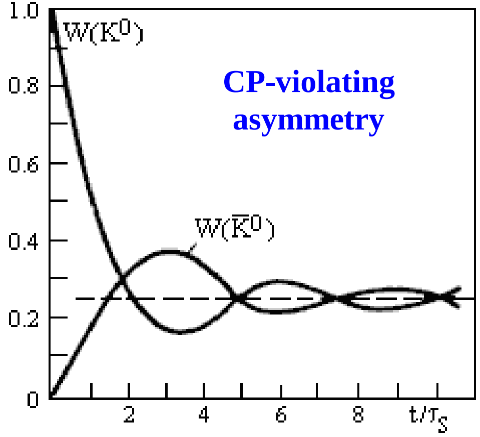
Experiment (pdg)

This value is within the available accuracy and agrees with the experimentally measured asymmetry.

In decays of neutral K-mesons, the CP-violating lepton asymmetry was measured quite accurately with the registration of decay products in the final state

$$A_L = \frac{\Gamma\left(K_L \to e^+\pi^-\nu\right) - \Gamma\left(K_L \to e^-\pi^+\bar{\nu}\right)}{\Gamma\left(K_L \to e^+\pi^-\nu\right) + \Gamma\left(K_L \to e^-\pi^+\bar{\nu}\right)}$$

$$A_L^{\exp} = \left(3.32 \pm 0.06\right) \times 10^{-3}$$ (pdg)



This asymmetry $A_L^{\exp}$ is two times smaller than $A_T^{\exp}$. The fact is that the effect of direct CP violation is measured during the progress of the $K_0\bar{K}_0$ oscillation process over 10 periods of the lifetime of the K_S-state, which is $0.86 \cdot 10^{-10}$ s. And the effect of CP violation in the final state is measured at the lifetimes of the K_L-state, which is $5.4 \cdot 10^{-8}$ s. By this time, the effect associated with the K_S-state reduces. Therefore, $A_T / A_L = 2$ as shown in [48].

CP-violating final-state asymmetry in neutral K-meson decays

$$A_L = \frac{\Gamma\left(K_L \to e^+\pi^-\nu\right) - \Gamma\left(K_L \to e^-\pi^+\overline{\nu}\right)}{\Gamma\left(K_L \to e^+\pi^-\nu\right) + \Gamma\left(K_L \to e^-\pi^+\overline{\nu}\right)}$$

$$A_L^{\exp} = \left(3.32 \pm 0.06\right) \times 10^{-3}$$

Lepton asymmetry

While the CP-violating asymmetry from our comparative analysis

V_{ud}^{nLR} and V_{ud}^{00LR}

$$A_{p-n} = \frac{(V_{ud}^{00LR})^2 - (V_{ud}^{nLR})^2}{(V_{ud}^{00LR})^2 + (V_{ud}^{nLR})^2} = (-3.2 \pm 1.6) \cdot 10^{-3} (2.0\sigma)$$

Another sign of baryon asymmetry

Another sign of baryon asymmetry indicates that, apparently, the condition of conservation of B-L, which is indicated in the famous work of A.D. Sakharov [49, 50], is fulfilled.

Experimental results for CP-violating asymmetries in the final state in units of 10-3.

	$p-n$	K_L^0
A^{exp}	-3.2 ± 1.6	3.32 ± 0.06

$A^{exp} < 0$ ⇒ **B > 0**

$A^{exp} > 0$ ⇒ **L < 0**

Baryon-lepton asymmetry of the Universe and the left-right model of weak interaction with CP-violation

In addition, the violation of both baryon and lepton asymmetry is discussed, and the conservation of the B-L difference is noted. (quote)

"If the baryon-lepton asymmetry with B $\neq L$ arises at a temperature above the range $T = 10^2 — 10^4$ GeV … then a state will be established (with high precision) in the low temperature region which corresponds to the entropy maximum at given constant value of B $— L =$ const (and under the condition of electric neutrality)."

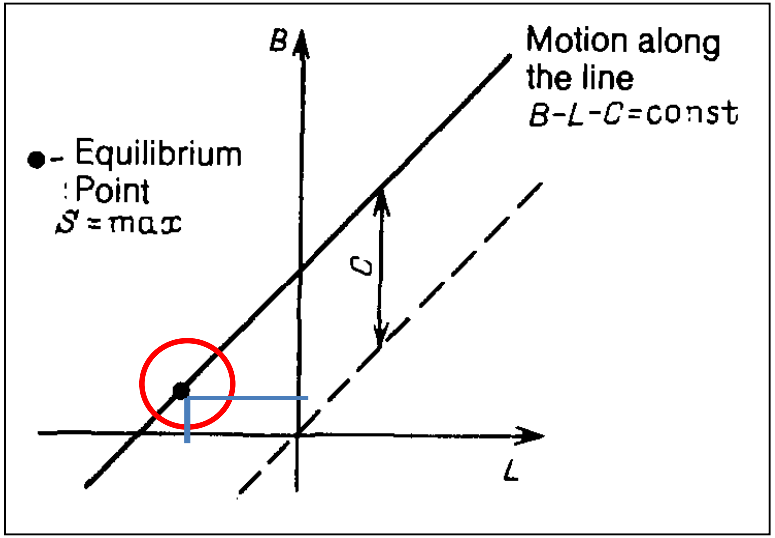


Figure from the article by A.D. Sakharov.

Consequences for cosmology

1. The **baryon-lepton asymmetry** with B $\neq L$ arises at a temperature above the range $T = 10^2$— 10^4 GeV due to **mixing W_L and W_R with CP-violation.**
2. **Violation of the baryon number** is possible in process of **neutron-antineutron oscillations** during the hadronization of quarks.
3. Extension of SM by introducing right vector bosons $W_R^{\pm}$ and right neutrinos (steril) is required. **Right neutrinos (sterile)** can be considered as candidates for **dark matter**.

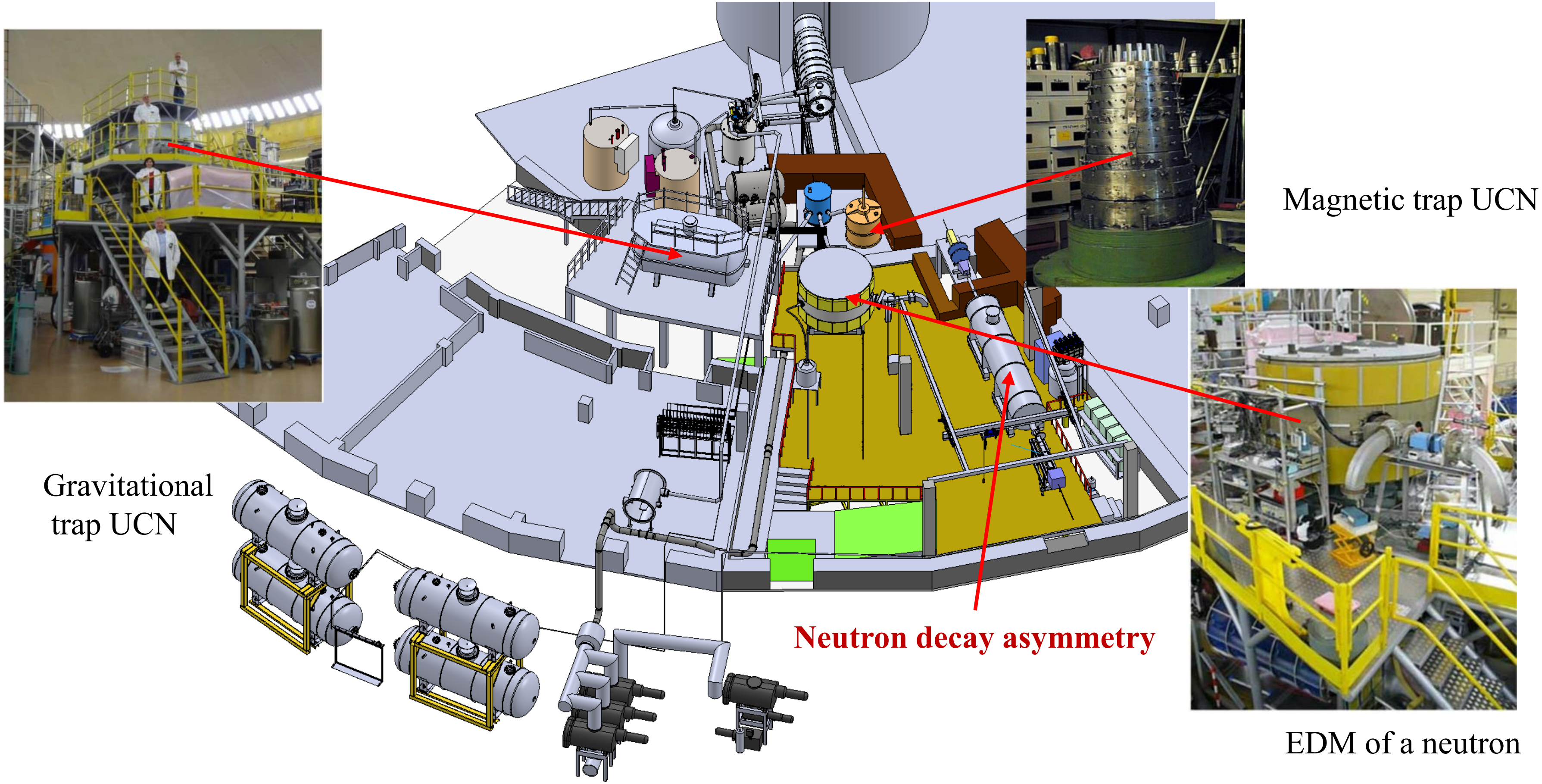
The nature of CP violation.

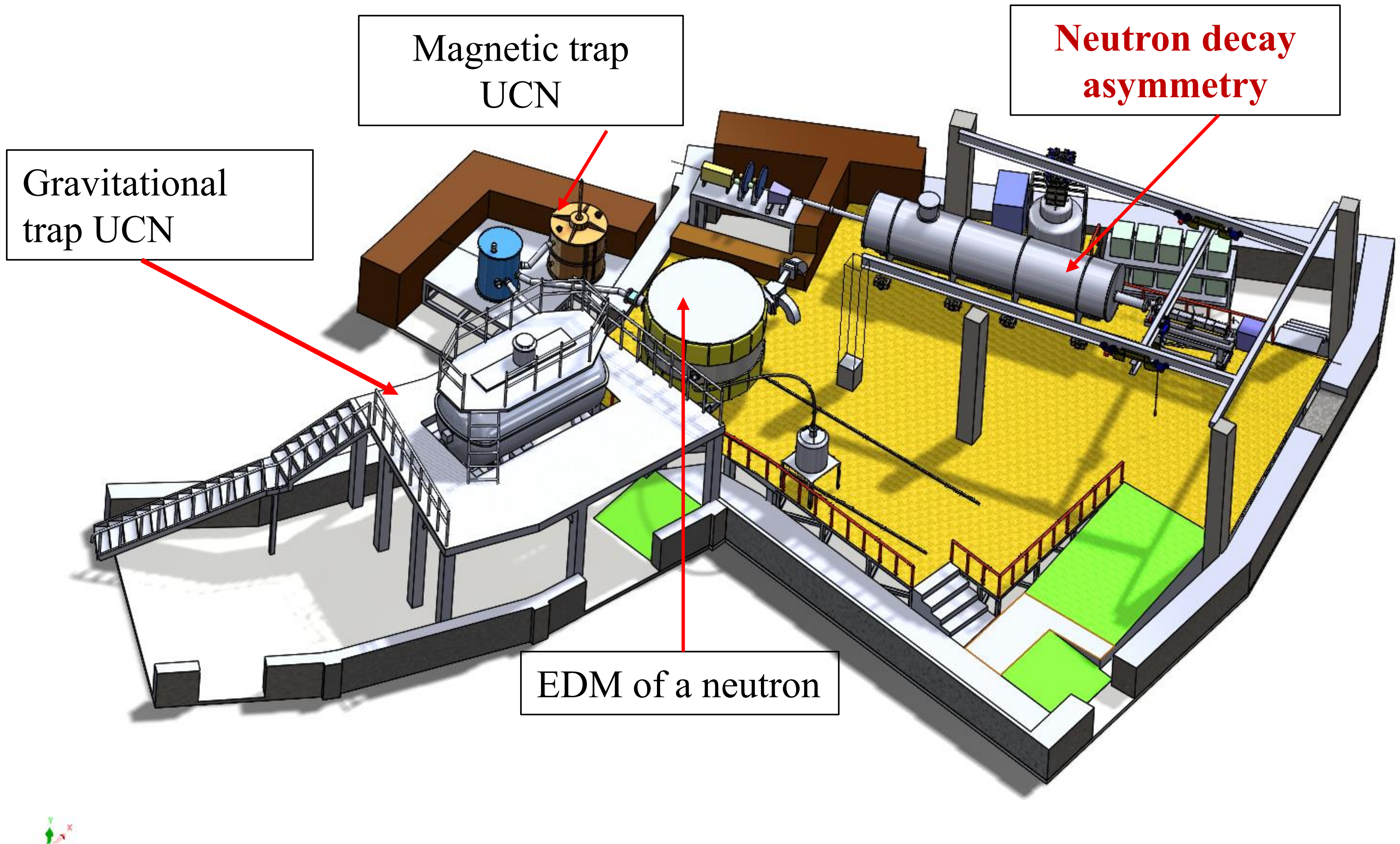
In our work, a left-right model of weak interaction with CP violation is proposed at mixing W_L and W_R, which indicates the nature of CP violation. In this regard, it is important to note that A.D. Sakharov's work speaks of the simultaneous formation of baryon and lepton asymmetry.

B-L is conserved.

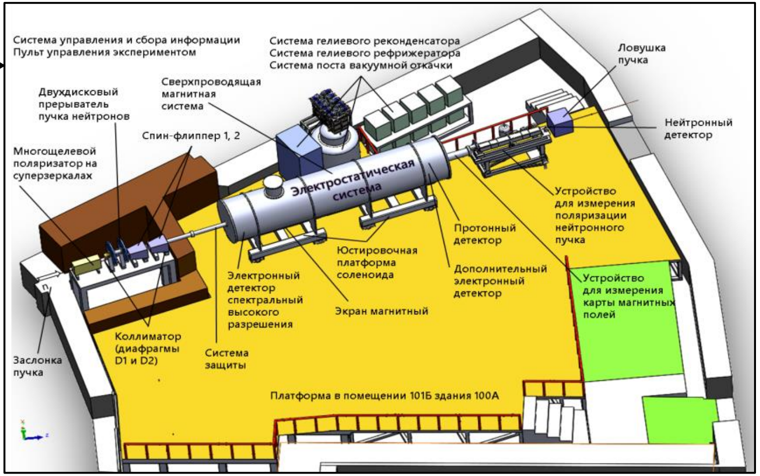
Part 3
Prospects of the experiment

SCIENTIFIC RESEARCH PROGRAMM
NEUTRON DECAY AT THE PEAK REACTOR




Magnetic trap
UCN
Neutron decay
asymmetry
Gravitational
trap UCN
EDM of a neutron

Project of the installation for measuring neutron decay asymmetries at the PIK reactor



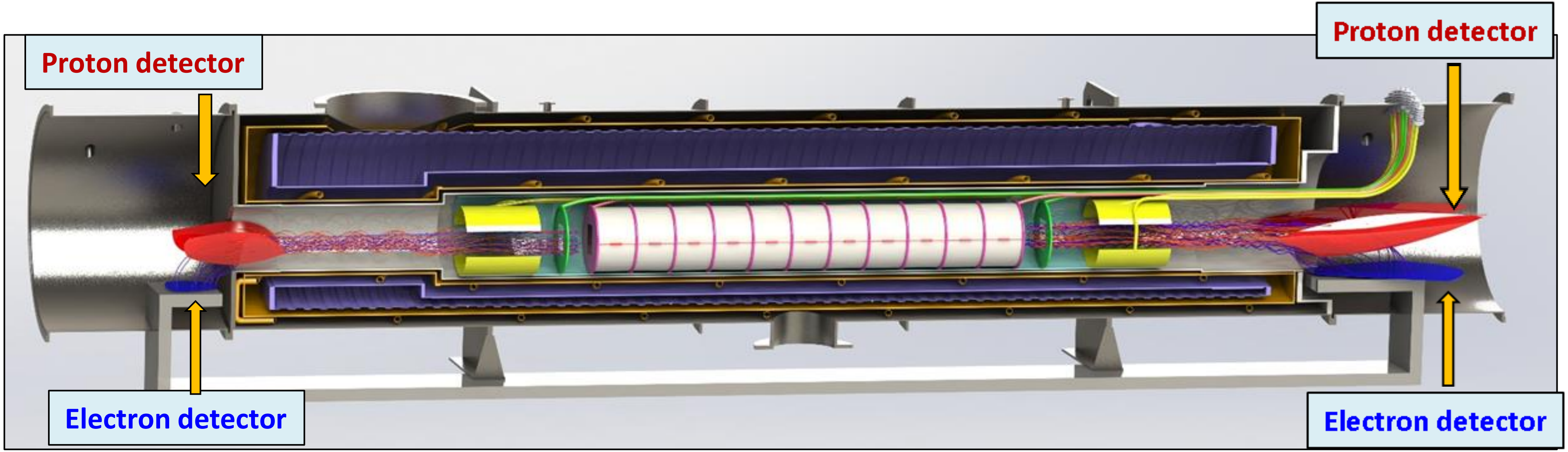
Manufacturing of the installation «NEUTRON DECAY»

Superconducting solenoid

Cryostat

Testing of the installation at NIIEFA 31.05.24.
A current of 1050 A was introduced into the superconducting solenoid.

Project of the installation for measuring all three neutron decay asymmetries (a, A and B) at the PIK reactor



The planned increase in measurement accuracy by a factor of 3 will provide an answer to the fundamentally important question about the discrepancy between precision measurements of neutron decay and the Standard Model.

Experiments will show what happens next

Thank you for your attention

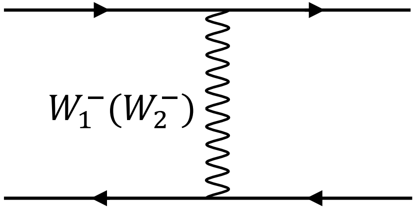
Scenario for the formation of baryon and lepton asymmetry in the Universe.

1. At temperatures of the order of 10^4 GeV, the degree of symmetry between left and right processes (processes with opposite CP parity) was quite high.
2. But when the temperature decreased due to CP-violation between left and right W, an advantage arose in preserving neutrons and protons in relation to antineutrons and antiprotons and simultaneously in preserving antineutrinos in relation to neutrinos.
3. The process of annihilation becomes incomplete. The remainder is our Universe.
4. Indeed, in the modern Universe we have protons and neutrons in nuclei, it is obvious that the baryon number is positive $B>0$. Charged leptons are electrons in atoms, which indicates a positive asymmetry in the charged leptons sector, which is compensated excess of negative asymmetry due to a significant number of sterile antineutrinos, therefore $L < 0$.
5. **If protons and neutrons formed galaxies**, then **neutrinos and antineutrinos formed dark matter** located on the periphery of galaxies.

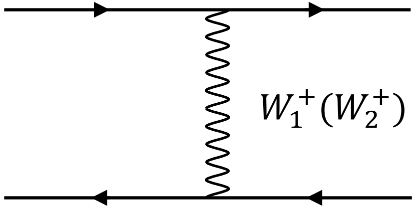
Dark matter

It is important to note that the existence of the W_R suggests the presence of right (so-called sterile) antineutrinos, which have a significantly greater mass than active neutrinos. **They provide a mass of dark matter approximately 5 times greater than the mass of baryonic matter.** The requirement for the stability of dark matter [1] and astrophysical observations [55] limit the mass of sterile neutrinos to below a few keV.

Mixing of W_1^L and W_2^R

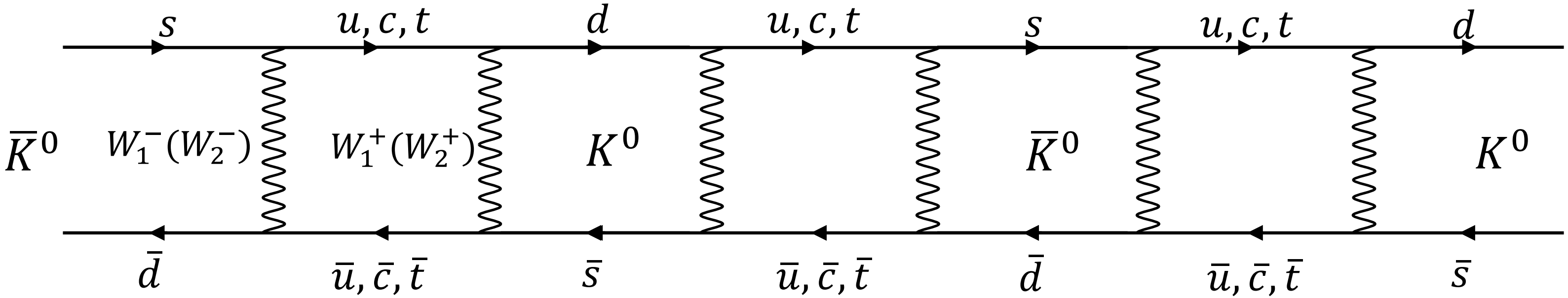


$\sim 3 \cdot 10^{-25} s$



$\sim 3 \cdot 10^{-25} s$

Mixing of K^0 and $\bar{K}^0$



$\sim 10^{-12} \div 10^{-10}\ s$

No mixing

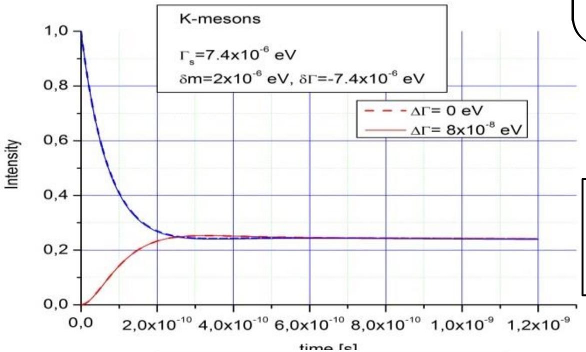
$$\begin{pmatrix} M - i\dfrac{\Gamma_0 - \frac{\Delta\Gamma}{2}}{2} & 0 \\ 0 & M - i\dfrac{\Gamma_0 + \frac{\Delta\Gamma}{2}}{2} \end{pmatrix}$$

Lifetime of meson and antimeson are equal

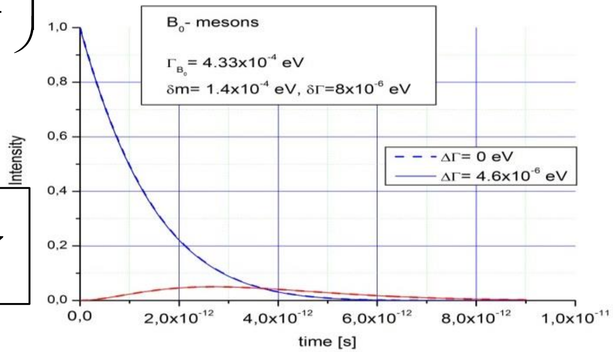
$$\begin{pmatrix} M - i\dfrac{\Gamma_0}{2} & \delta m - i\dfrac{\delta\Gamma}{2} \\ \delta m - i\dfrac{\delta\Gamma}{2} & M - i\dfrac{\Gamma_0}{2} \end{pmatrix}$$

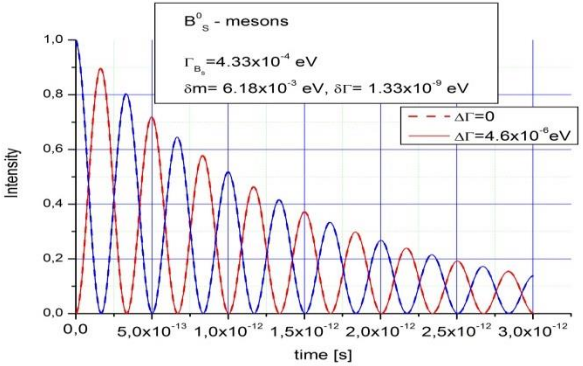
Lifetime of meson and antimeson are not equal

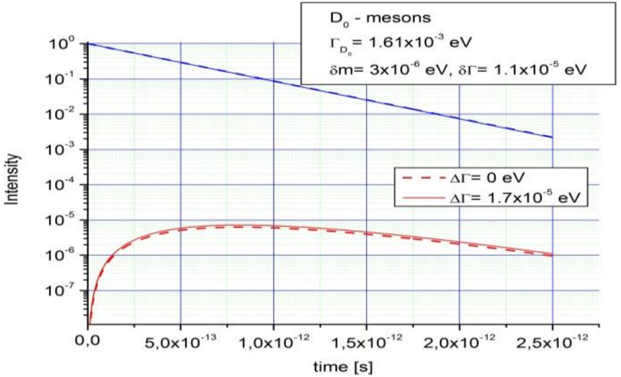
$$\begin{pmatrix} M - i\dfrac{\Gamma_0 - \frac{\Delta\Gamma}{2}}{2} & \delta m - i\dfrac{\delta\Gamma}{2} \\ \delta m - i\dfrac{\delta\Gamma}{2} & M - i\dfrac{\Gamma_0 + \frac{\Delta\Gamma}{2}}{2} \end{pmatrix}$$

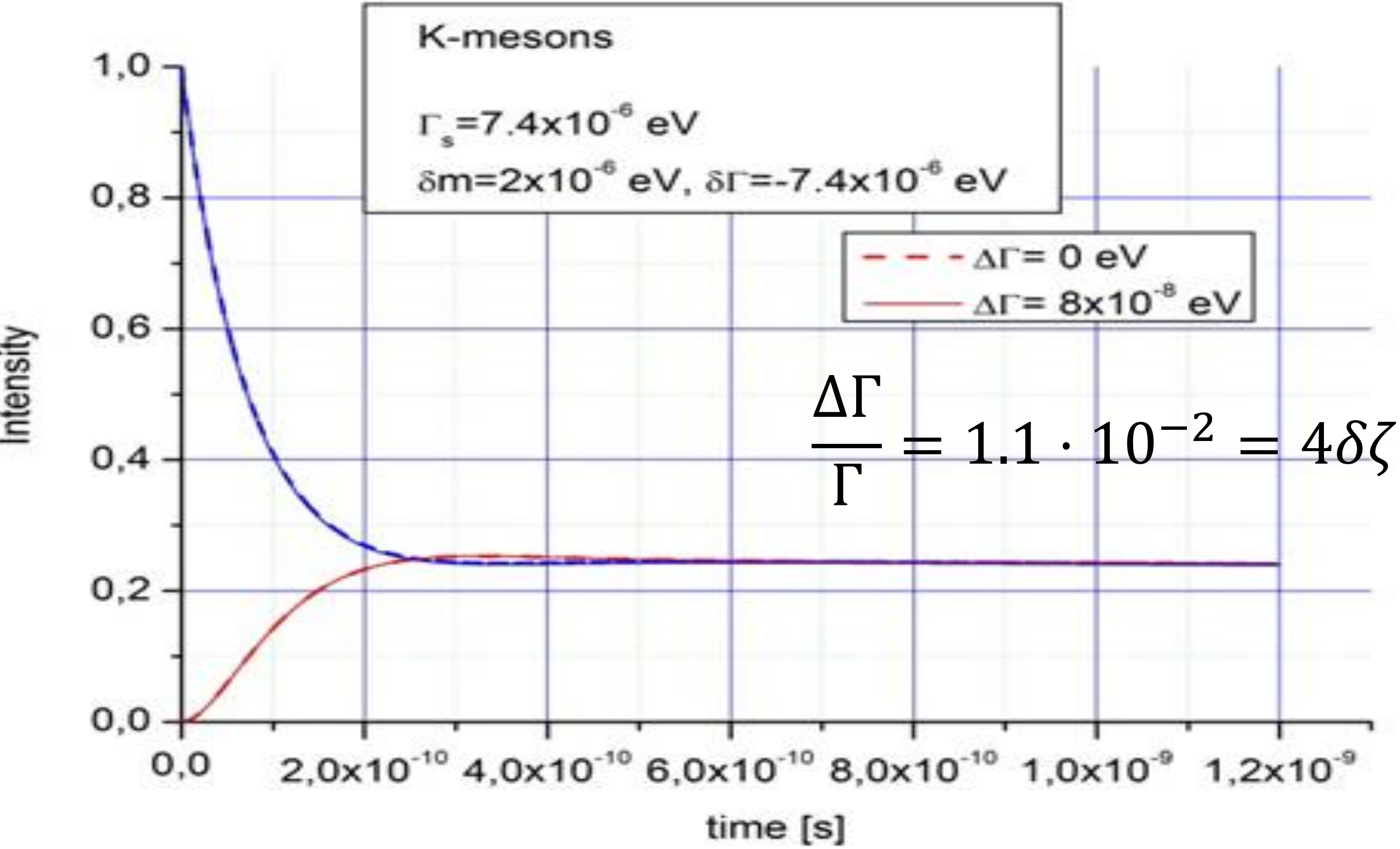


$$\frac{\Delta\Gamma}{\Gamma} = 1.1 \cdot 10^{-2} = 4\delta\zeta$$





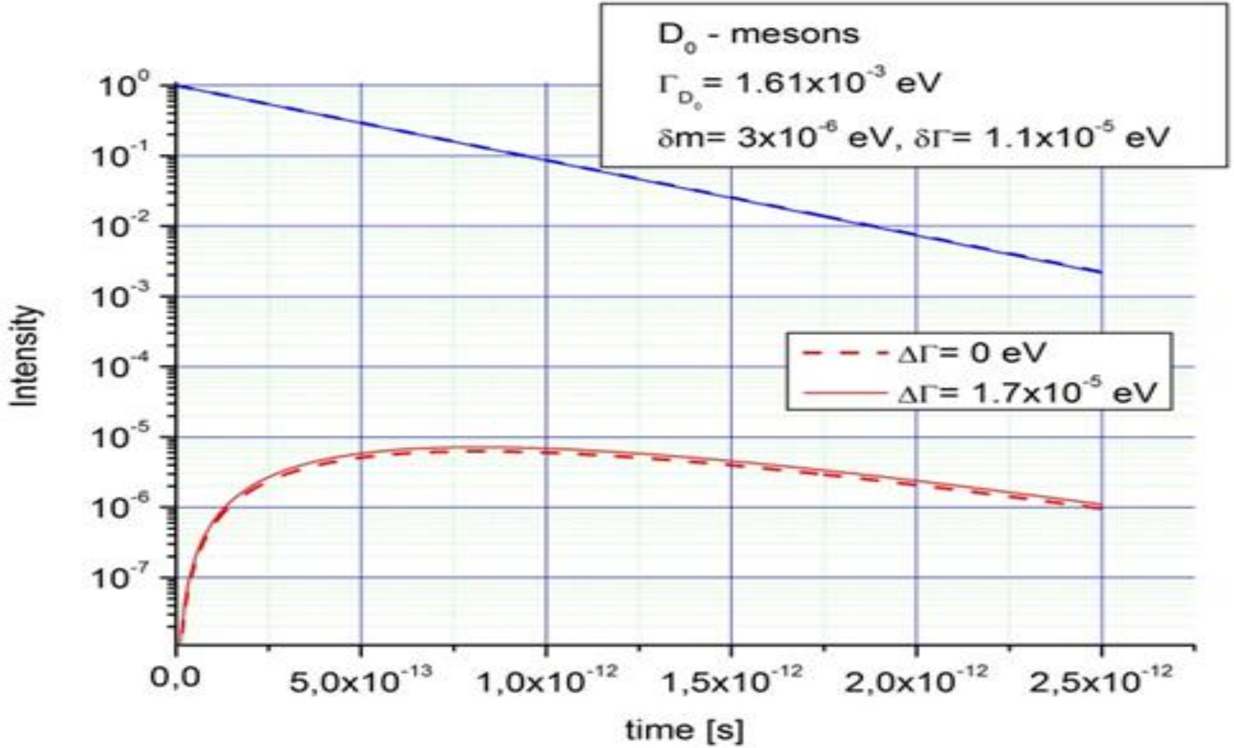




$$\frac{\Delta\Gamma}{\Gamma} = 1.1 \cdot 10^{-2} = 4\delta\zeta$$

$$\left(\frac{\delta m}{\delta\Gamma}\right)_{K_0} = 0.27$$

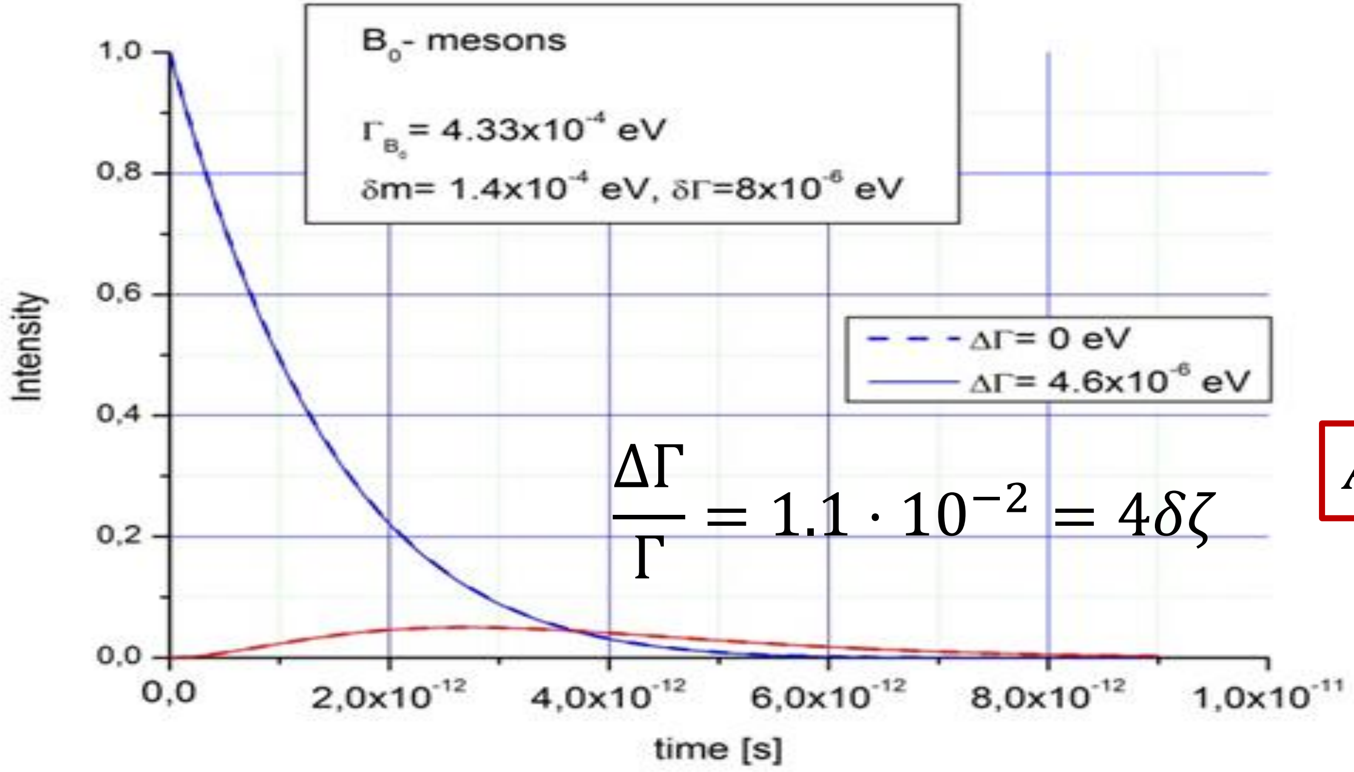
$$\omega_{ocs} < \Delta\tau^{-1}$$



$$\left(\frac{\delta m}{\delta \Gamma}\right)_{D_0} = 0.27$$

$$\omega_{ocs} < \Delta\tau^{-1}$$

$$\frac{\Delta\Gamma}{\Gamma} = 1.1 \cdot 10^{-2} = 4\delta\zeta$$

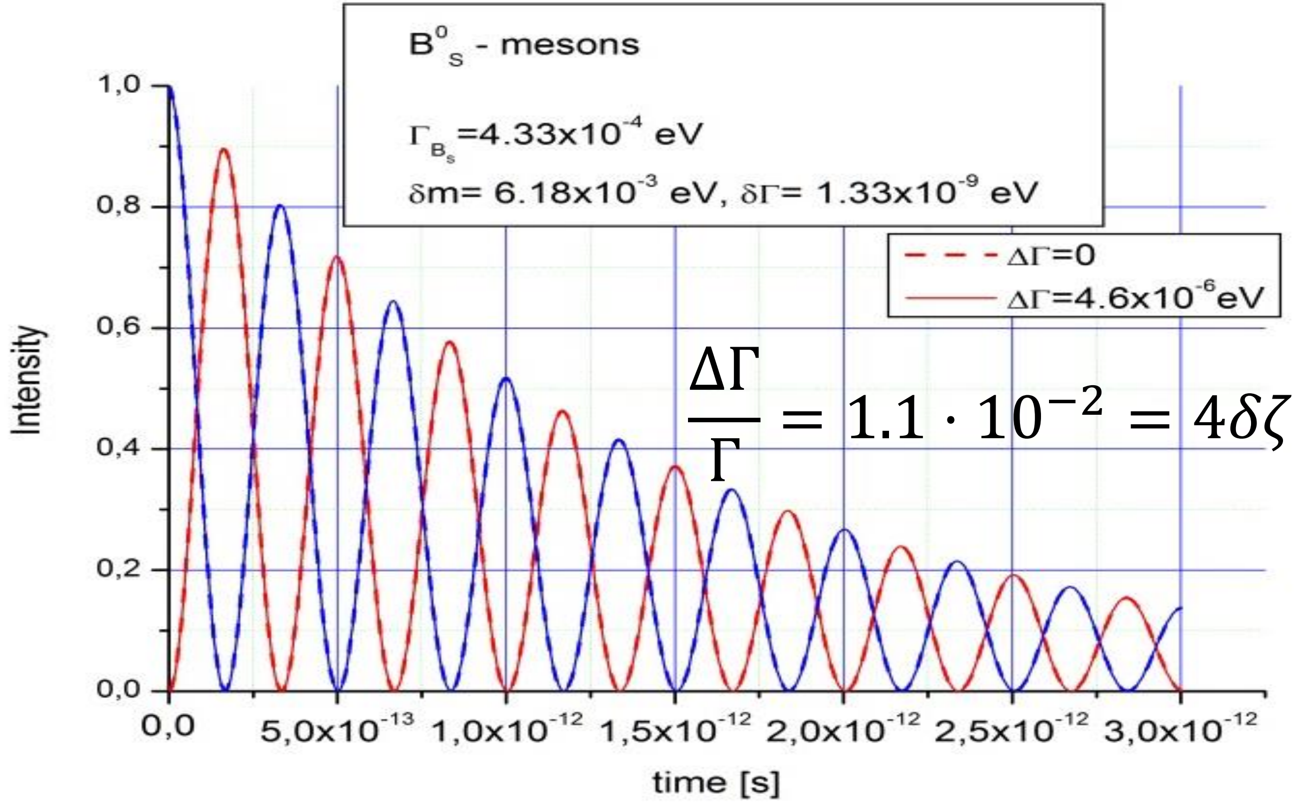


$$\frac{\Delta\Gamma}{\Gamma} = 1.1 \cdot 10^{-2} = 4\delta\zeta$$

$$\left(\frac{\delta m}{\delta\Gamma}\right)_{B^0} = 0.0017$$

$$\omega_{ocs} << \Delta\tau^{-1}$$

$$A_{T/CP} = 0.005 \pm 0.018$$



$$\left(\frac{\delta m}{\delta\Gamma}\right)_{B_S^0} = 4.7 \cdot 10^6$$

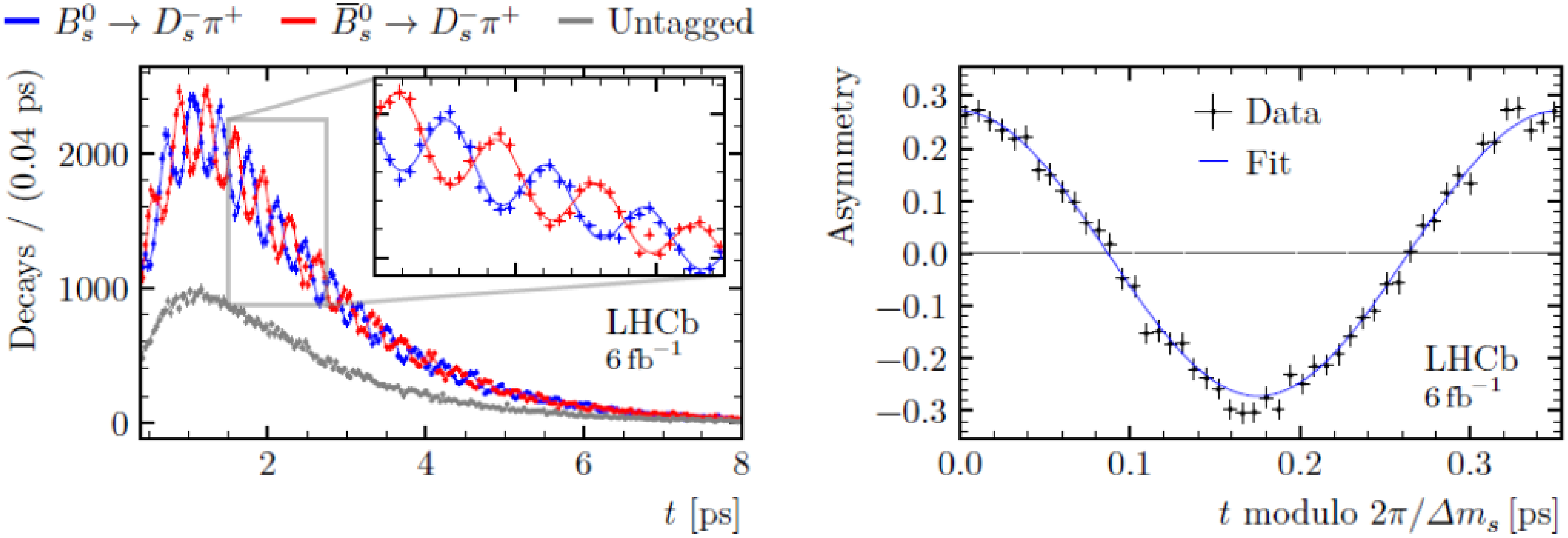
$$\omega_{ocs} >> \Delta\tau^{-1}$$

!!!

$$\frac{\delta\Gamma}{\Delta\Gamma} = 3 \cdot 10^{-4}$$

$$\delta\Gamma << \Delta\Gamma$$

!!!



$B_s^0 \to D_s^- \pi^+$
$\overline{B}_s^0 \to D_s^- \pi^+$
Untagged
Decays / (0.04 ps)
2000
1000
0
2
4
6
8
t [ps]
LHCb
6 fb^{-1}
Data
Fit
Asymmetry
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.0
0.1
0.2
0.3
t modulo $2\pi/\Delta m_s$ [ps]
LHCb
6 fb^{-1}

$$H_{V,A}^{N} = \bar{e}\gamma_\mu (C_V + C'_V\gamma_5)\nu \cdot \bar{p}\gamma_\mu n - \bar{e}\gamma_\mu\gamma_5 (C_A + C'_A\gamma_5)\nu \cdot \bar{p}\gamma_\mu\gamma_5 n + h.c.$$

$$C_V = g_V \frac{G_F V_{ud}}{\sqrt{2}}(1-2\zeta+\delta), \quad C'_V = g_V \frac{G_F V_{ud}}{\sqrt{2}}(1-\delta) \qquad C_A = g_A \frac{G_F V_{ud}}{\sqrt{2}}(1+2\zeta+\delta), C'_A = g_A \frac{G_F V_{ud}}{\sqrt{2}}(1-\delta)$$

$$|C_V|^2 + |C'_V|^2 = |g_V G_F V_{ud}|^2 (1-\zeta)^2 (1+(\delta-\zeta)^2) \qquad |C_A|^2 + |C'_A|^2 = |g_A G_F V_{ud}|^2 (1+\zeta)^2 (1+(\delta+\zeta)^2)$$

Для $0^+ - 0^+$ переходов

Фермиевский

$$(f\tau)_{00}^{-1} = |M_F|^2 (|C_V|^2 + |C'_V|^2) =$$

$$= |M_F|^2 |g_V\, G_F V_{ud}|^2 (1+\zeta)^2 (1+(\delta+\zeta)^2),$$

$$\tilde{V}_{ud}^{+} = V_{ud}^{+}(1+\zeta) \equiv V_{ud}^{00(V)}$$

$$V_{ud}^{00LR} = V_{ud}^{00(V)} \sqrt{\frac{[1+(\delta+\zeta)^2]}{1+\zeta^2}}$$

$$V_{ud}^{00LR} \equiv V_{ud}^{W_1^+(W_2^+)}$$

Для распада нейтрона

Гамово-Теллеровский

$$(f\tau)_n^{-1} = |M_F|^2 (|C_V|^2 + |C'_V|^2) + |M_{GT}|^2 (|C_A|^2 + |C'_A|^2)$$

$$= |M_F|^2 |g_V G_F V_{ud}|^2 (1-\zeta)^2 (1+(\delta-\zeta)^2) +$$

$$+ |M_{GT}|^2 |g_A G_F V_{ud}|^2 (1+\zeta)^2 (1+(\delta+\zeta)^2),$$ где $|M_F|^2 = 1, |M_{GT}|^2 = 3$

$$(f\tau)_n^{-1} = G_F^2 |g_V|^2 (V_{ud}^{n(V-A)})^2 \left(1+3\lambda_{n,V-A}^2\right) \times (1+\zeta^2)^{-1} \left\{1+(\delta^2+\zeta^2) + 2\frac{(3\lambda_{n,V-A}^2 - 1)}{(3\lambda_{n,V-A}^2 + 1)}\delta\zeta\right\}$$

$$\tilde{V}_{ud}^{-} = V_{ud}^{-}(1-\zeta) \equiv V_{ud}^{n(V-A)}$$

$$V_{ud}^{nLR} = V_{ud}^{n(V-A)} \times \sqrt{\frac{1+3\lambda_{n,V-A}^2}{1+3\lambda_{\exp,LR}^2} \frac{[1+(\delta^2+\zeta^2) + 2\frac{(3\lambda_{n,V-A}^2 - 1)}{(3\lambda_{n,V-A}^2 + 1)}\delta\zeta]}{(1+\zeta^2)}}$$

$$V_{ud}^{nLR} \equiv V_{ud}^{W_1^-(W_2^-)}$$