

Numerical estimate on minimal active-sterile neutrino mixing

Krasnov I. V.

INR RAS

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Model

$$\mathcal{L} = i\bar{N}_I \gamma^\mu \partial_\mu N_I - \frac{1}{2} M_I \bar{N}_I^c N_I - Y_{\alpha I} \bar{L}_\alpha \tilde{H} N_I + h.c., \quad (1)$$

$$Y \equiv \frac{i\sqrt{2}}{\nu} \sqrt{M_R} R \sqrt{m_\nu} U_{PMNS}^\dagger, \quad (2)$$

$$M_R \equiv diag\{M_1, M_2, M_3\},$$

$$m_\nu \equiv diag\{m_1, m_2, m_3\},$$

$$R^T R = 1.$$

$$R = diag\{\pm 1, \pm 1, \pm 1\} \times \begin{pmatrix} c_2 c_1 & c_2 s_1 & s_2 \\ -c_3 s_1 - s_3 s_2 c_1 & c_3 c_1 - s_3 s_2 s_1 & s_3 c_2 \\ s_3 s_1 - c_3 s_2 c_1 & -s_3 c_1 - c_3 s_2 s_1 & c_3 c_2 \end{pmatrix}, \quad (3)$$

$$c_i = \cos z_i, s_i = \sin z_i, z_i \subset \mathbb{C}.$$

Model's advantages

- Renormalizable theory
- Experimental confirmation prospects
- SM neutrino mass scale explanation
- (Optional) Baryon asymmetry mechanism
- (Optional) Dark matter candidate

Matrix of mixing angles

$$U = \frac{v}{\sqrt{2}} M_R^{-1} Y = i M_R^{-\frac{1}{2}} R m_v^{\frac{1}{2}} U_{PMNS}^\dagger \quad (4)$$

$M_1 < 2\text{GeV}$, $M_2 < 2\text{GeV}$, $M_3 > 2\text{GeV}$ case observables:

$$\begin{aligned} U_e &\equiv |U_{1e}|^2 + |U_{2e}|^2 \\ U_\mu &\equiv |U_{1\mu}|^2 + |U_{2\mu}|^2 \end{aligned} \quad (5)$$

BBN constraint

$$\Gamma \sim G_F^2 \frac{\sin^2 2\theta}{\left(1 + c(T) \times 10^{-7} \left(\frac{T}{\text{GeV}}\right)^6 \left(\frac{M_I}{\text{GeV}}\right)^{-2}\right)^2} T^5, \quad (6)$$

For $M_I = 500 \text{ MeV}$ the equilibrium $H = \Gamma$ can be achieved for $|U|^2 \gtrsim |U_b|^2 \approx 2 \times 10^{-11}$.

$$\tau_I \approx 20 \frac{|U_b|^2}{|U|^2} \left(\frac{500 \text{ MeV}}{M_I}\right)^5 \text{ sec.} \quad (7)$$

$$\zeta_I \equiv M_I \frac{n_I}{s} = 1.3 \times 10^{-2} \left(\frac{M_I}{500 \text{ MeV}}\right) \frac{|U|^2}{|U_b|^2} \text{ GeV} \quad (8)$$

Values $10^{-23} < |U|^2 < 2 \times 10^{-11}$ are excluded by BBN.

Numerical part

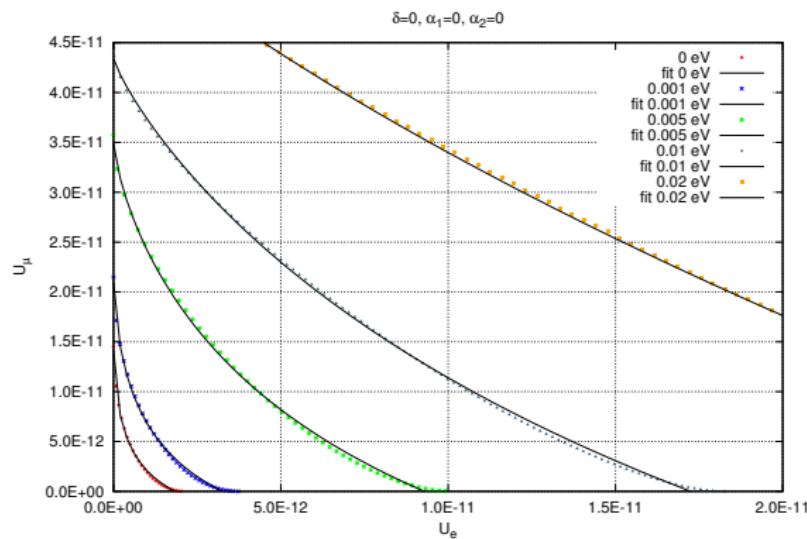


Figure 1: Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = \alpha_1 = \alpha_2 = 0$. Different curves correspond to different m_{lightest} values.



Numerical part

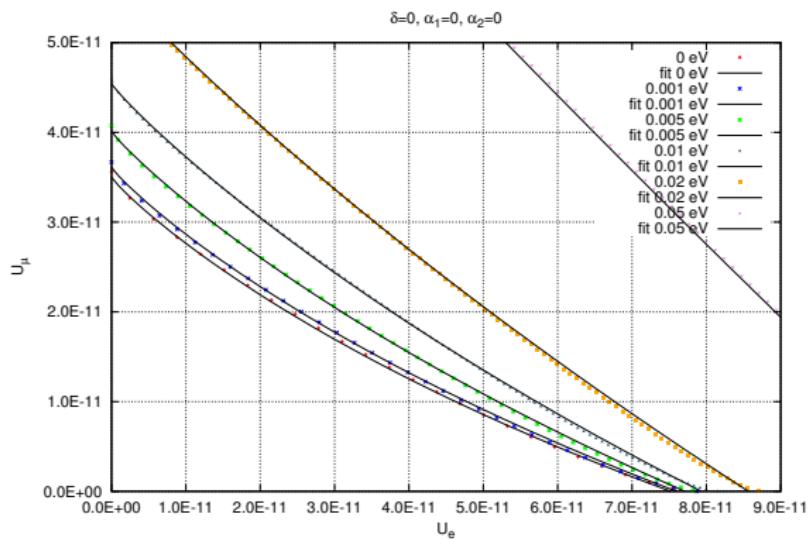


Figure 2: Dependence of minimal U_μ on minimal U_e for the inverted hierarchy and $\delta = \alpha_1 = \alpha_2 = 0$. Different curves correspond to different m_{lightest} values.



Numerical part

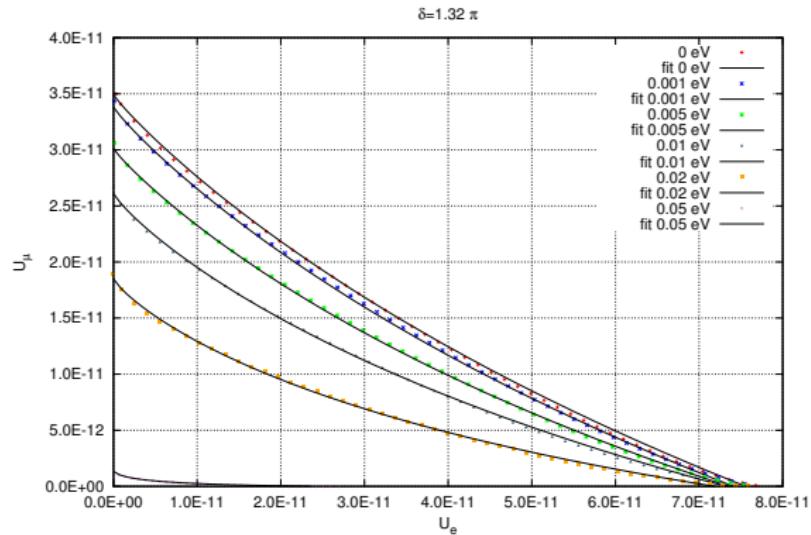


Figure 3: Dependence of minimal U_μ on minimal U_e for the inverted hierarchy and $\delta = 1.32\pi$ (the best fit value for the inverted hierarchy). Different curves correspond to different $m_{lightest}$ values, α_1, α_2 are minimization variables.



Numerical part

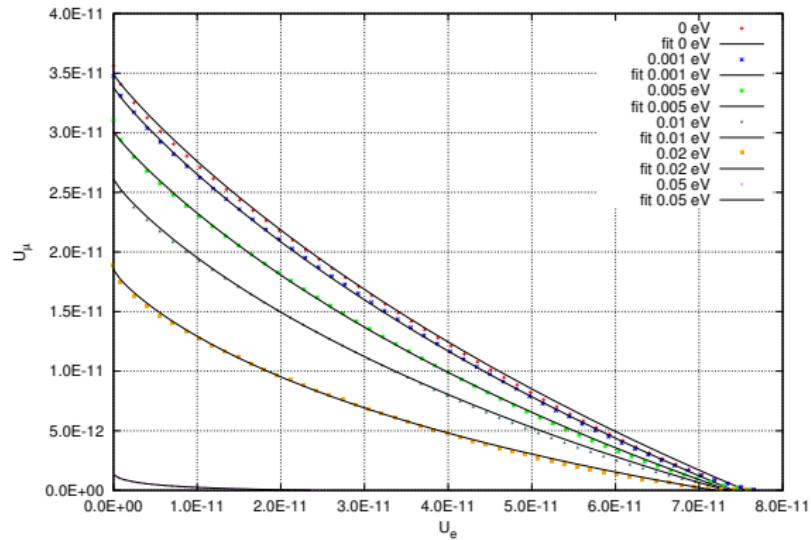


Figure 4: Dependence of minimal U_μ on minimal U_e for the inverted hierarchy. Different curves correspond to different $m_{lightest}$ values, $\delta, \alpha_1, \alpha_2$ are minimization variables.

Numerical part

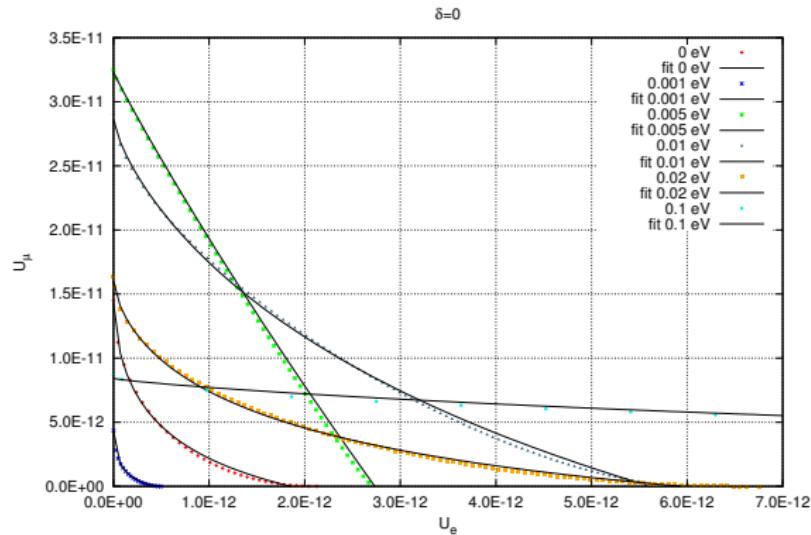


Figure 5: Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = 0$. Different curves correspond to different $m_{lightest}$ values, α_1, α_2 are minimization variables.

Numerical part

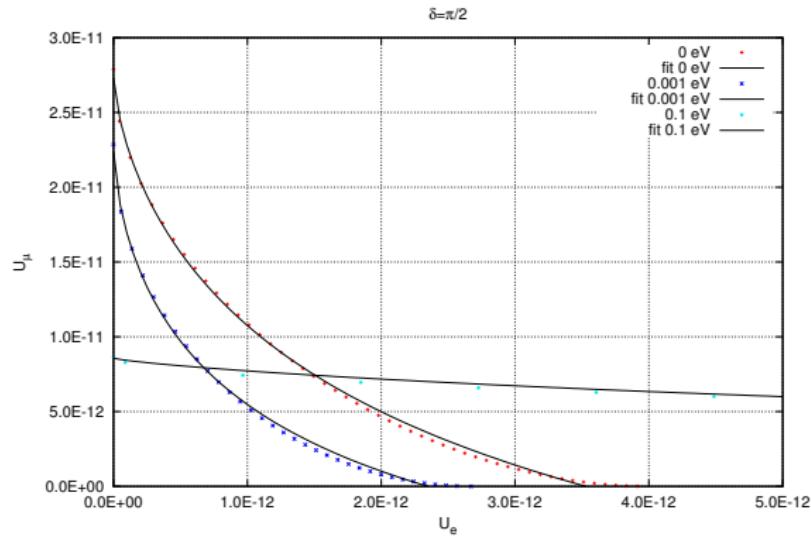


Figure 6: Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = \frac{\pi}{2}$. Different curves correspond to different m_{lightest} values, α_1, α_2 are minimization variables.

Numerical part

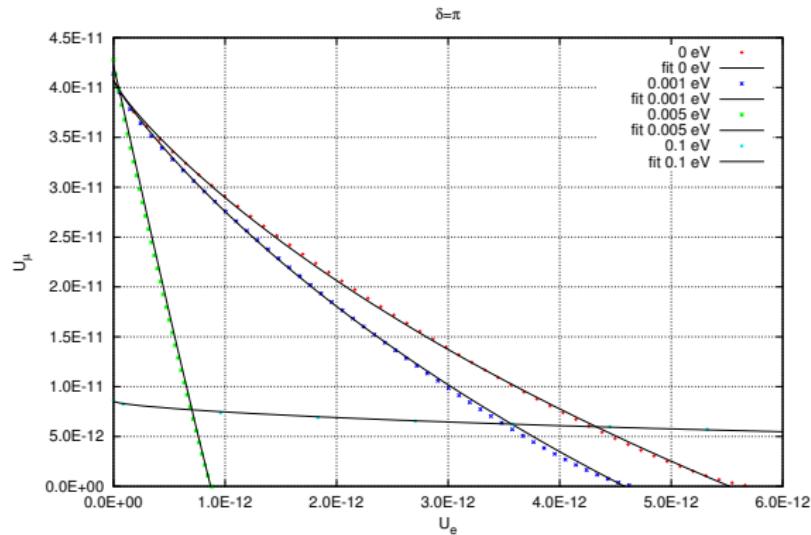


Figure 7: Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = \pi$. Different curves correspond to different $m_{lightest}$ values, α_1, α_2 are minimization variables.

Numerical part

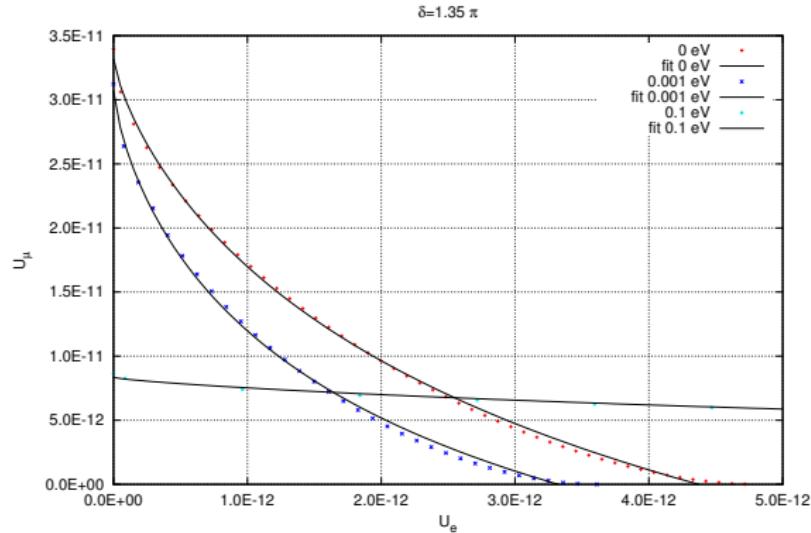


Figure 8: Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = 1.35\pi$ (the best fit value for the normal hierarchy). Different curves correspond to different $m_{lightest}$ values, α_1, α_2 are minimization variables.

Numerical part

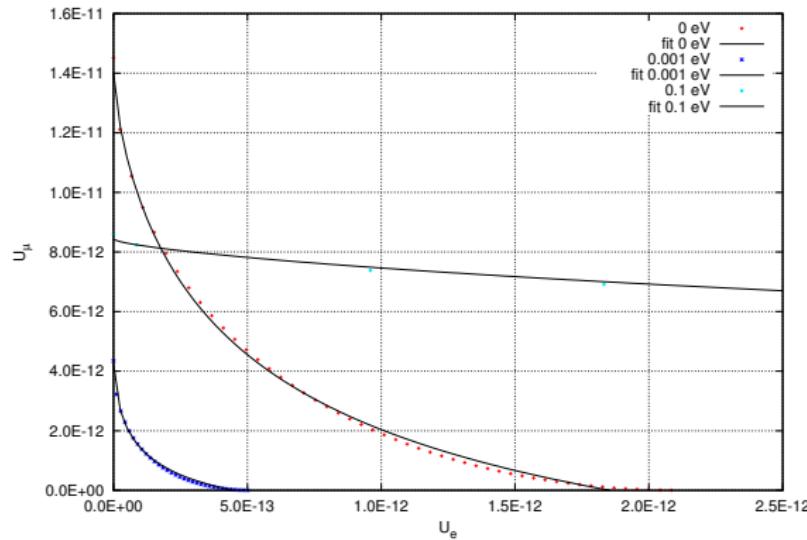


Figure 9: Dependence of minimal U_μ on minimal U_e for the normal hierarchy. Different curves correspond to different $m_{lightest}$ values, $\delta, \alpha_1, \alpha_2$ are minimization variables.

Numerical part

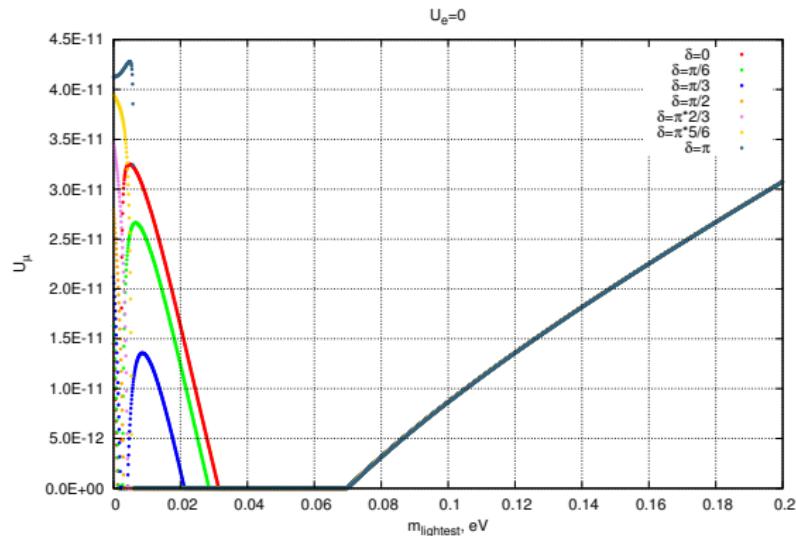


Figure 10: Dependence of minimal U_μ on m_{lightest} at $U_e = 0$ for the normal hierarchy. Different curves correspond to different δ values.

Numerical part

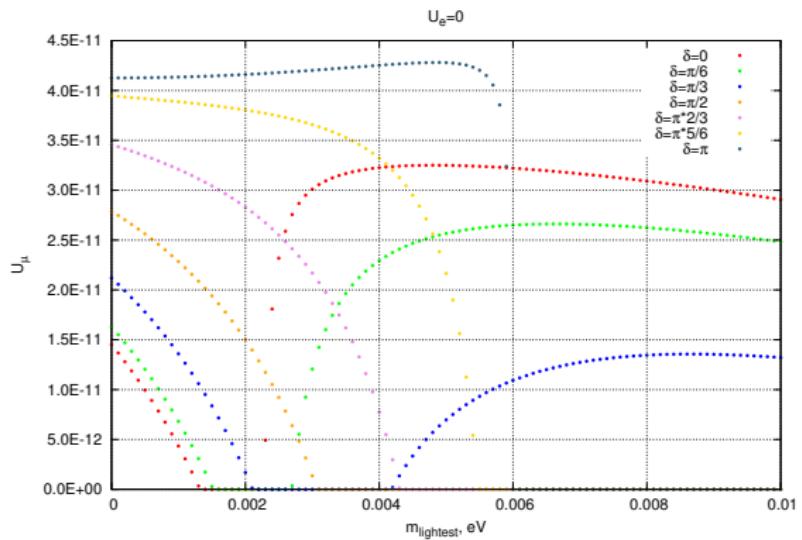


Figure 11: Zoom in the small scale area of Fig 10.

Numerical part

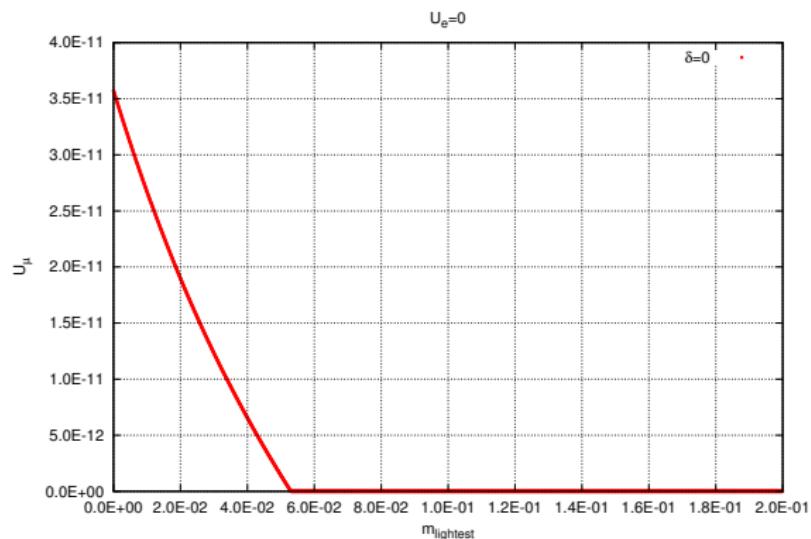


Figure 12: Dependence of minimal U_μ on $m_{lightest}$ at $U_e = 0$ and $\delta = 0$ for the inverted hierarchy.

Conclusion

- Zero phases case reestimated with characteristic values $|U_{I\alpha}|^2 \sim 10^{-11}$.
- Dependence on CP -violating phases and $m_{lightest}$ added
- Limits on U_e and U_μ lowered down to the values of 10^{-20} at least.

$m_{lightest}, \delta, \alpha_1, \alpha_2$ may significantly change the mixing pattern and should be taken into account in future experiments

Thank you for your attention!



Backup slides

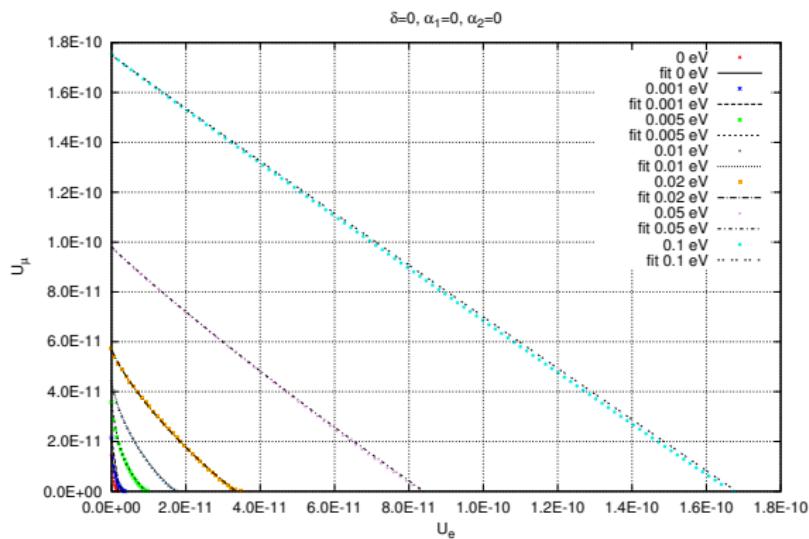


Figure 13: Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = \alpha_1 = \alpha_2 = 0$. Different curves correspond to different m_{lightest} values.



Backup slides

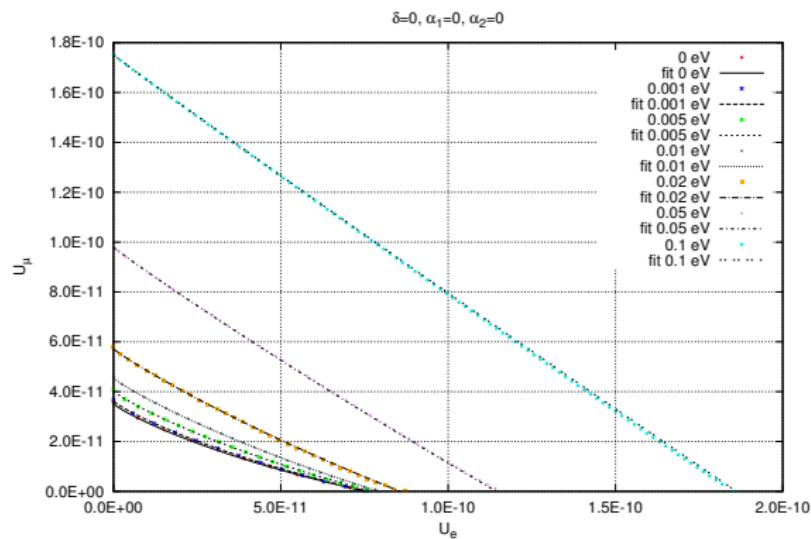


Figure 14: Dependence of minimal U_μ on minimal U_e for the inverted hierarchy and $\delta = \alpha_1 = \alpha_2 = 0$. Different curves correspond to different $m_{lightest}$ values.

Backup slides

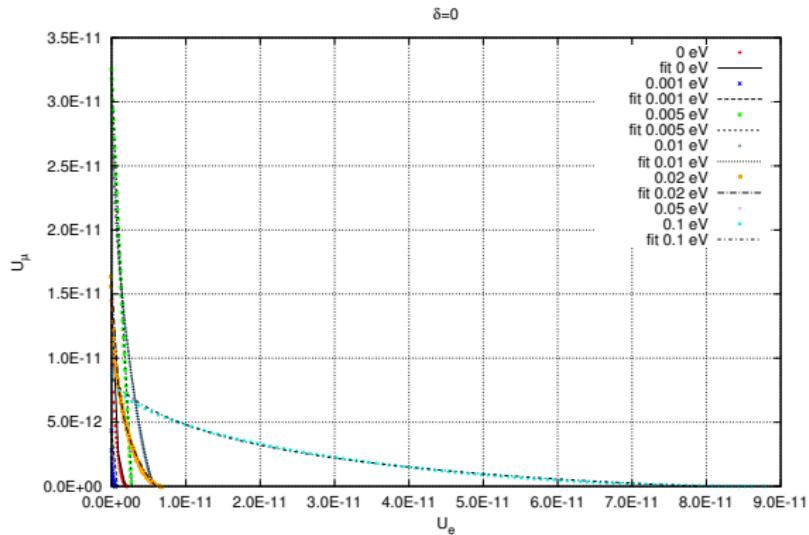


Figure 15: Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = 0$. Different curves correspond to different m_{lightest} values, α_1, α_2 are minimization variables.

Backup slides

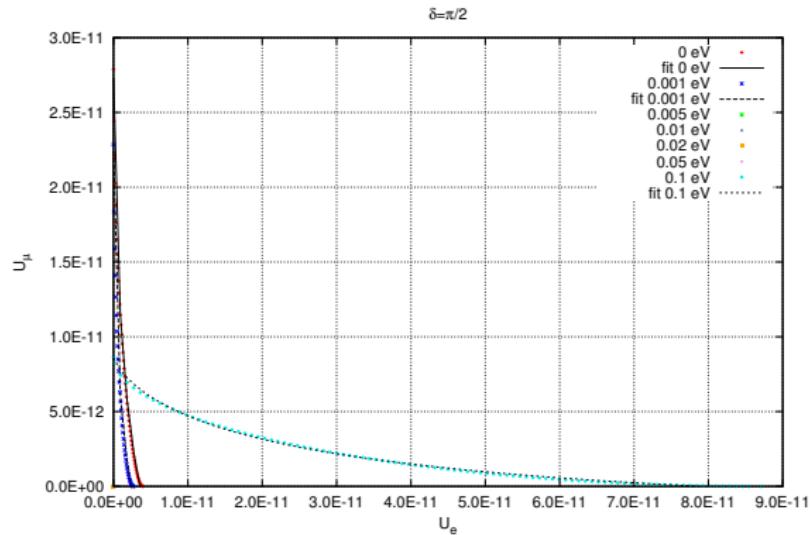


Figure 16: Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = \frac{\pi}{2}$. Different curves correspond to different m_{lightest} values, α_1, α_2 are minimization variables.

Backup slides

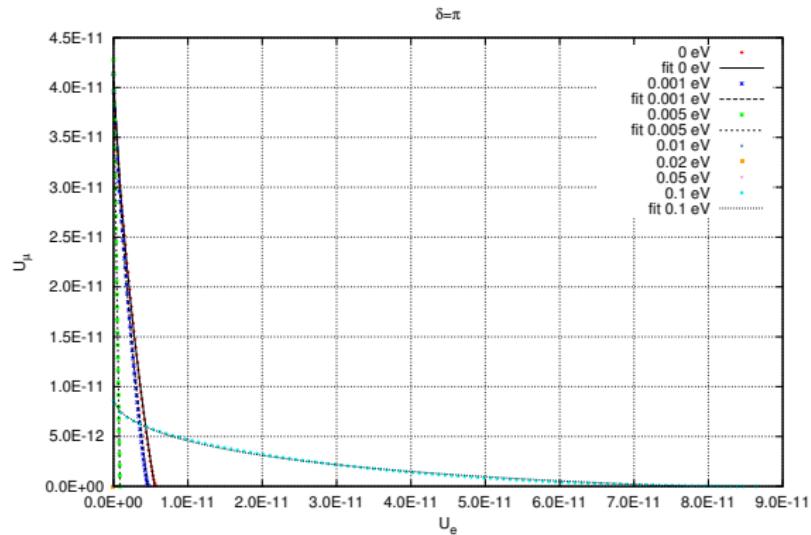


Figure 17: Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = \pi$. Different curves correspond to different m_{lightest} values, α_1, α_2 are minimization variables.

Backup slides

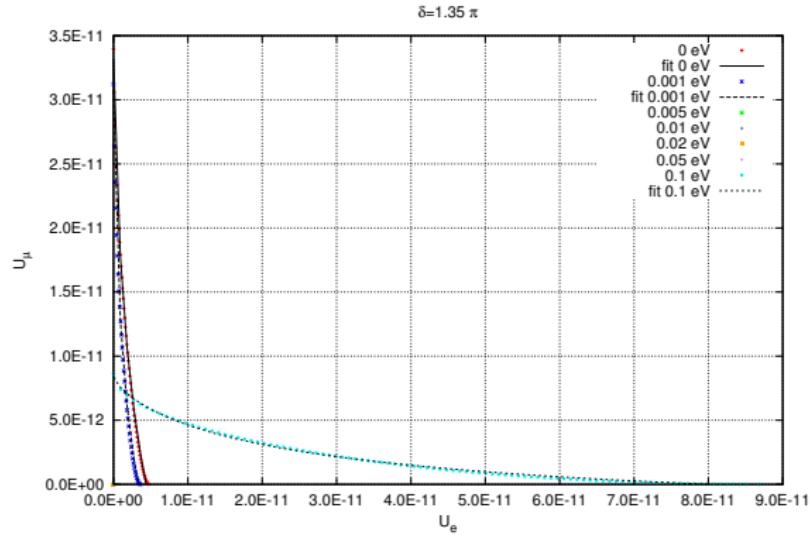


Figure 18: Dependence of minimal U_μ on minimal U_e for the normal hierarchy and $\delta = 1.35\pi$ (the best fit value for the normal hierarchy). Different curves correspond to different $m_{lightest}$ values, α_1, α_2 are minimization variables.



Backup slides

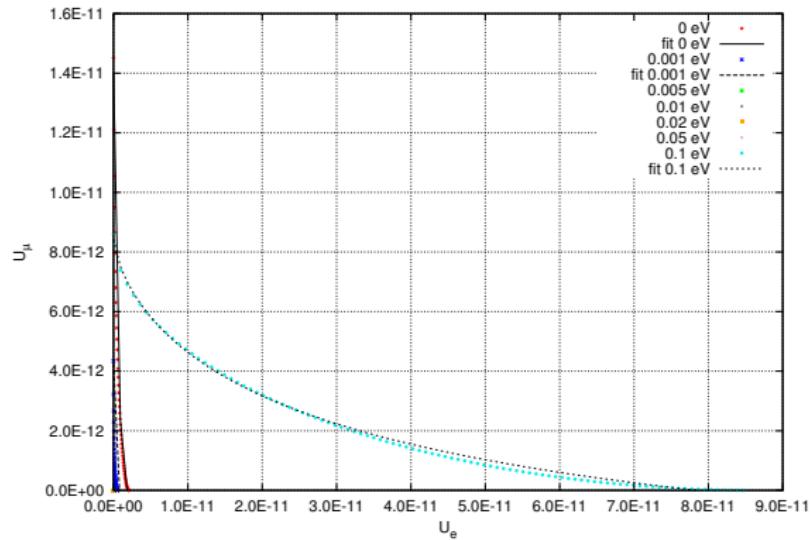


Figure 19: Dependence of minimal U_μ on minimal U_e for the normal hierarchy. Different curves correspond to different m_{lightest} values, $\delta, \alpha_1, \alpha_2$ are minimization variables.

Backup slides

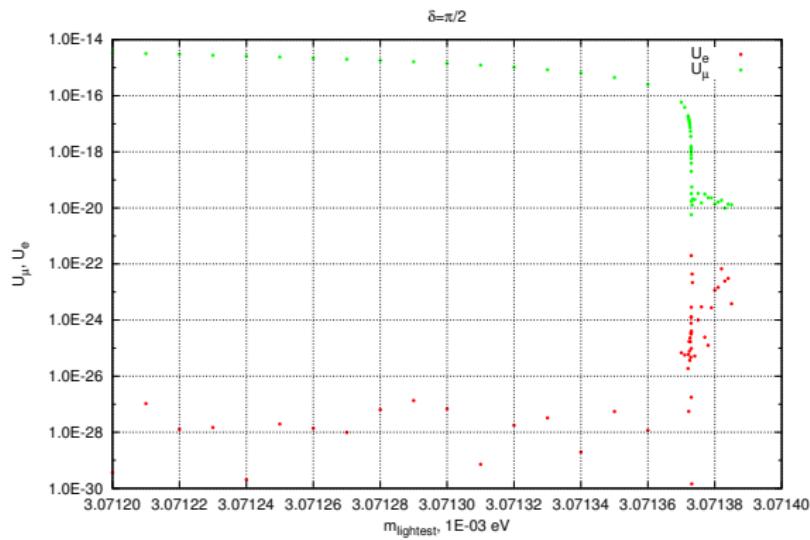


Figure 20: Dependence of minimal U_μ on m_{lightest} at $U_e = 0$ in the “plateau” proximity for the normal hierarchy.

