

A consistent interpretation of the KARMEN anomaly

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Abstract

The Karmen anomaly can be interpreted as being due to a heavy neutrino of mass around 137 MeV and mean life 14 s produced in π_{e2} decays. This interpretation is consistent with the present limits on the couplings of such an object.

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1 What is the KARMEN anomaly ?

The Karmen collaboration has reported a distortion in the time distribution of their events [1]. The experiment studies low energy neutrinos produced by the dump of 800 MeV protons at the ISIS facility of the Rutherford Laboratory. The accelerator has a unique time structure which allows to discriminate between neutrinos coming from π decaying at rest and from the subsequent μ decay at rest. It is in this last process that an anomaly was observed in the time distribution of interactions, which overall reproduces the lifetime of the muon but for an excess of events at a time delay centered on $3.6\mu\text{s}$ w.r.t. the arrival of the protons. The signature is a deposition of energy in the range 11 to 35 MeV.

This is interpreted by the Karmen collaborators as possibly coming from the production of a heavy neutral object X of mass 33.9 MeV, travelling with a $\beta = v/c$ of 1/60 and decaying in the detector, 17.5m away from the dump. The X particle is produced in π decays : $\pi \rightarrow \mu X$ with a very small branching ratio and decays in turn into the *a priori* open channels: $X \rightarrow \nu\gamma$ or $X \rightarrow \nu e^+e^-$ or $X \rightarrow \nu\gamma\gamma$

The Karmen experiment finds about 100 events compatible with X production and decay in a sample of 3000 neutrino interactions. This is a more than 4σ effect.

Experimentally, there are two unknowns in the problem: the branching fraction Br of π 's decaying into the X particle and the lifetime τ of the latter. In order to reproduce the observed number of events, Br and τ must be related by the curve shown in Fig.1 as given in [1]. For long lifetimes, the probability of decay in the detector is inversely proportionnal to the lifetime. For shorter lifetimes, a good fraction of X 's has decayed before reaching the detector. Observe that, for very short τ , the distribution of excess events in the detector should be uneven because of the stronger probability to decay close to the upper end. Taking this into account would change the shape of the curve in the low τ region. However, Karmen sees no such effect, which can be taken as an indication that of the two possible τ values corresponding to a given Br , only the higher one must be considered.

A direct search for X production in $\pi_{\mu 2}$ decay by looking at the muon spectrum was performed at PSI [2], [3]. It excludes branching fractions larger than 2.6×10^{-8} , as also indicated in Fig. 1.

2 Production and decay of massive neutrinos

Massive neutrinos, arising, for example, from the introduction of right-handed chiral states, occur naturally in most extensions of the standard model. They have been searched through their decays in various experiments [4, 5]

2.1 Production

If massive neutrinos exist, the so-called weak eigenstates (associated to charged leptons via weak currents) which we will call generically ν_λ , are linear combinations of mass eigenstates ν_h . Let us call $U_{h\lambda}$ the coefficient of ν_h in the expansion of ν_λ (λ being e or μ for the production processes envisioned here). In any ' ν_λ ' neutrino beam, there is a ν_h component at the $|U_{h\lambda}|^2$ level up to phase space factors and weak currents matrix elements.

For example, π_{e2} decays may yield ν_h at the level $|U_{he}|^2$ up to the above mentioned factors, provided that ν_h has a mass below $m(\pi) - m(e) = 139$ MeV, while $\pi_{\mu 2}$ decays would produce ν_h at the level $|U_{h\mu}|^2$ with masses up to $m(\pi) - m(\mu) = 34$ MeV.

Note that the well known chirality suppression of π_{e2} no longer occurs as soon as $m_\nu \approx$ a few MeV.

For the X particle, $\lambda = \mu$ and the mixing discussed in Fig 1 is $U_{h\mu}$. Since m_X is supposed to be at the limit of the available phase-space in $\pi_{\mu 2}$ (in order to ensure $\beta = 1/60$), one would expect it to be produced more abundantly in $K_{\mu 2}$. The ratio of the branching ratios $\frac{Br(K \rightarrow \mu X)}{Br(\pi \rightarrow \mu X)} \approx 18$ instead of .63 for massless ν 's. However, this is very sensitive to the precise value of m_X .

2.2 Decays

Several decay modes can be investigated. Heavy neutrinos with masses below 1 MeV can only decay radiatively by emitting one or two photons. As soon as the mass is above 1 MeV, the most favoured decay mode is $e^+e^-\nu_e$. The matrix element is analogous to that of muon decay and the width is given by

$$\Gamma(\nu_h \rightarrow e^-e^+\nu) = \frac{G_F^2}{192\pi^3} m_{\nu_h}^5 f(m_{\nu_h}) |U_{he}|^2$$

where f tends rapidly to 1 for masses above 10 MeV ([5]) and $|U_{he}|$ is the same mixing which appears at production if ν_h is produced together with an electron. For higher masses, other decay channels open: $\nu e^\pm \mu^\mp, e^- \pi^+, \mu^- \pi^+, \nu \mu^- \mu^+ \dots$ each one involving a mixing matrix element which depends on the final state leptons.

3 X or X^* particle?

The X particle could be such a massive neutrino undergoing weak decays. However for a 33.9 MeV object $e^+e^-\nu_e$ is the only open non-radiative channel and its width, far above those of the radiative modes, dominates the lifetime. An upper limit of $|U_{he}|^2 \leq 5 \times 10^{-6}$ has been obtained [4] for such a mass. This translates into a limit $\tau \geq 120$ s which is reported in Fig. 1 and excludes most of the allowed parameter region. For the highest mass eigenstate, published limits on $\Gamma(\pi \rightarrow e\nu)/\Gamma(\pi \rightarrow \mu\nu)$ ([8]) allow to infer $|U_{he}|^2 \leq 1.23 \times 10^{-6}$ and $\tau \geq 500$ s

Moreover, taking the experimental Karmen curve (see Fig. 1) into account, this implies

$Br(\pi^+ \rightarrow \mu^+ X) \geq 4.5 \times 10^{-9}$ which is barely compatible with the upper limits from the two PSI groups who tried a direct X search [2], [3])¹

An alternative interpretation has been proposed [6] in terms of exotic muon decays. It involves unknown scalars. We study here yet another possibility, which implies an 'ordinary' massive neutrino, call it X^* .

As already remarked, many channels open as soon as phase-space permits. If we assume a π_{e2} production mode, masses up to 139 MeV are possible, and $\nu e^\pm \mu^\mp$ decays are allowed for sufficiently high m_{X^*} , as schematically shown in Fig. 2. For such modes, the time delay between beam on target and the events in excess in the Karmen detector would be the sum of the final state muon lifetime with the time necessary for X^* to fly from the proton target to the detector. Indeed, the kinetic energy of μ^\pm is small and that of e^\mp may fall short of the Karmen detection energy threshold, depending on m_{X^*} , rendering it necessary to wait for the muon to decay.²

This would yield an average (electron) energy around 36 MeV after an average delay of $2.2\mu s$ following the undetected X^* decay.

The Karmen anomalous events appear to be rather tightly clustered in time if they are interpreted in the lines of [1] and their apparent dispersion cannot be understood as due to a muon decay. However, the authors of [6] show that a rather narrow bump can be interpreted as the superposition of two exponentials, both with the same (muon) decay time constant, but with the second shifted by a more or less fixed amount representing a time of flight.

¹As quoted in the Review of Particle Physics [7] the PSI results would seem to contradict the lower bound we have just given and rule out altogether the Karmen solution. However the PDG are wrong in that they call limits on $|U_{X\mu}|^2$ figures which are really limits on the branching ratio. Since, on the other hand, the way the PSI groups compute their upper bounds does not yield the tightest possible result, there is ample room for argument, and very little room, if any, for X

²for X^* at rest, one finds $\overline{E}_e \leq 14$ MeV and $\overline{T}_\mu \leq 2$ MeV.

3.1 Model for the time distribution

Therefore, we have tried to perform a two component fit to the Karmen time distribution. The first component is an exponential reflecting ordinary muon decay in the target followed by practically instantaneous interaction of the normal light neutrinos thus produced in the detector (the ToF is about 60 ns)

The second component is the convolution of a uniform and an exponential distribution representing the sum of the transit time of a heavy neutrino from the target to the detector (which is also the heavy neutrino lifetime in the lab and is practically uniform in the window of interest) plus the lifetime of the muon produced in the heavy neutrino decay.

However, this turned out to be inconsistent. The fitted ToF of the heavy neutrinos implies a mass close to 137 MeV which in turn means a positron energy distribution (in $X^* \rightarrow \mu^- e^+ \nu$) rather evenly distributed around an expectation value of 14 MeV, thereby invalidating the hypothesis that the delay would always comprise the μ lifetime. It was therefore necessary to add a third component representing those 'direct' positrons. Thus, there are altogether 5 parameters representing the intensities of the three components and the lower and upper limits of the time window corresponding to the passage of the X^* 's in the Karmen detector.

In principle, this gives us a potential consistency check of the fact that the anomaly is really due to a particle since its speed can be estimated from the last two parameters using the average distance between the proton target and the detector on the one hand, and the length of the latter on the other hand. However, the data at our disposal are not accurate enough to decide between different fit results which do or do not conform with this expectation. Given the large errors on the fitted parameters, the results presented on Fig. 3 cannot be considered as inconsistent with the expectation.

Here, $T1$ and $T2$ are the lower and upper edges of the time window, and the three following items are constants multiplying the three normalized distributions superposed in the fit. Since the bin width is $.5\mu s$, the corresponding number of $\mu^- \rightarrow e^-$ and $X^* \rightarrow e^+$ are about 66 and 38 respectively.

The fit yields: ToF = $3.66\mu s$, hence $\beta = .0159$ and $m_{X^*} \approx 137.3$ MeV.

3.2 Interpretation

It must be remarked now that for an 'ordinary' heavy Dirac neutrino, there are really two (non mutually exclusive) possibilities:

- either it decays to e^- and a virtual W^+ which yields $\mu^+ \nu_\mu$
- or it decays to μ^- and the virtual boson goes into $e^+ \nu_e$.

The first possibility involves the same mixing matrix element, namely U_{he} , which appears at production, whilst in the second case, the decay is due to $U_{h\mu}$. Clearly enough, in any case $U_{he} \neq 0$ and the $e^+ e^- \nu_e$ mode is also widely open. If we assume the first channel, the unknown mixing cancels in the ratio of the

two modes which is given by the following formula:

$$\frac{\Gamma(e^-\mu^+\nu_\mu)}{\Gamma(e^-e^+\nu_e)} = (1 - 8r + r^2)(1 - r^2) - 12r \text{Log}(r)$$

where $r = (m_\mu/m_{X^*})^2$ and $m_e = m_{\nu_e} = m_{\nu_\mu} = 0$ [5]. The width ratio is about 0.5% for $m_{X^*} = 137$ MeV.

This shows two things: first, for the range of masses of interest, the lifetime is dominated by the $e^+e^-\nu_e$ mode, which gives us another relation between $|U_{he}|$ and τ and allows to draw further conclusions. Second, decays through this mode must have occurred abundantly in the Karmen experiment, but the corresponding (large) deposition of energy is probably rejected by the Karmen selection.

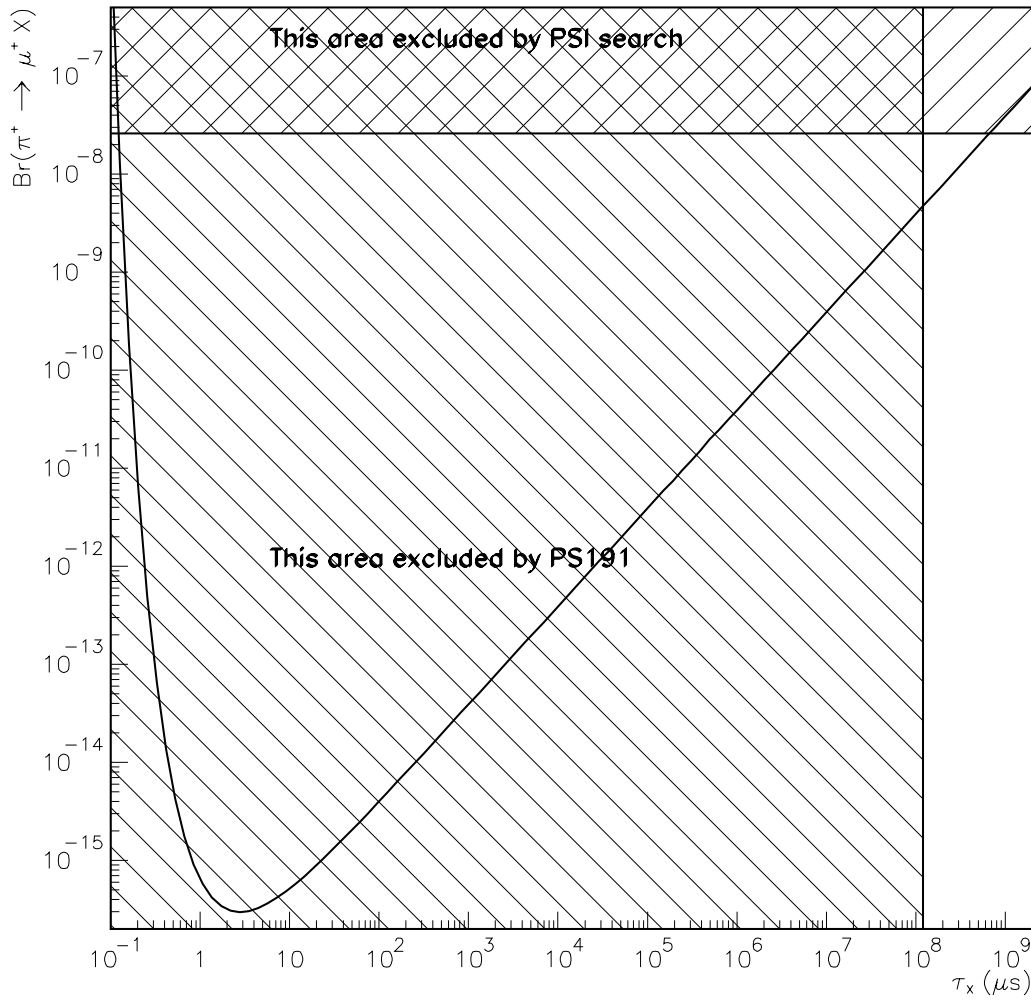
The results of this analysis are summarized on Fig. 4 It reproduces the Karmen 'efficiency' curve corrected for the π decay mode considered here (The unknown constant was taken from the asymptotic direction of the Karmen plot [1]); also drawn is the branch of hyperbola corresponding to the $Br \times \tau$ value fixed by the X^* mass and the hypothesis of an $e^-e^+\nu$ dominated X^* lifetime. The latter is found to be $\tau_{X^*} \approx 14s$ and the $\pi^+ \rightarrow e^+X^*$ branching ratio is around 4×10^{-10} This entails a mixing matrix element $|U_{X^*e}|^2 \approx 4.2 \times 10^{-8}$ compatible with the previously published upper limits [4, 5]

Here again, this object should be much more abundantly produced in kaon decays. The 'ratio of ratios' is around 100 in this case.

Of course, we do not claim that this is "the" solution, but only wish to point out another possibility. It could probably be easily disproved through confrontation with more detailed Karmen data.

4 Conclusion

In short, the Karmen collaboration have chosen to explain their anomalous events by assuming they originate from a rare $\pi_{\mu 2}$ decay, because a 'neutrino' with a mass at the edge of phase-space (around 34 MeV) has both a low enough velocity to explain the $3.6\mu s$ delay and a low enough mass to explain the 30 MeV energy deposition. We claim that both features can be explained by a $\pi_{e 2}$ decay yielding a much heavier 'neutrino' which decays itself through a $e^\pm\mu^\mp\nu_l$ channel, the signature of which is a visible energy in the range of interest after the (apparently) observed delay. The more mundane $e^\pm e^\mp\nu_l$ channel is supposedly hidden by the experimental energy cut off and the apparent clustering in time due to a fixed time of flight followed by a short detectability window is not spoiled upon taking the muon lifetime into account.



$Br-\tau$ relation as given by Karmen coll. Hatched areas are excluded by other experiments (see text)

Fig. 1

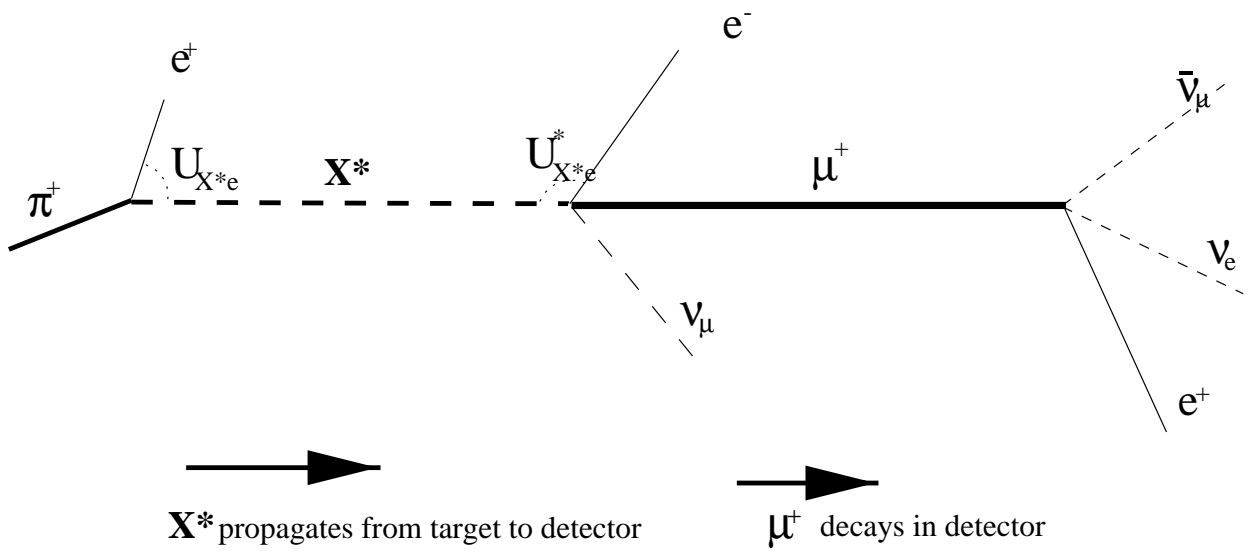


Fig. 2 The process hypothesized in this paper

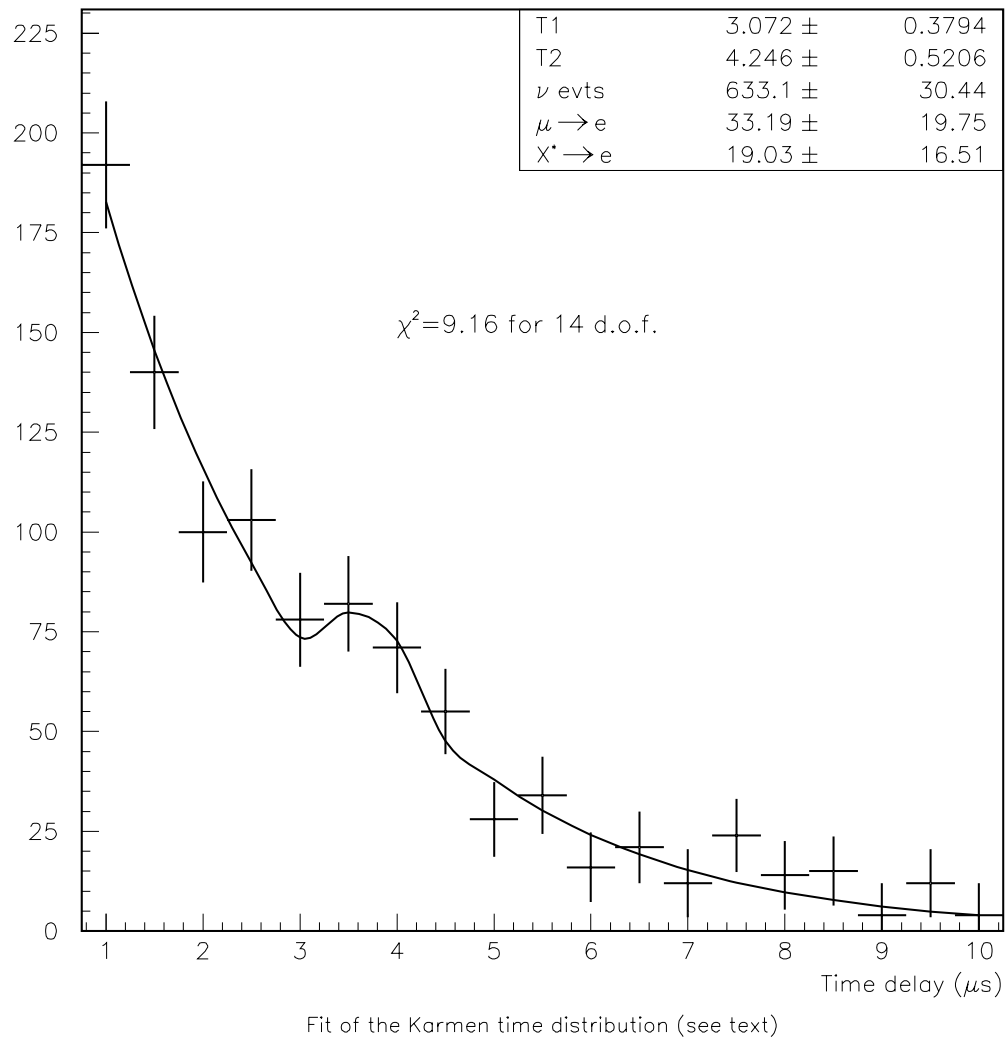


Fig. 3

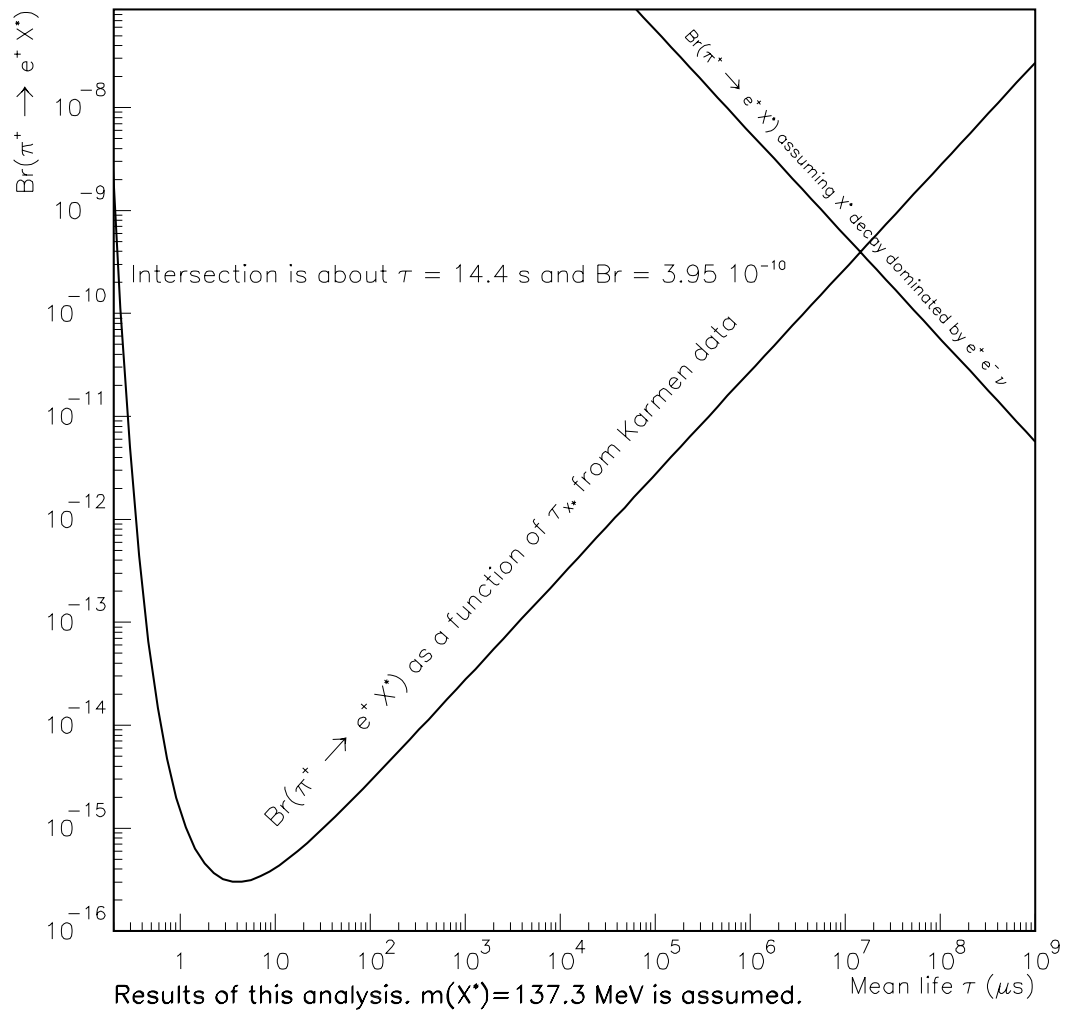


Fig. 4

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