Title: Muon Capture Constraints on Sterile Neutrino Properties

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Abstract: We show that ordinary and radiative muon capture impose stringent constraints on sterile neutrino properties. In particular, we consider a sterile neutrino with a mass between \$40\$ and \$80~{\rm MeV}\$ that has a large mixing with the muon neutrino and decays predominantly into a photon and light neutrinos due to a large transition magnetic moment. Such a model was suggested as a possible resolution to the puzzle presented by the results of the LSND, KARMEN, and MiniBooNE experiments. We find that the scenario with the radiative decay to massless neutrinos is ruled out by measurements of the radiative muon capture rates at TRIUMF in the relevant mass range by a factor of a few in the squared mixing angle. These constraints are complementary to those imposed by the process of electromagnetic upscattering and de-excitation of beam neutrinos inside the neutrino detectors induced by a large transition magnetic moment. The latter provide stringent constraints on the size of the transitional magnetic moment between muon, electron neutrinos and \$N\$. We also show that further extension of the model with another massive neutrino in the final state of the radiative decay may be used to bypass the constraints derived in this work.

Muon Capture Constraints on Sterile Neutrino Properties

David McKeen
University of Victoria

D. M. and Maxim Pospelov, Phys. Rev. D 82, 113018 (2010) [arXiv:1011.3046]

Outline

- Neutrino Experiment Anomalies
- A sterile neutrino solution?
- (Radiative) Muon Capture implications
- Mag. Moment Production
- $\mu \to e$ conversion prospects

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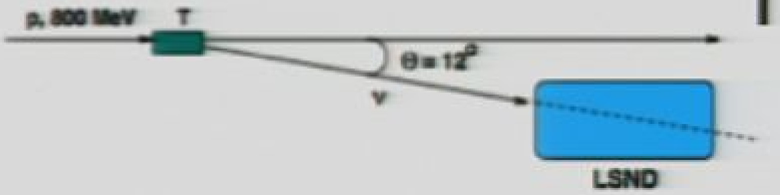
LSND

Phys. Rev. D 64, 112007 (2001)



167 t of dilute mineral oil liquid scintillator

Looked for $\bar{\nu}_\mu \to \bar{\nu}_e$ in the reaction

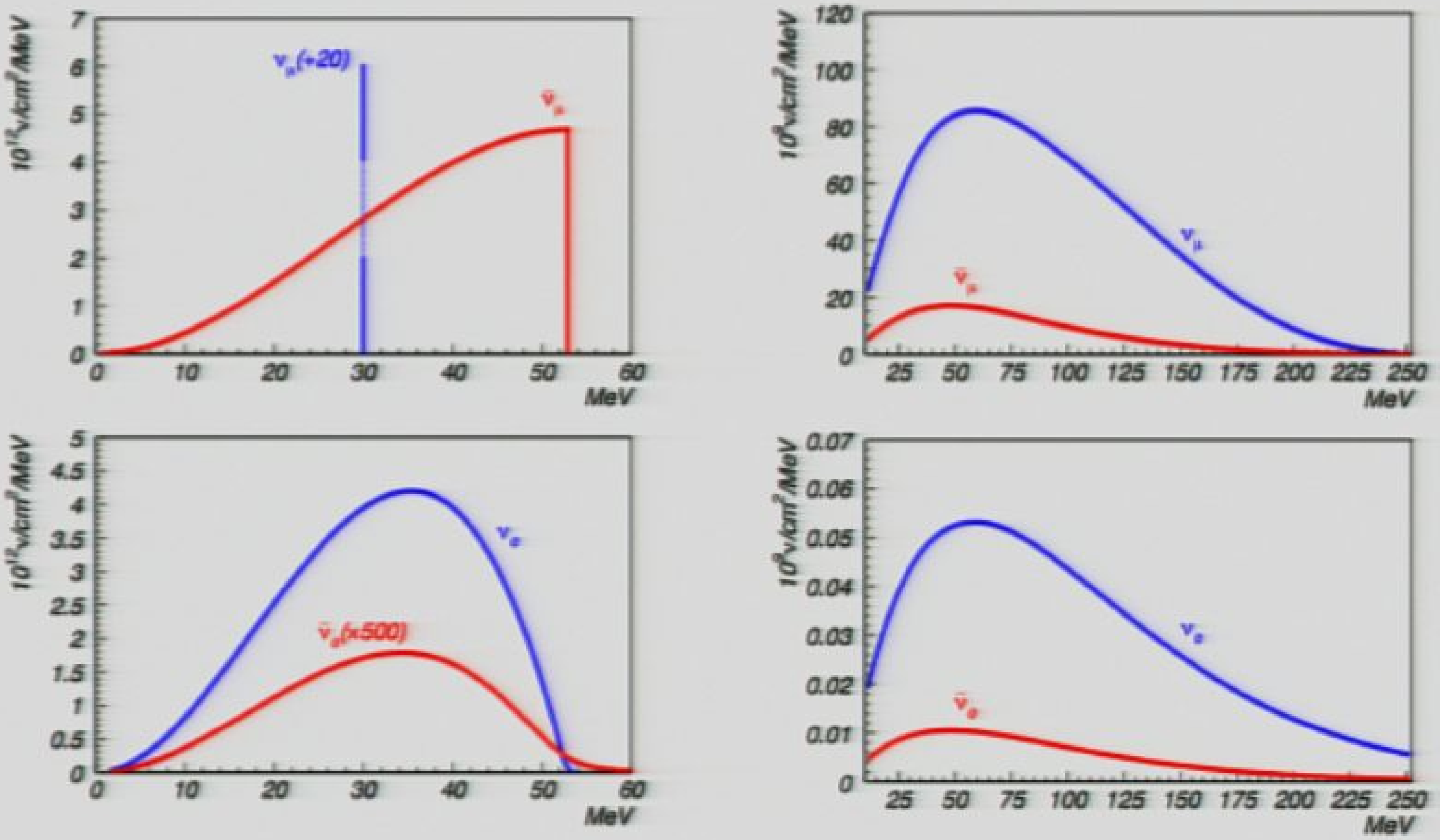
$\bar{\nu}_e p \to e^+ n$ then 2.2 MeV photon from neutron capture

Found a background-subtracted excess of

$87.9 \pm 22.4 \pm 6.0$ events consistent with signal,

i.e. a nonzero oscillation probability at $\sim 4\sigma$

LSND neutrino fluxes



μ

e

DAR

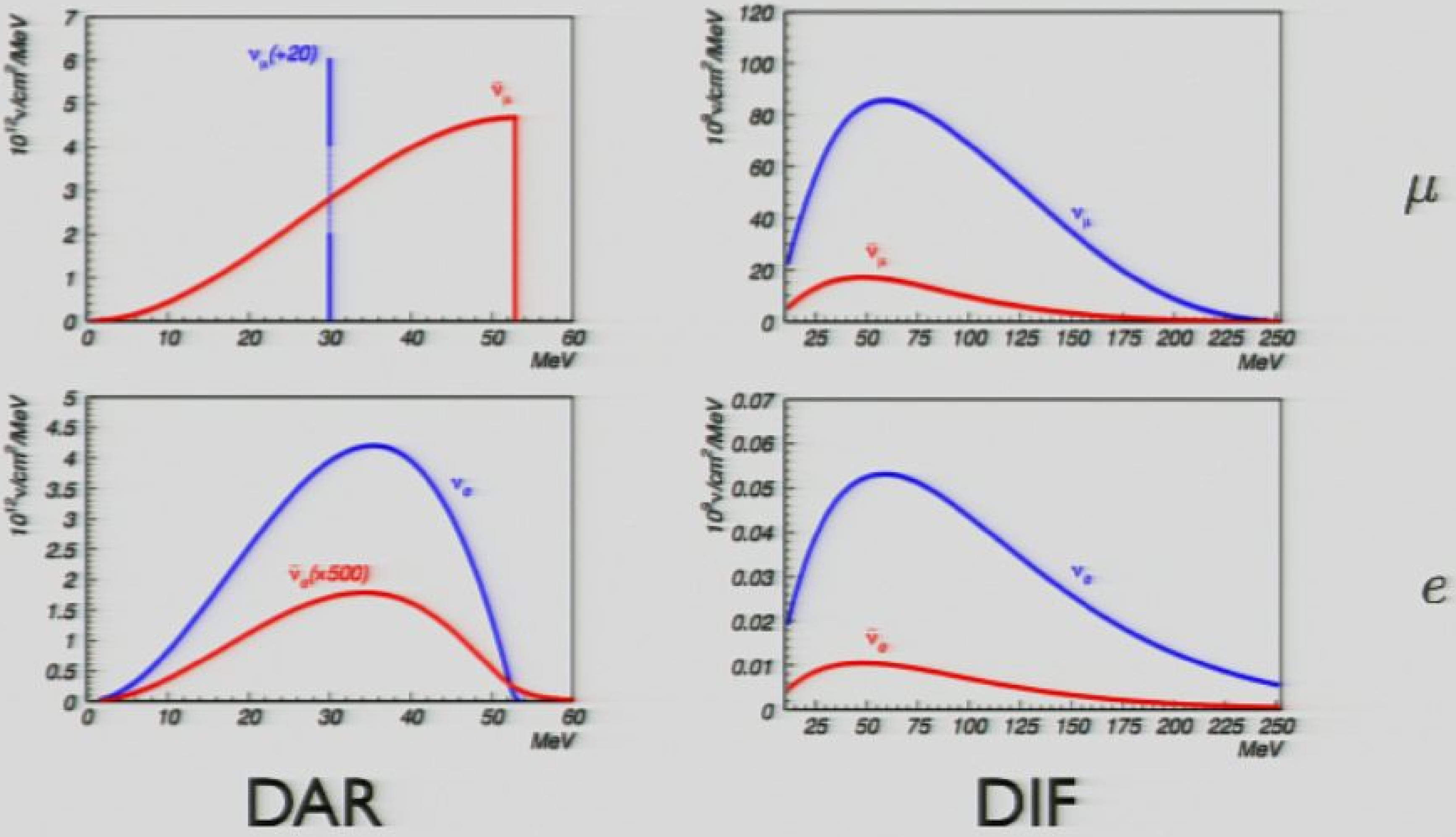
DIF

KARMEN

Phys. Rev., D65, 112001 (2002)

- Very similar to LSND, only ~5 times fewer anti-muon neutrinos
- But no excess

LSND neutrino fluxes



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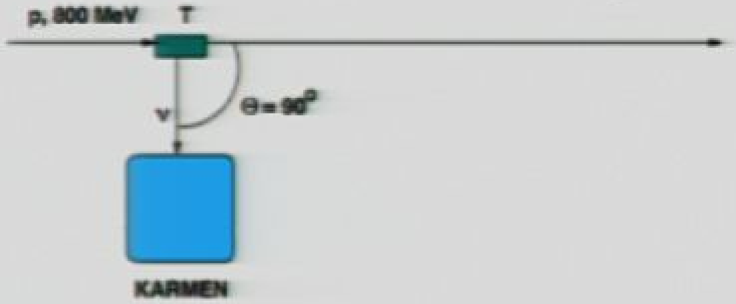

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MiniBooNE

- 8 GeV protons on Be target
- 800 t mineral oil detector
- Look for Cerenkov rings from charged particles (includes converted photons)
- Unlike LSND, KARMEN don’t observe the photon from neutron capture

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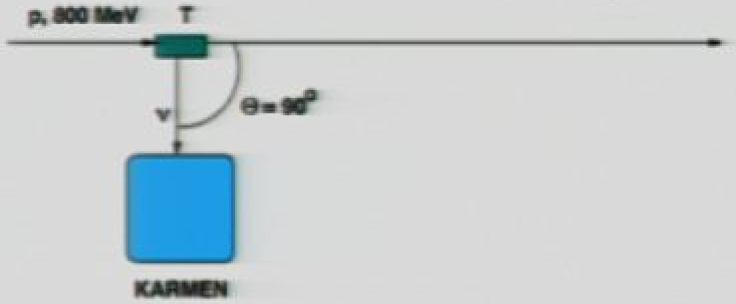

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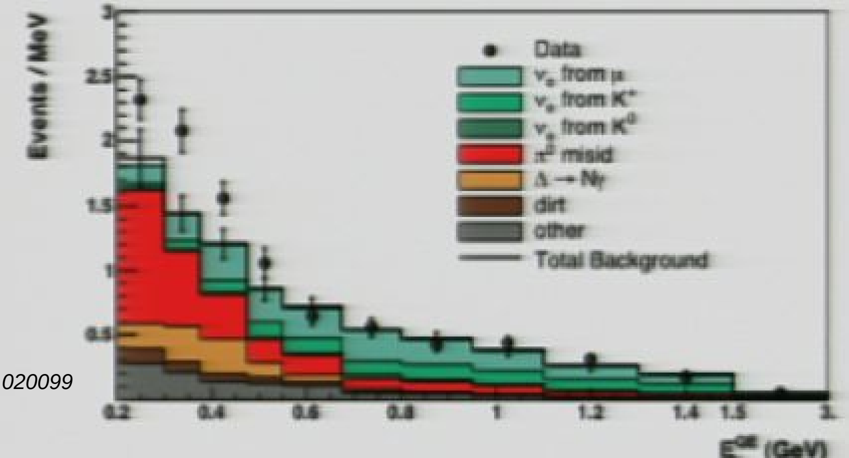
MiniBooNE

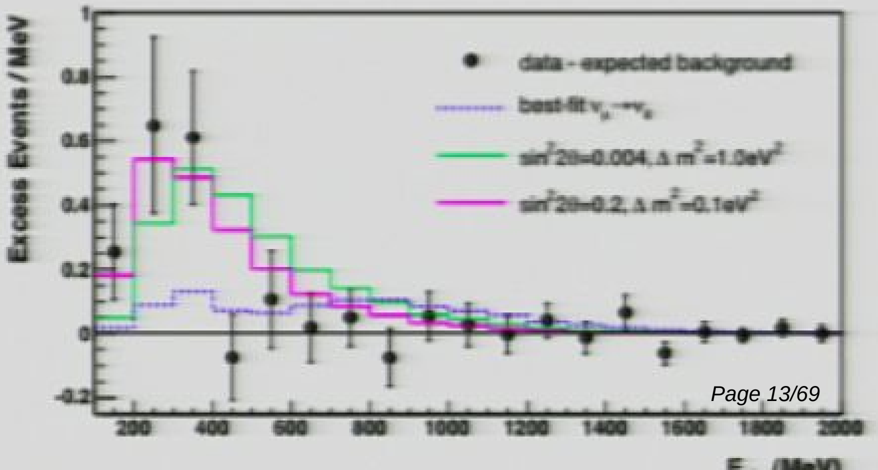
Phys. Rev. Lett., 102, 101802 (2009)

First data analyzed looking for $\nu_\mu \to \nu_e$

Found an excess of $128.8 \pm 20.4 \pm 38.3$ at low energies

Consistent with
$$\nu_e C \to e^- X$$
$$\bar{\nu}_e C \to e^+ X$$
$$\nu C \to \nu\gamma X$$





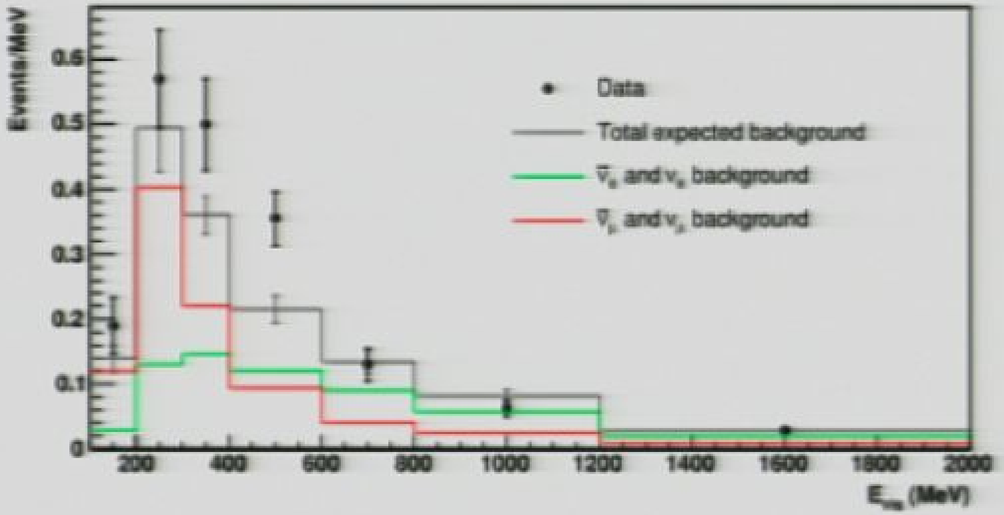
MiniBooNE

Phys. Rev. Lett., 105, 181801 (2010)

A recent search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations finds

43.2 ± 22.5 excess events (not at the lowest energies)

This does not contradict LSND



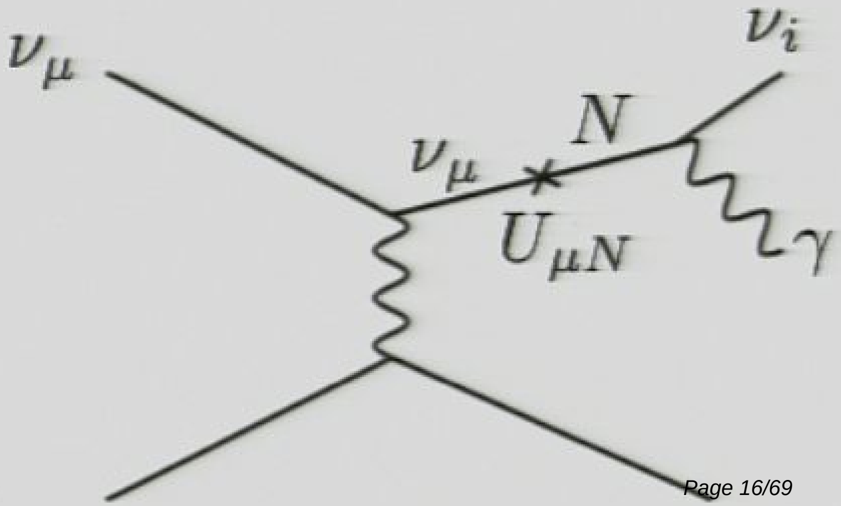
What does it mean?

- Could be a misunderstanding of neutrino fluxes
- Could be unaccounted for SM background (Harvey, Hill, & Hill)
- Maybe something new?

Model by Gninenko

- Introduce a sterile neutrino, N which mixes with the muon with strength $U_{\mu N}$
- Give it a large transition magnetic moment so that it decays radiatively to lighter neutrinos

$$\mathcal{L}_{\rm int} = \mu_{\rm tr} \nu_i \sigma_{\mu\nu} N \partial^\mu A^\nu$$

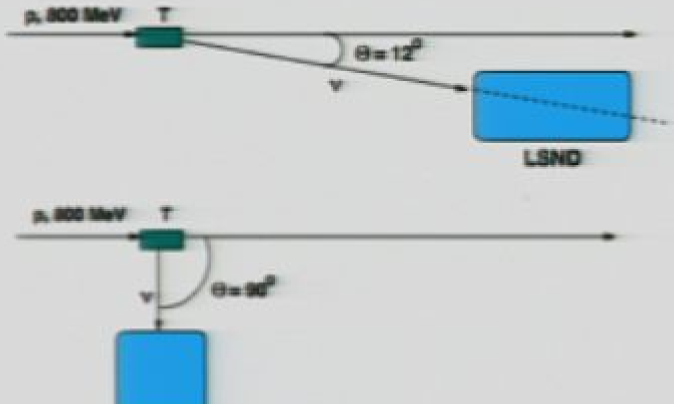


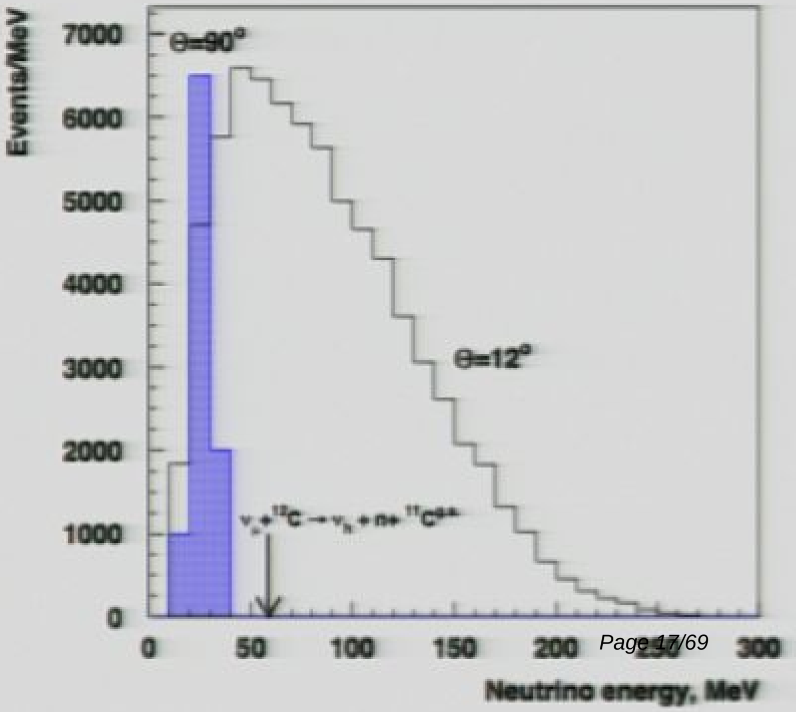
arXiv:1009.5536

PRL, 103, 241802 ('09)

Gninenko (cont'd)

- LSND is explained by $\nu_\mu\,{}^{12}C \to NnX \to \gamma\nu n X$
- KARMEN's geometry means that muon neutrinos from pion DIF are below threshold if $m_N > 40\ \mathrm{MeV}$
- Similar for MiniBooNE





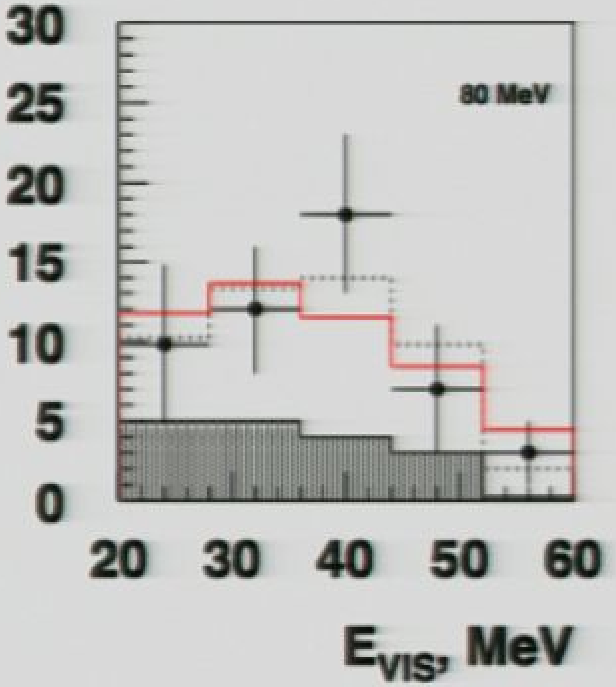
LSND fit

- Obtain a reasonable fit for

  $10\ \mathrm{MeV} < m_N < 90\ \mathrm{MeV}$

  $|U_{\mu N}|^2 = (2-8) \times 10^{-3}$

  $\tau_N < 10^{-8}\ \mathrm{s}$



- KARMEN requires $m_N > 40\ \mathrm{MeV}$

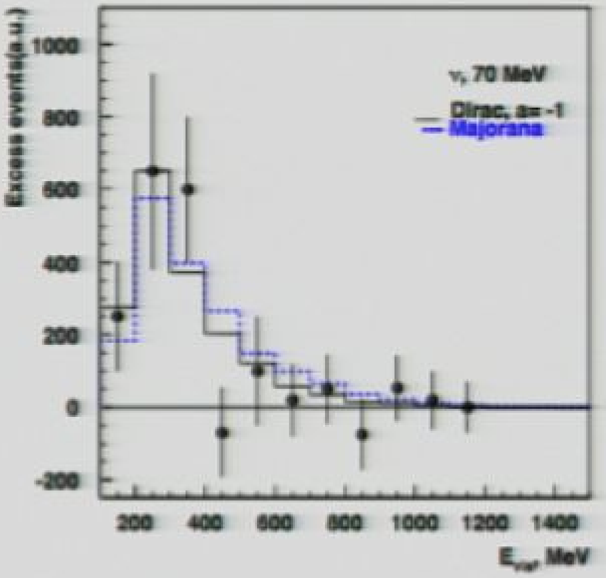
MiniBooNE fit

- To get a good fit to ν_μ:

$$20 \text{ MeV} \lesssim m_N \lesssim 600 \text{ MeV}$$

$$|U_{\mu N}|^2 = (1-6) \times 10^{-3}$$

$$\tau_N \lesssim 10^{-9} \text{ s}$$



- The $\bar{\nu}_\mu$ data is compatible with:

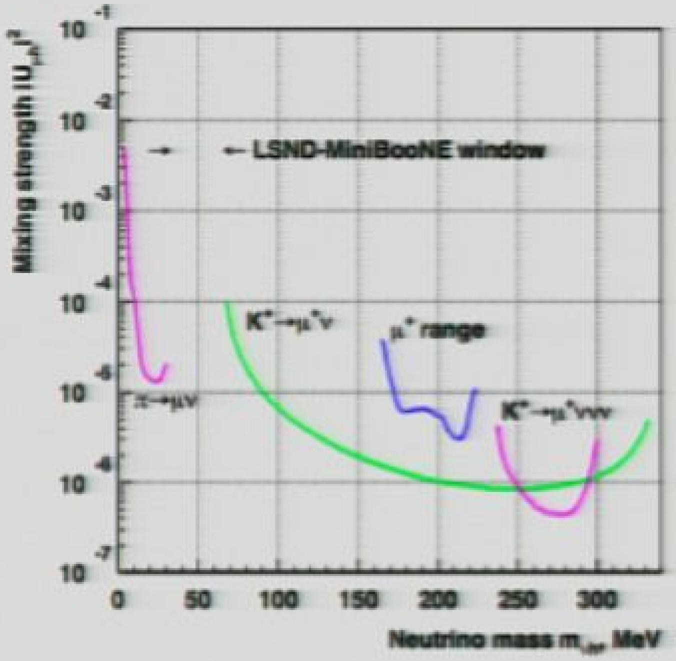
$$|U_{\mu N}|^2 \, (0-8) \times 10^{-3}$$

Other Constraints

- Search for peaks in $\pi \to \mu\nu$ $K \to \mu\nu$
- For $m_N \lesssim 80\ \mathrm{MeV}$ background from $K \to \mu\nu\gamma$ decreases reach
- Radiative decays will also help (also beam dump exps.)
- LEP $Z \to \nu\nu\gamma$

$$\tau_N \gtrsim 10^{-11}\ \mathrm{s}$$

- TWIST



see arXiv:0901.3589

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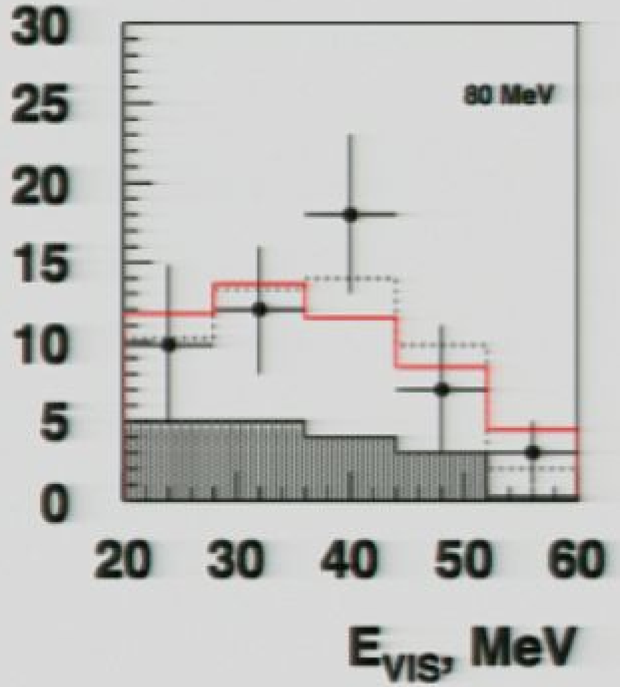

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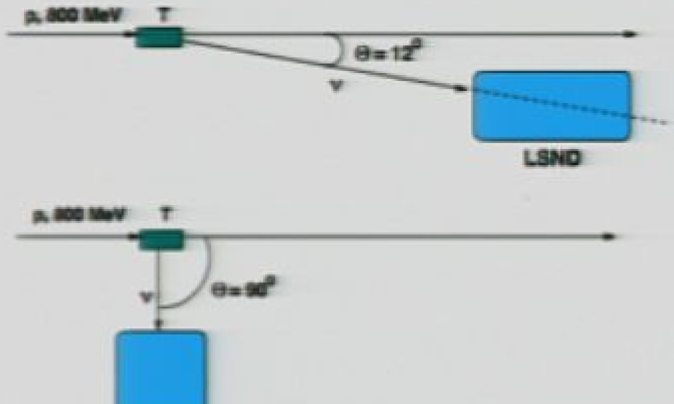

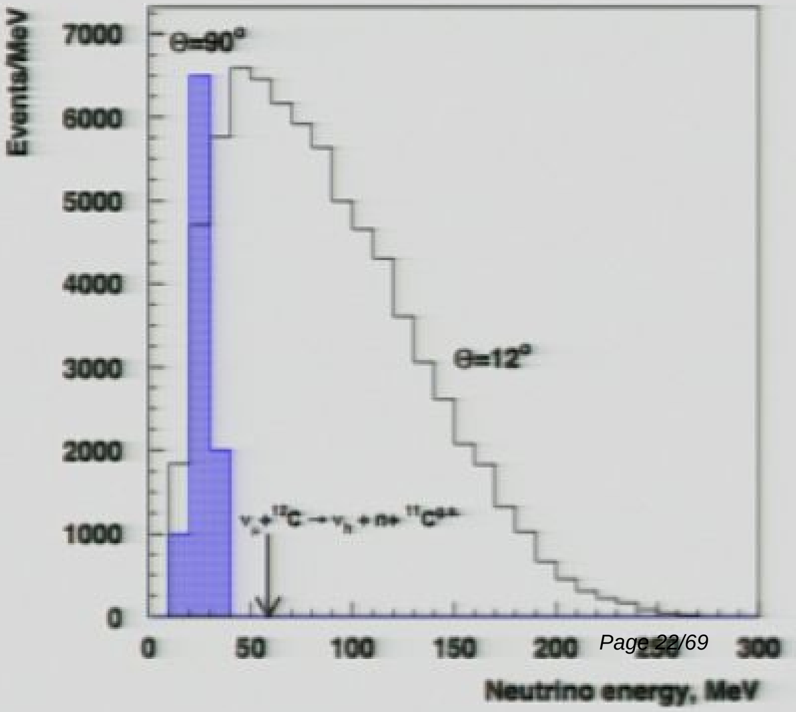

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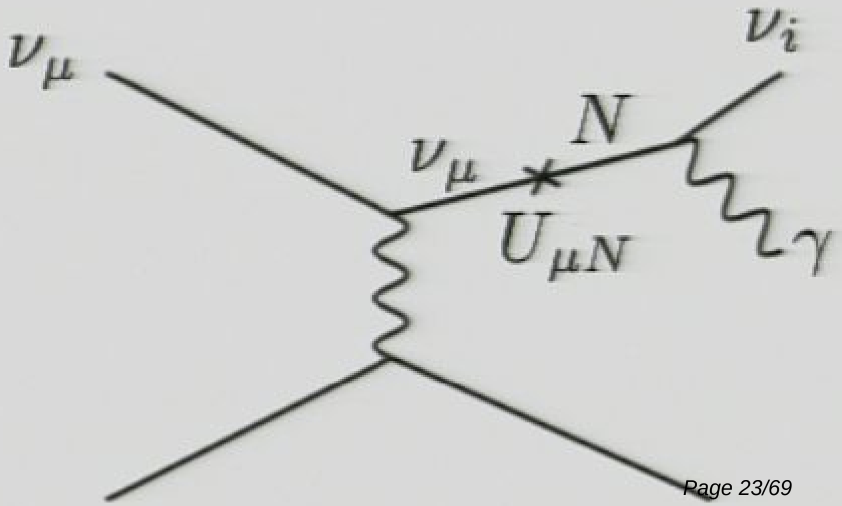

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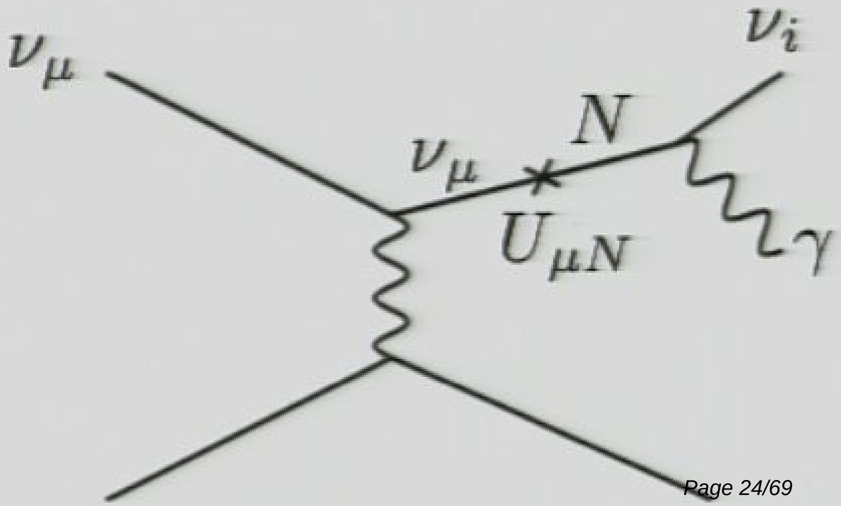

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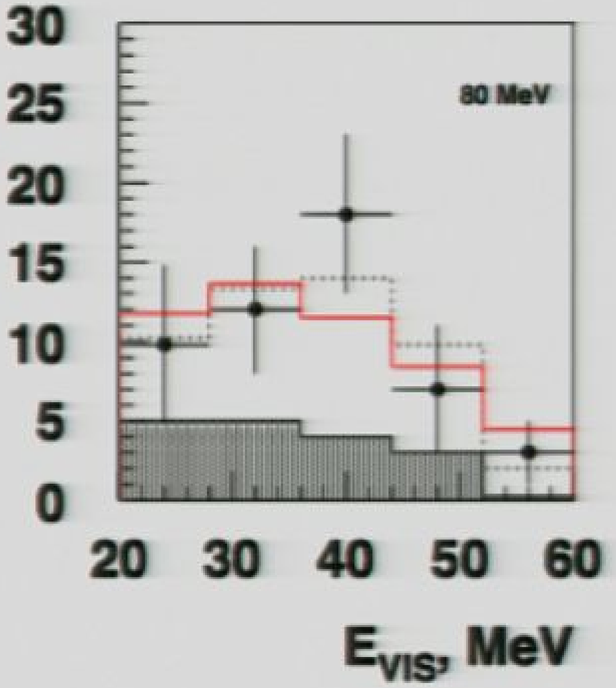

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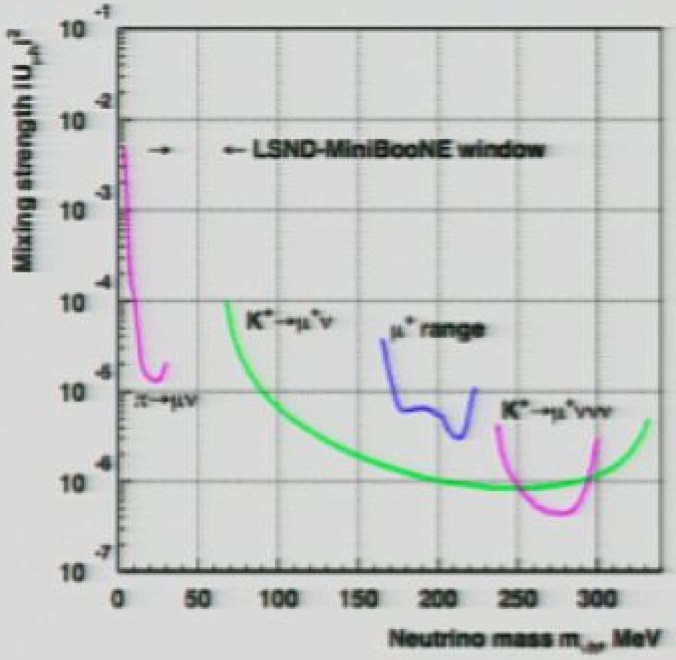

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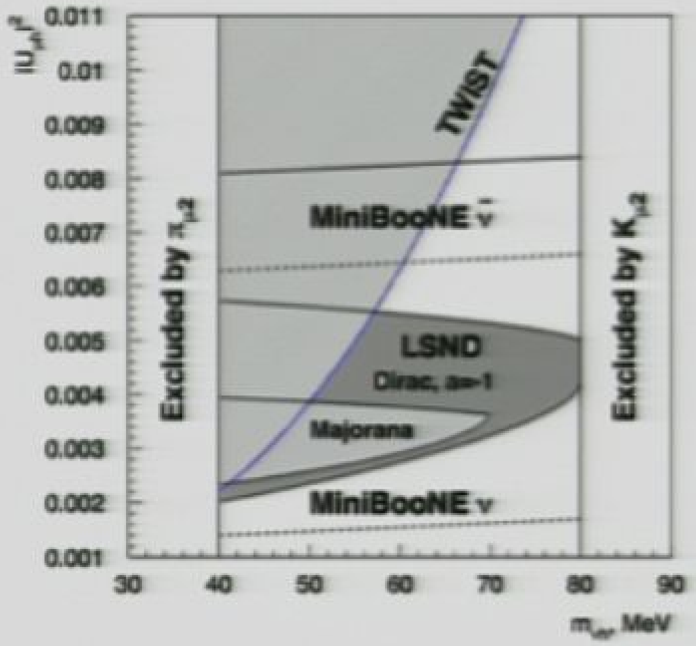
To Summarize:

- To explain the anomalies while not running afoul of other measurements requires



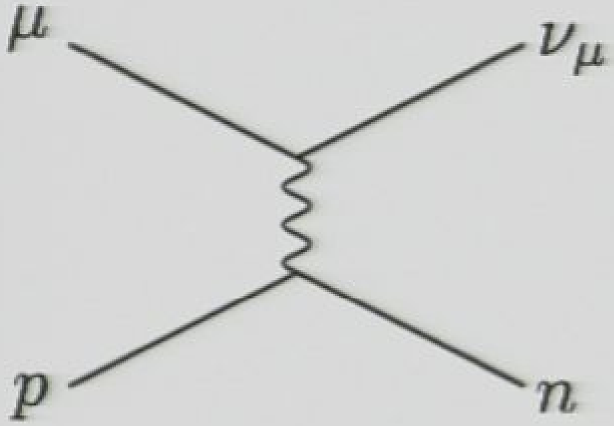
$$|U_{\mu N}|^2 \simeq (3-6)\times 10^{-3}$$

$$40 \text{ MeV} \lesssim m_N \lesssim 80 \text{ MeV}$$

$$10^{-11} \text{ s} \lesssim \tau(N\to\gamma\nu) \lesssim 10^{-9} \text{ s}$$

$$\mathcal{B}(N\to\gamma\nu)\simeq 1$$

(Radiative) Muon Capture



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RMC: $\mu p \to \nu n \gamma$

Write the Hadronic portion of the OMC matrix elem. as:

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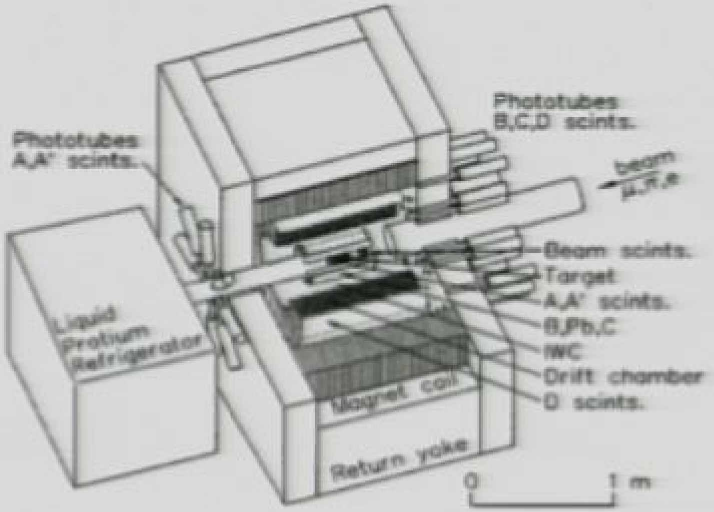
$$\left. - g_A\left(q^2\right)\gamma^\alpha\gamma^5 - \frac{1}{m_\mu}g_P\left(q^2\right)q^\alpha\gamma^5\right]u_p(p_1)$$

MC is the best source of info on g_P

TRIUMF RMC on hydrogen exp.

D. H. Wright et al., PRC, 57, 373 ('98)

- Liquid hydrogen at 16 K
- Need singlet and triplet N-producing OMC rates
- Mostly molecular, not atomic:



$$f_{\text{sing}} = 0.061\,, \quad f_{\text{para}} = 0.085\,, \quad f_{\text{ortho}} = 0.854$$

$\mathcal{B}(\mathrm{RMC}) \simeq 10^{-8}$ in hydrogen $\qquad \dfrac{\Gamma_{\mathrm{RMC}}}{\Gamma_{\mathrm{OMC}}} \simeq 10^{-5}$

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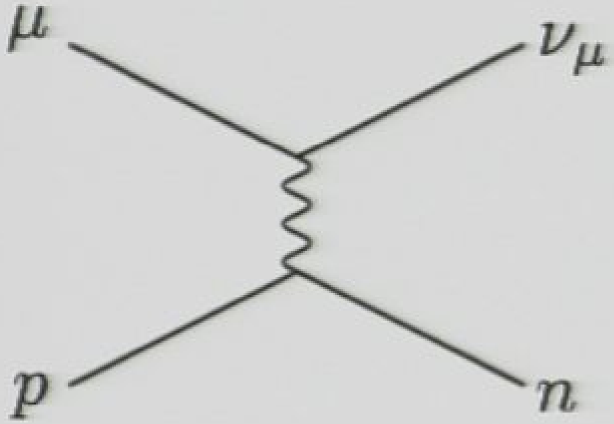

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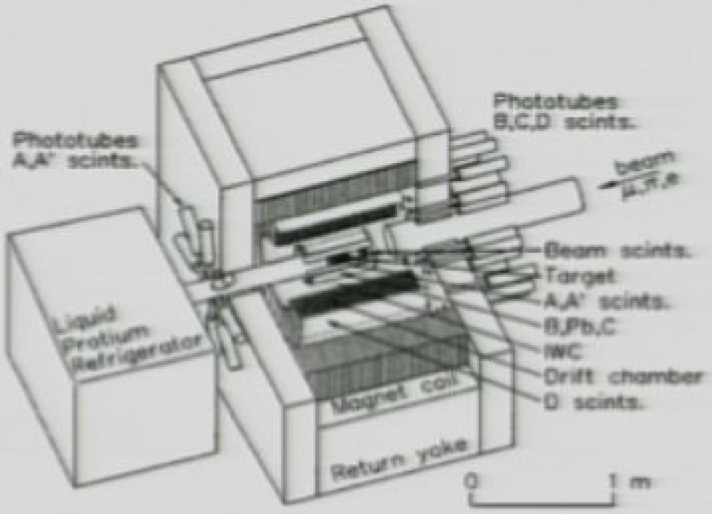

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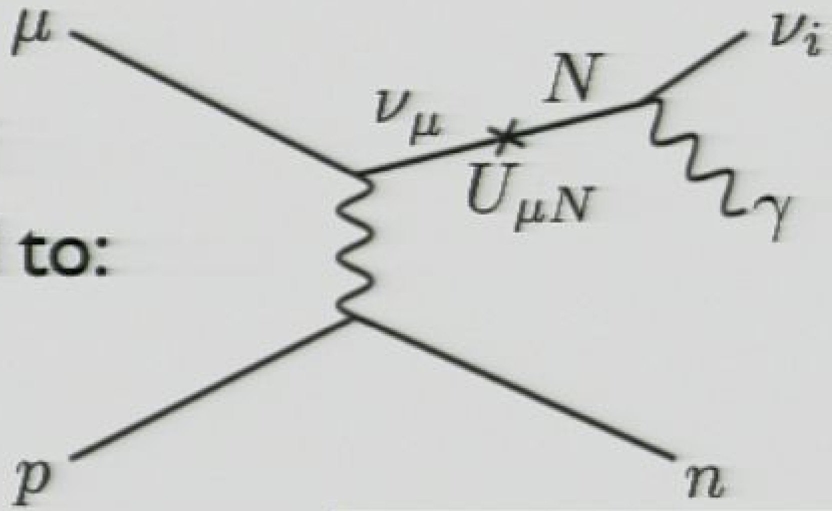

The rate can be written as

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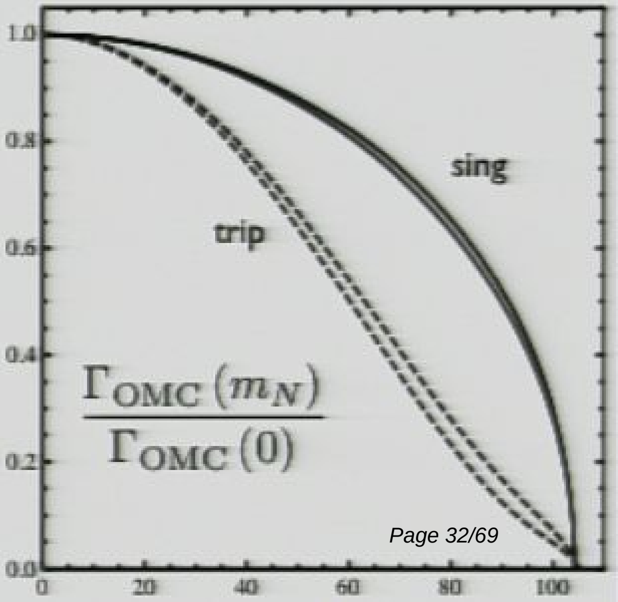

Form Factors from V. Bernard, H. W. Fearing, T. R. Hemmert, and U. G. Meissner, Nucl. Phys., A635, 121 (1998)

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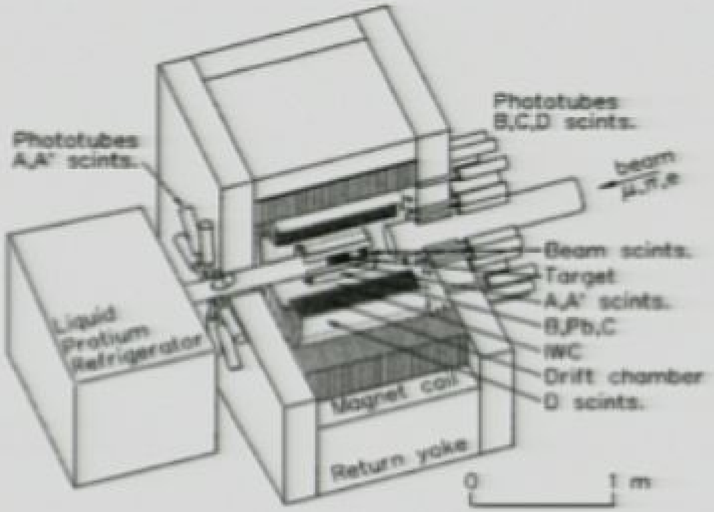

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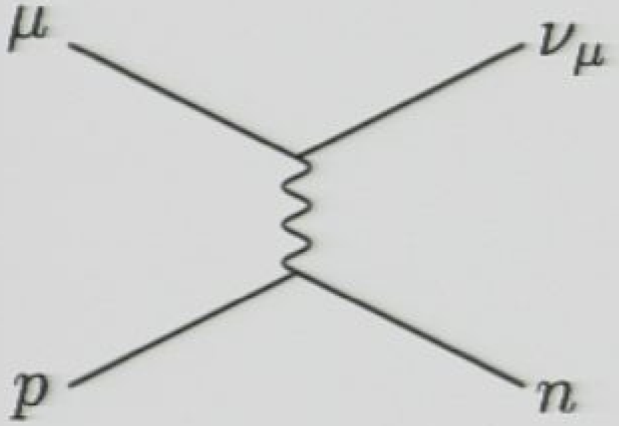

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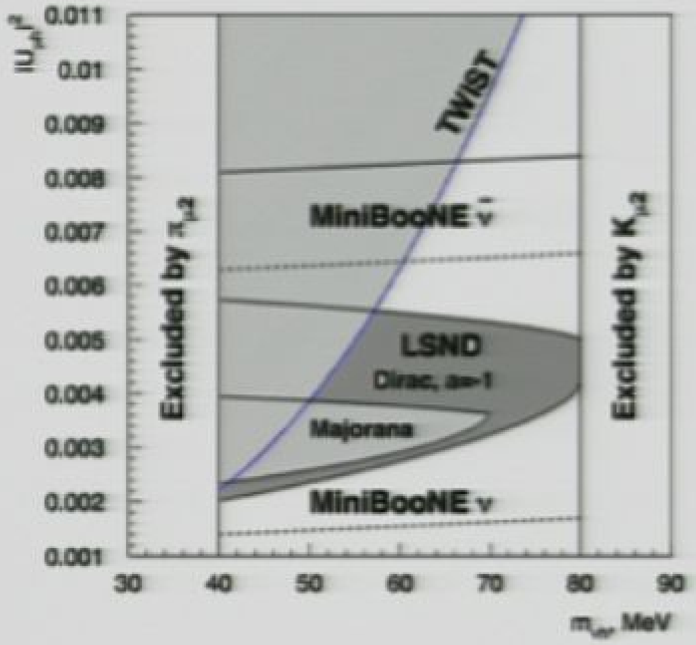

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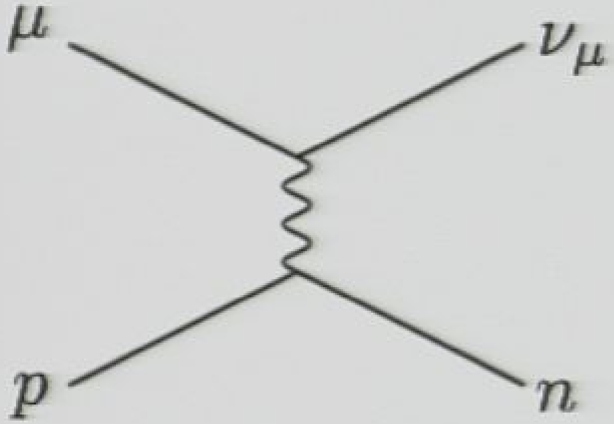

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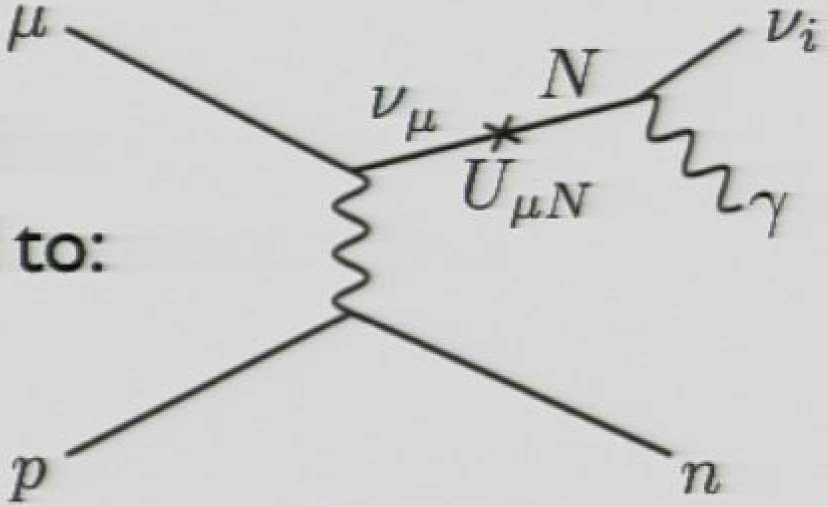

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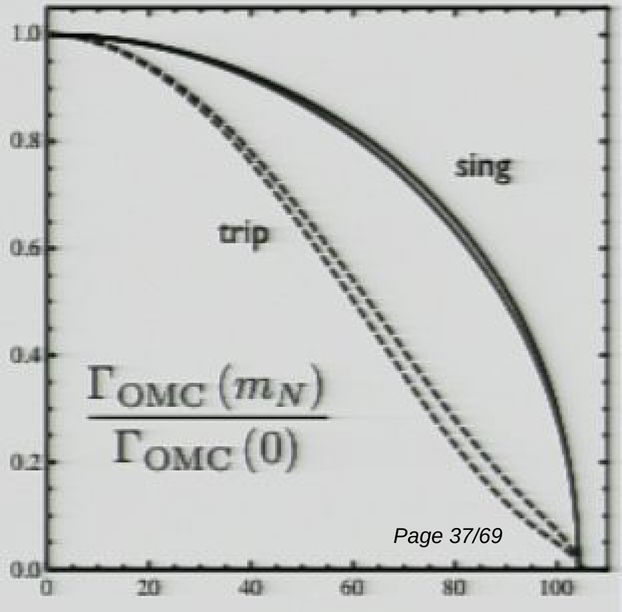
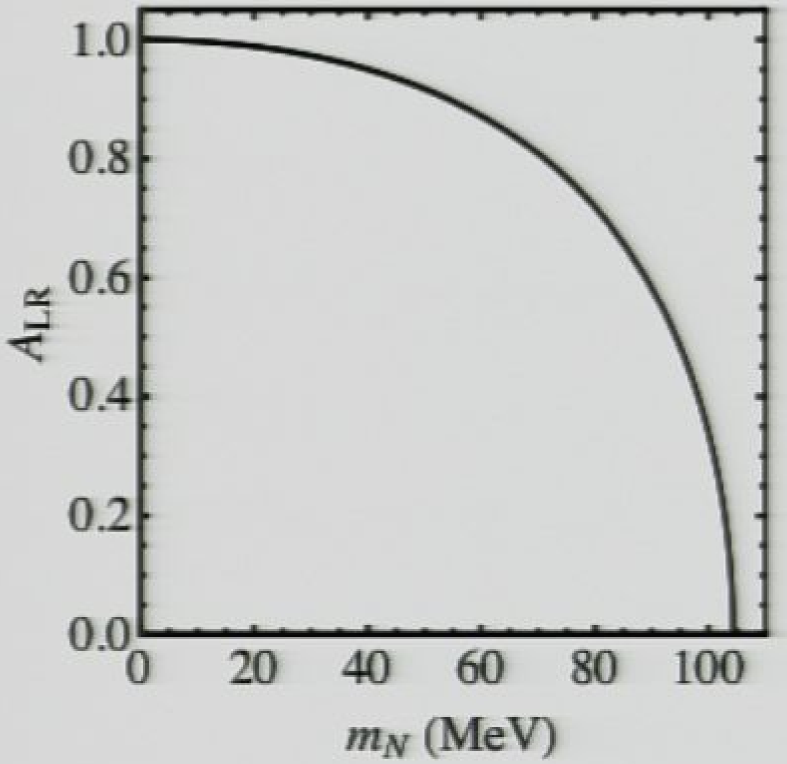
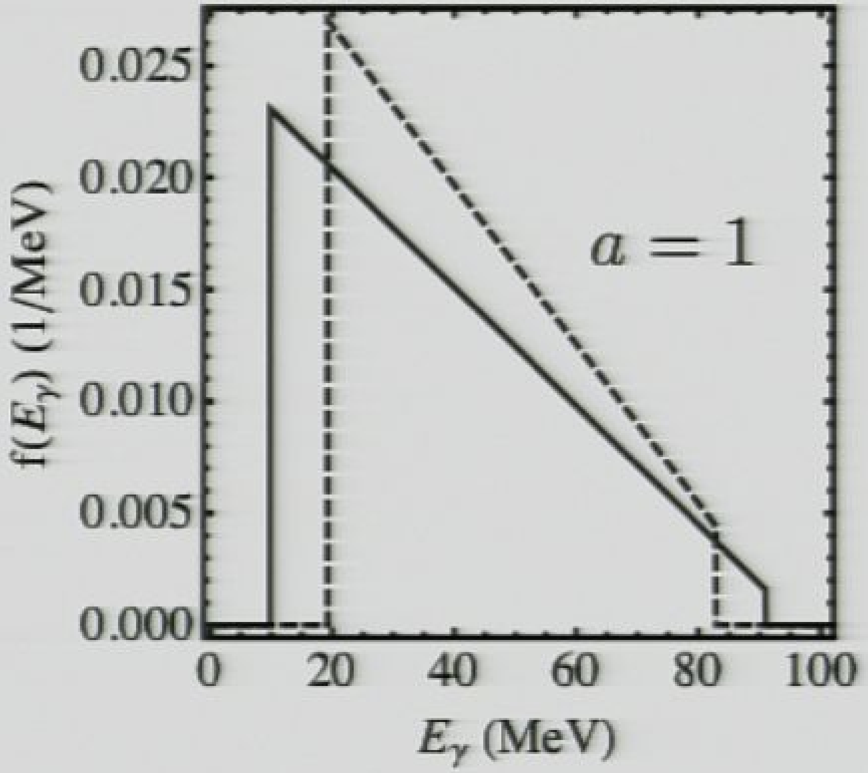


N-induced RMC (cont'd)





$$\frac{1}{\Gamma(N \to \gamma\nu)} \frac{d\Gamma(N \to \gamma\nu)}{d\cos\theta} = \frac{1}{2}(1 + a\cos\theta)$$

$$f(E_\gamma) = \frac{1}{\Delta E} - \frac{2A_{LR}a}{(\Delta E)^2}(E_\gamma - E_{\rm av})$$

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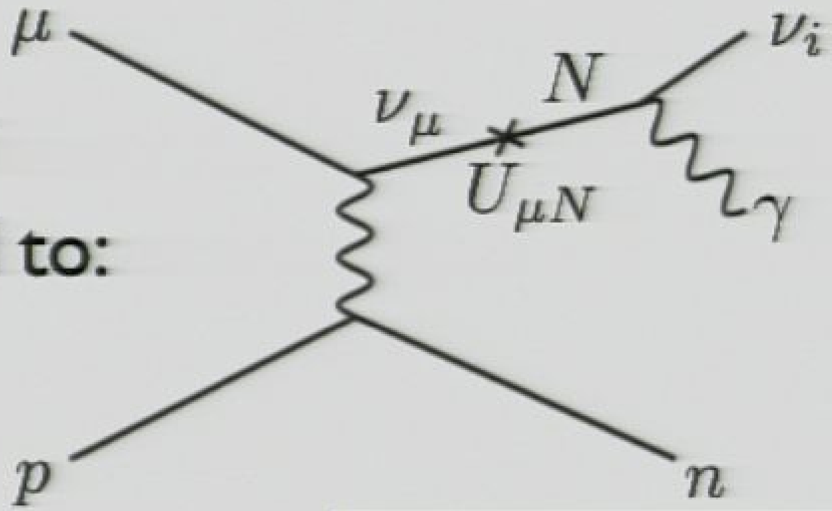

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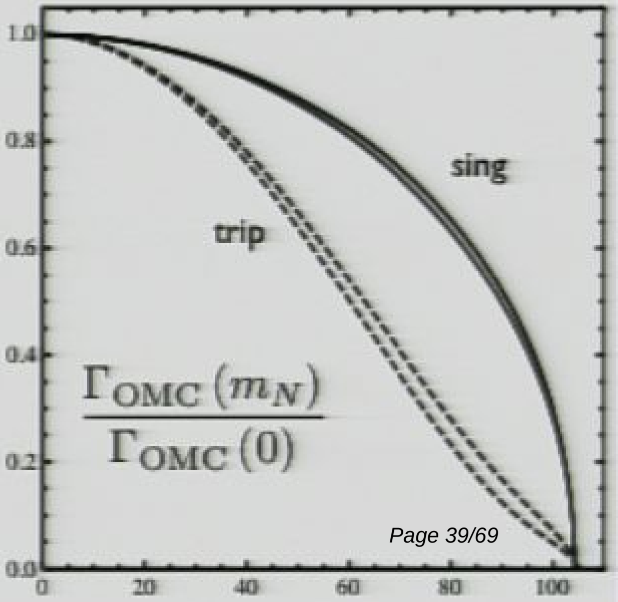

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D. H. Wright et al., PRC, 57, 373 ('98)

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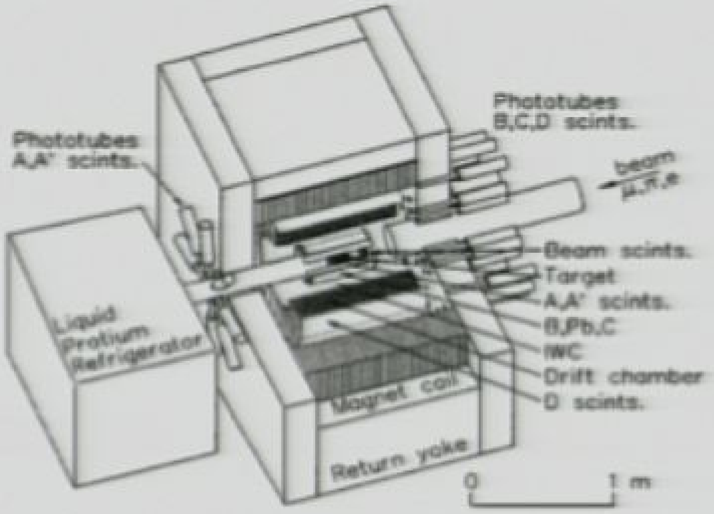

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N-induced RMC

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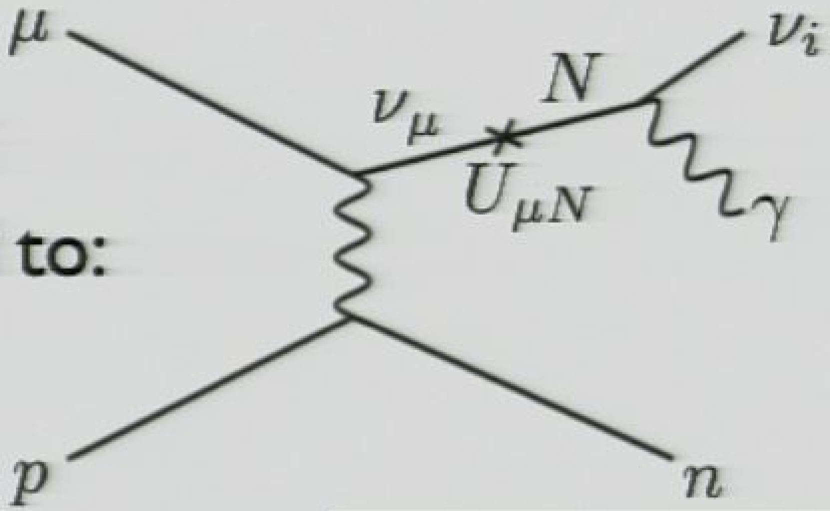

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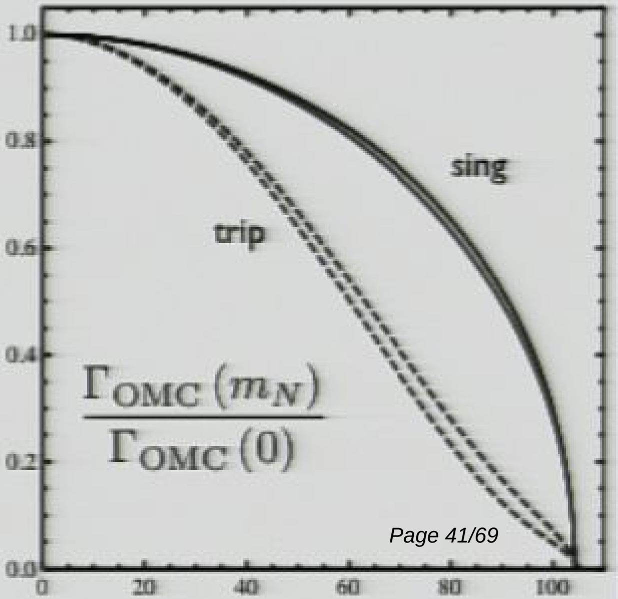

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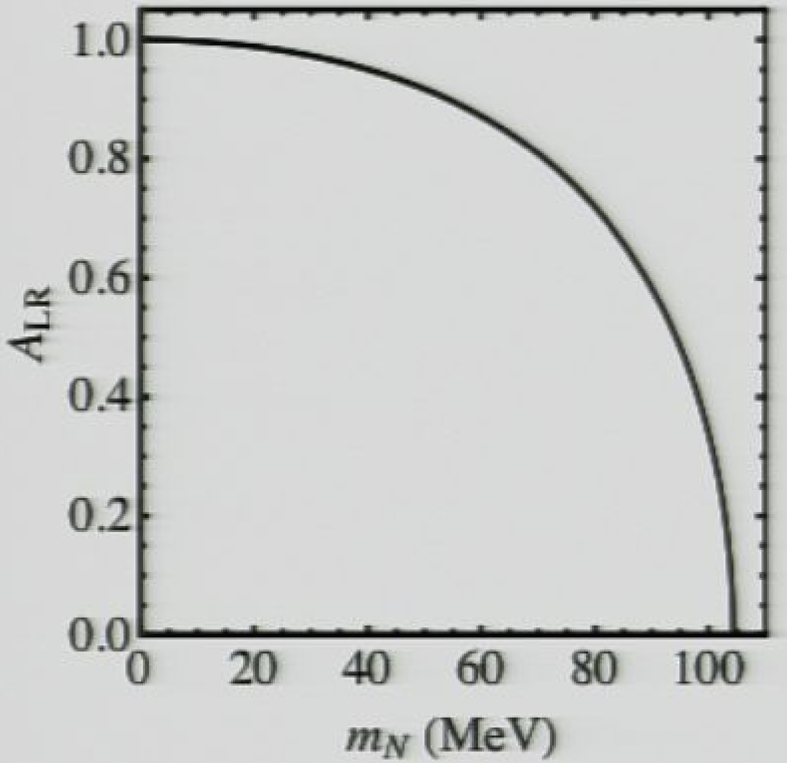
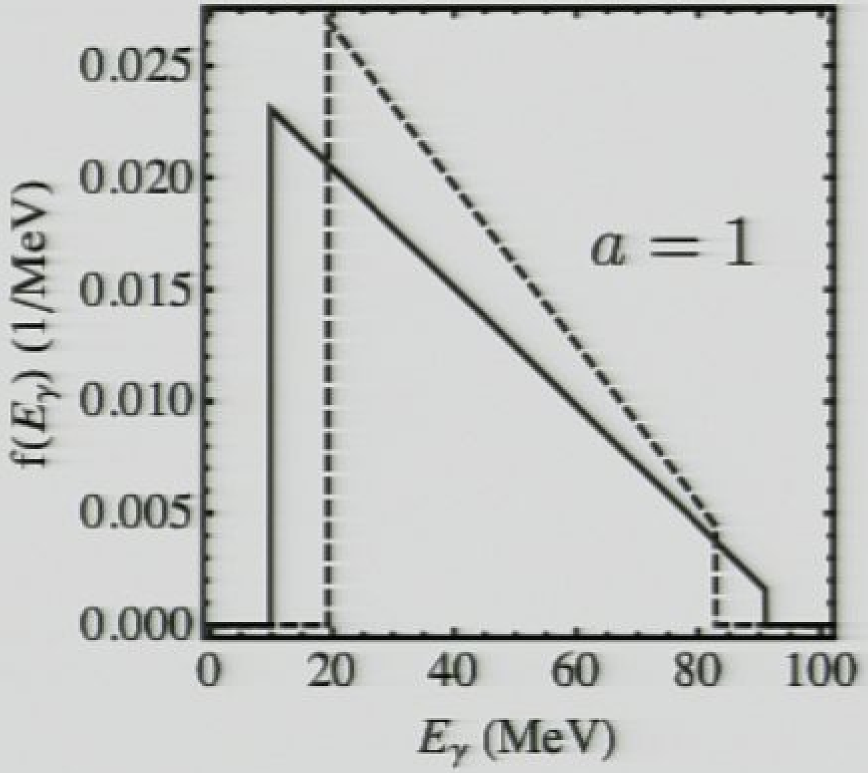


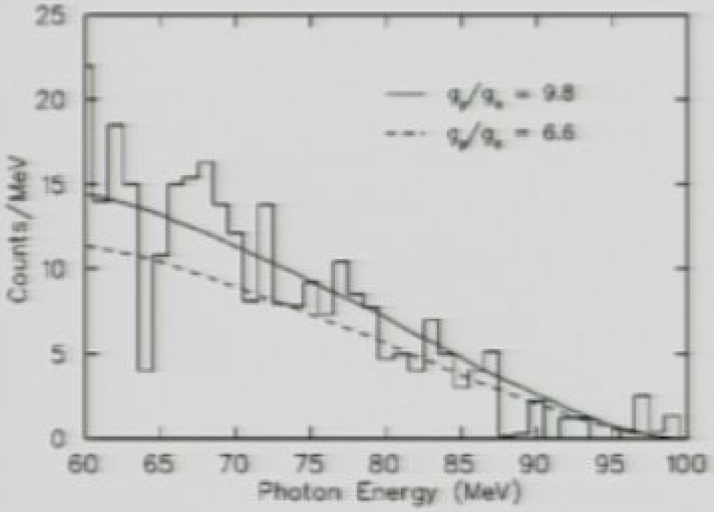


$$\frac{1}{\Gamma(N \to \gamma\nu)} \frac{d\Gamma(N \to \gamma\nu)}{d\cos\theta} = \frac{1}{2}(1 + a\cos\theta)$$

$$f(E_\gamma) = \frac{1}{\Delta E} - \frac{2A_{LR}a}{(\Delta E)^2}(E_\gamma - E_{\rm av})$$

Limit from RMC measurement

Measurement: $R_\gamma = \left.\frac{\Gamma_{\rm RMC}}{\Gamma_{\rm tot}}\right|_{E_\gamma > 60\ {\rm MeV}} = (2.10 \pm 0.21) \times 10^{-8}$



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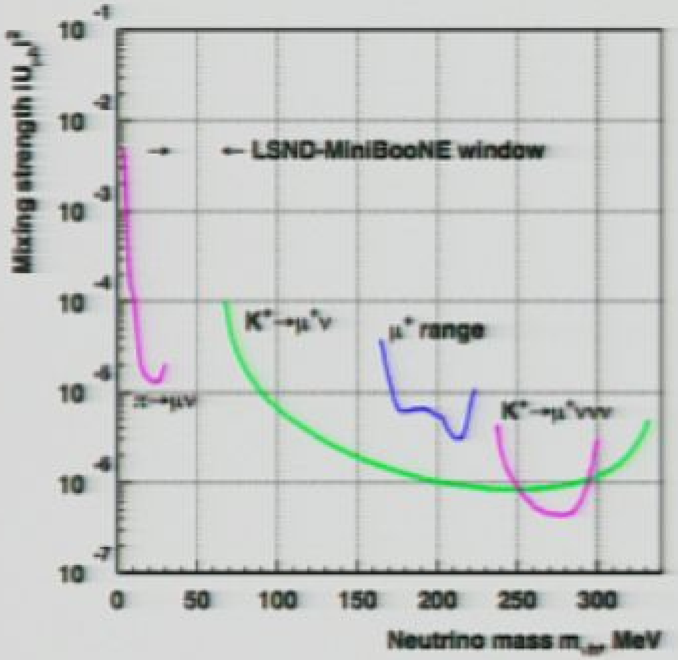

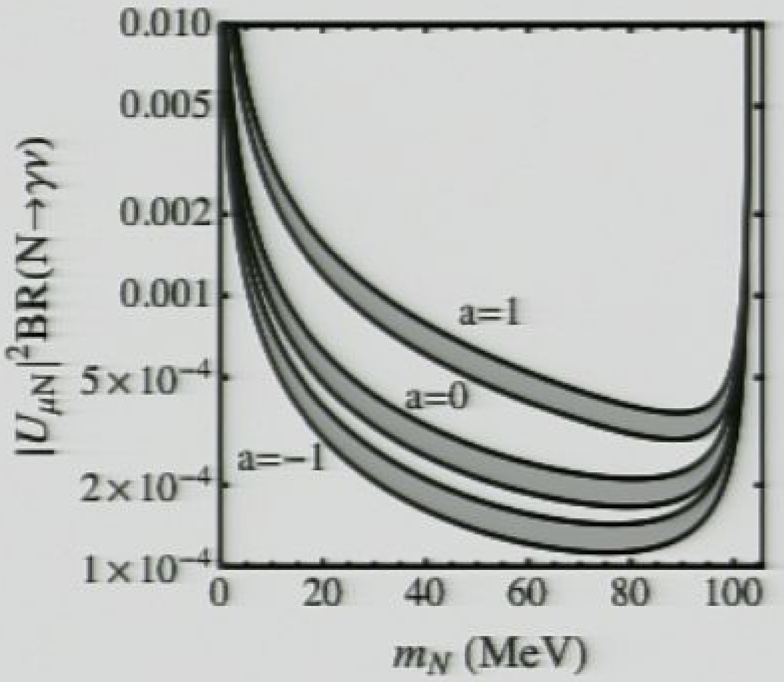

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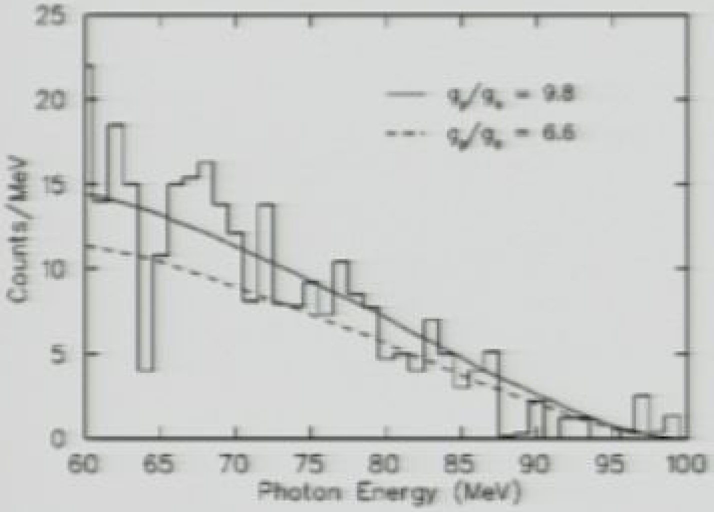

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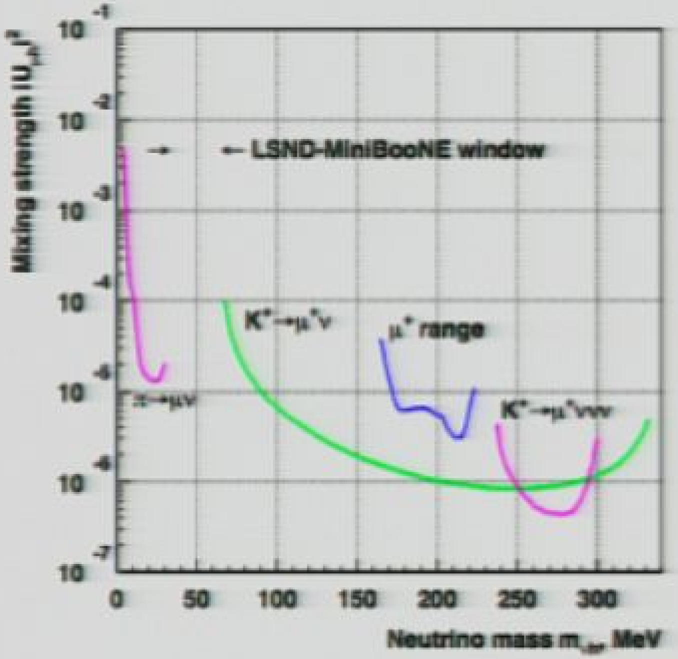

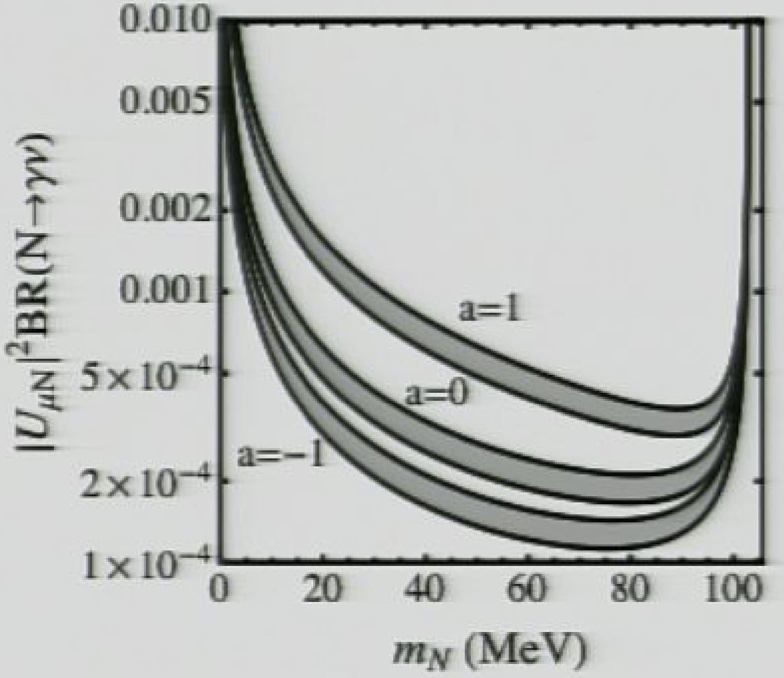

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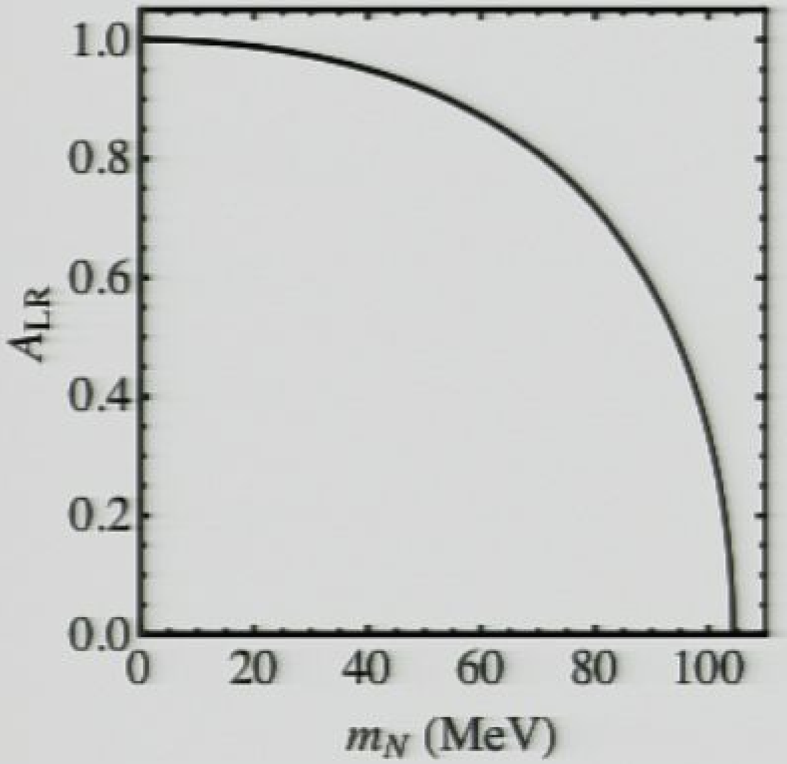

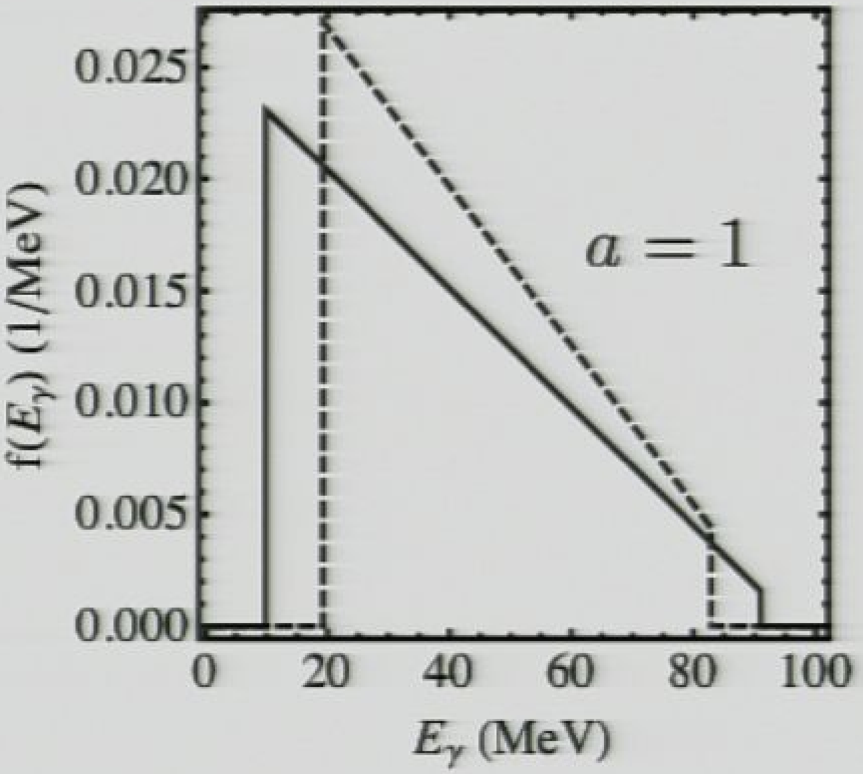

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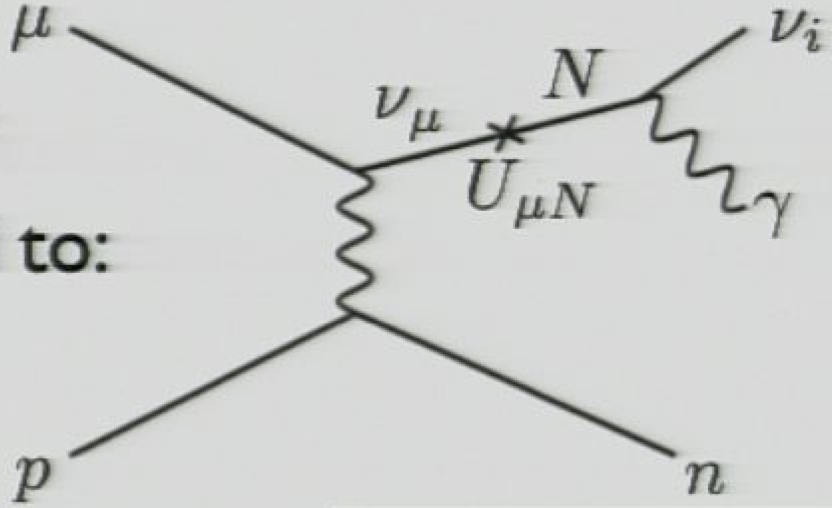

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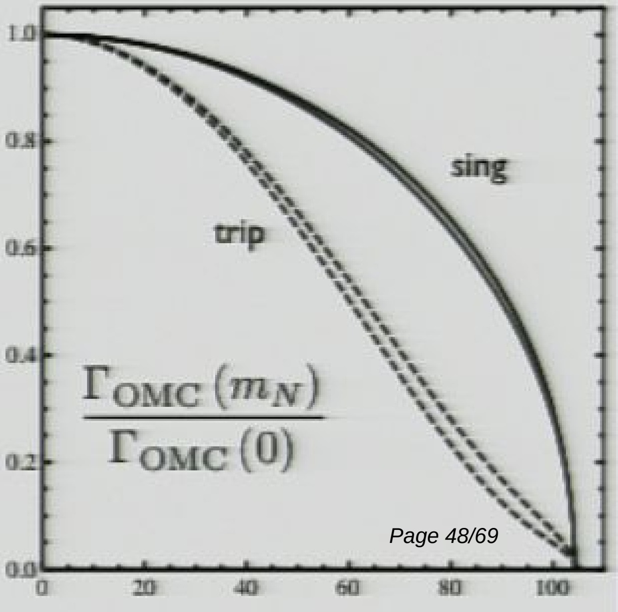

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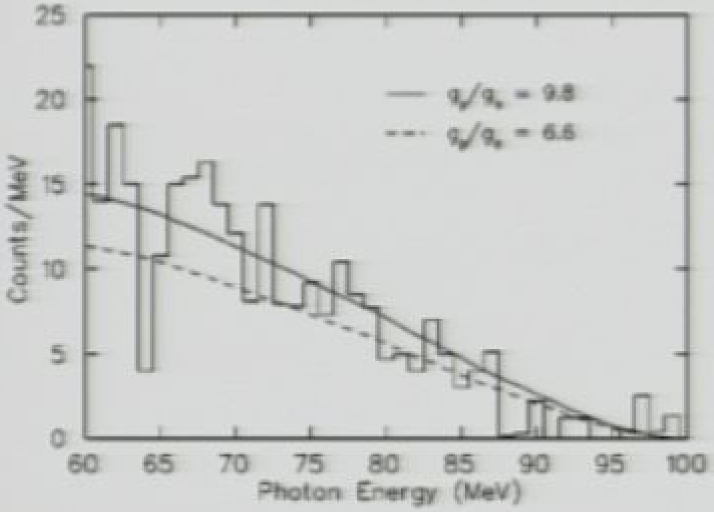

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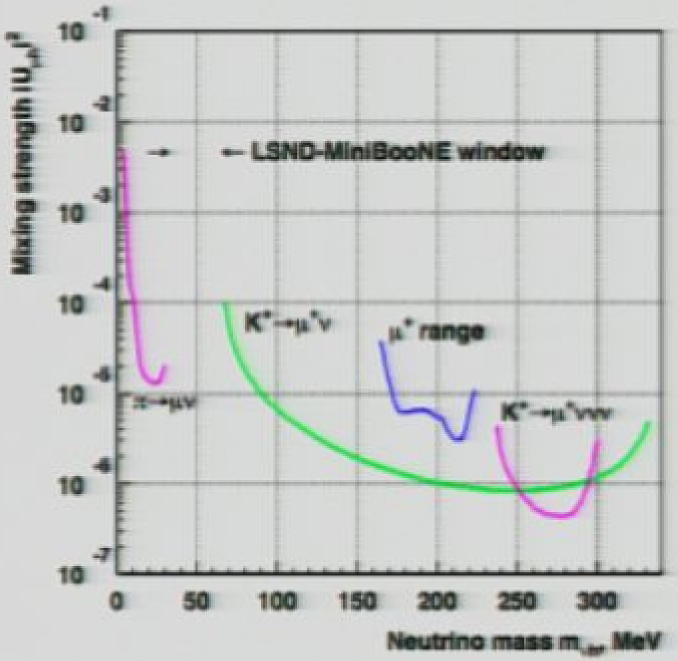

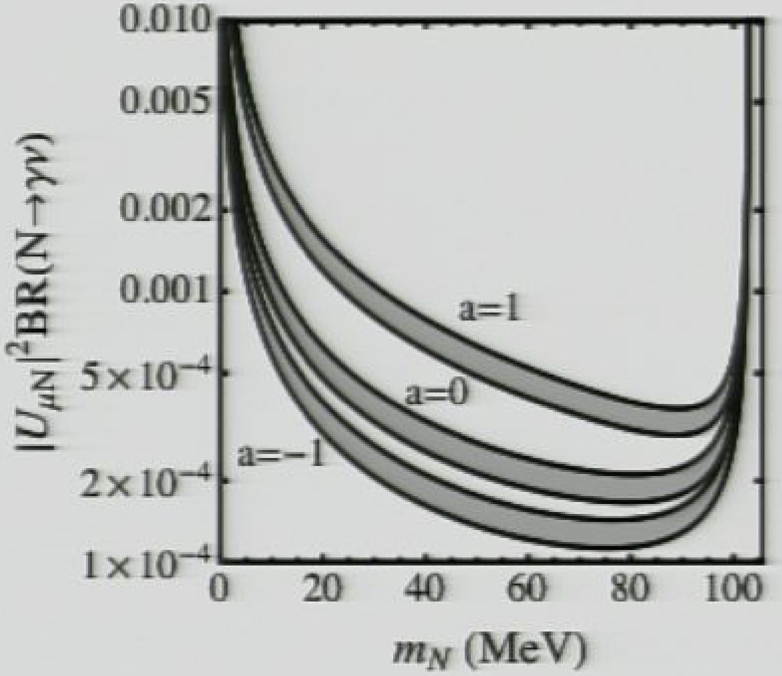

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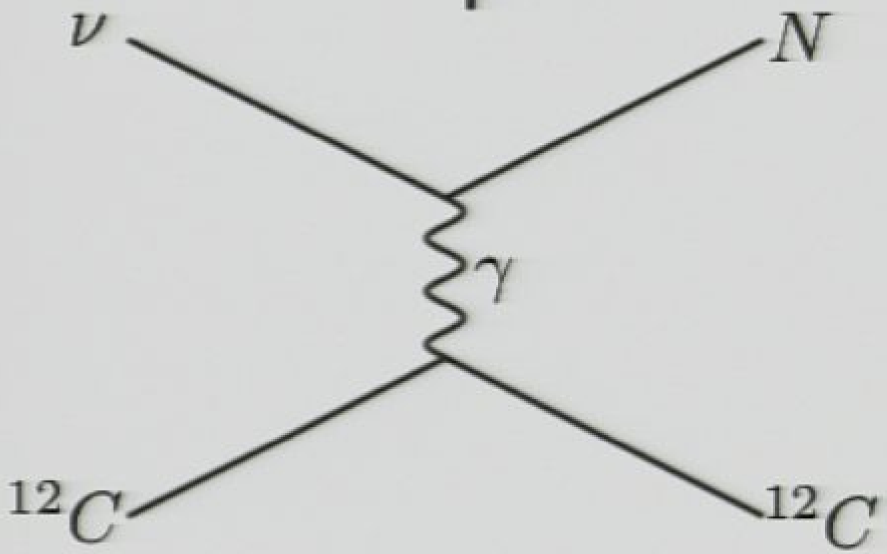

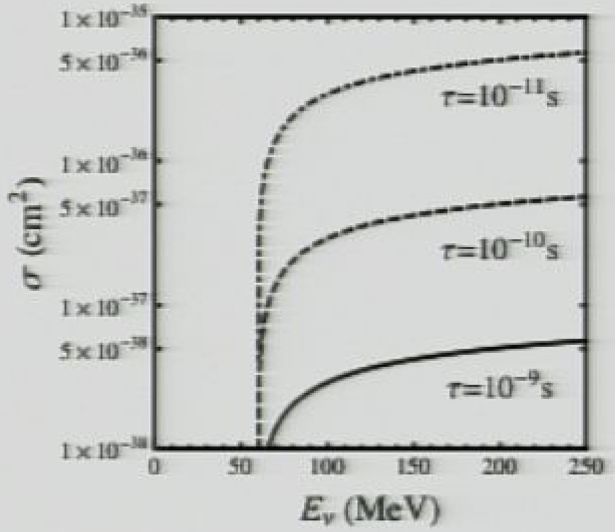

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$$\mu_{\rm tr}^{\tau} \gg \mu_{\rm tr}^{\mu},\ \mu_{\rm tr}^{e}$$

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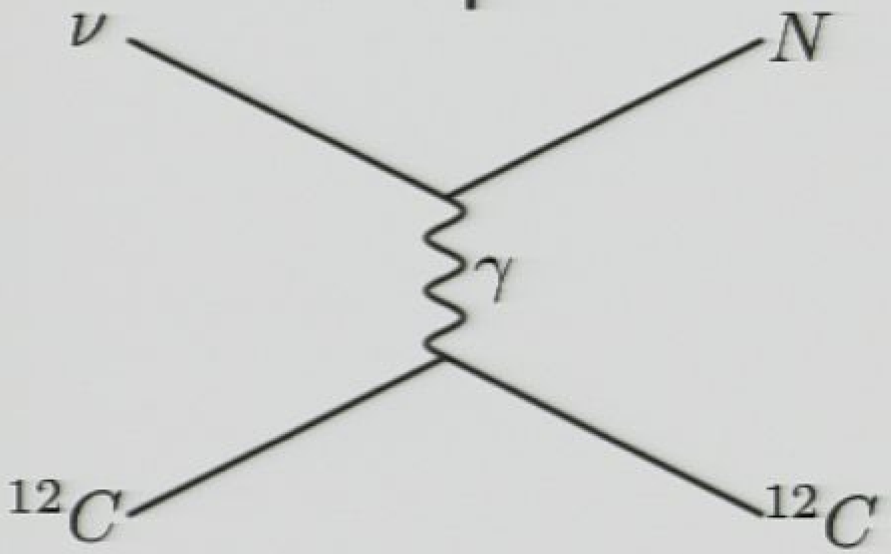

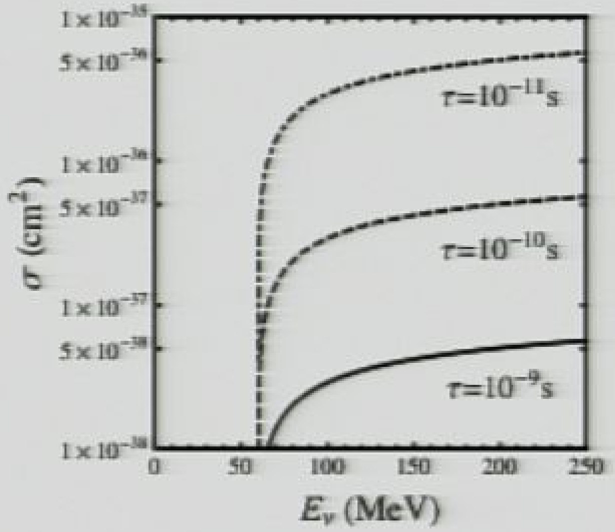

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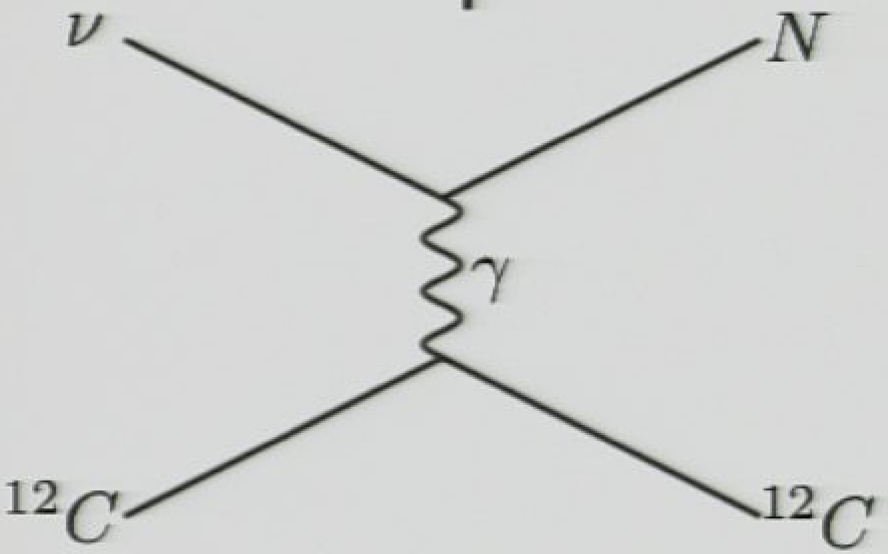

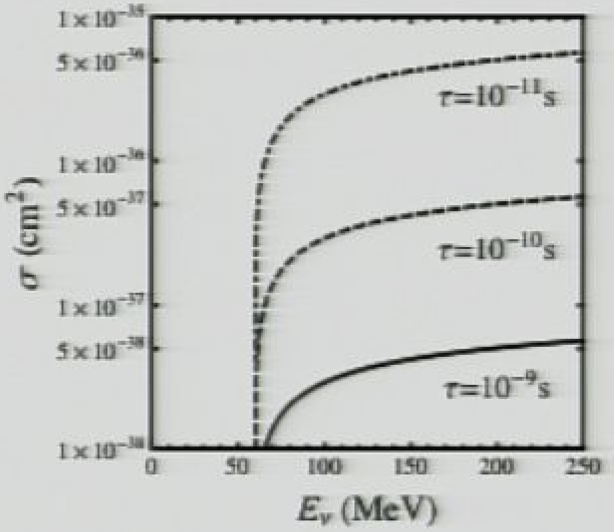

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Conclusions

- Neutrino experiment anomalies are interesting
- Radiatively decaying sterile neutrino proposed to explain them
- RMC measurements exclude this particular model
- Offer clues about a fix (maybe?)
- MC can say something about sterile neutrinos

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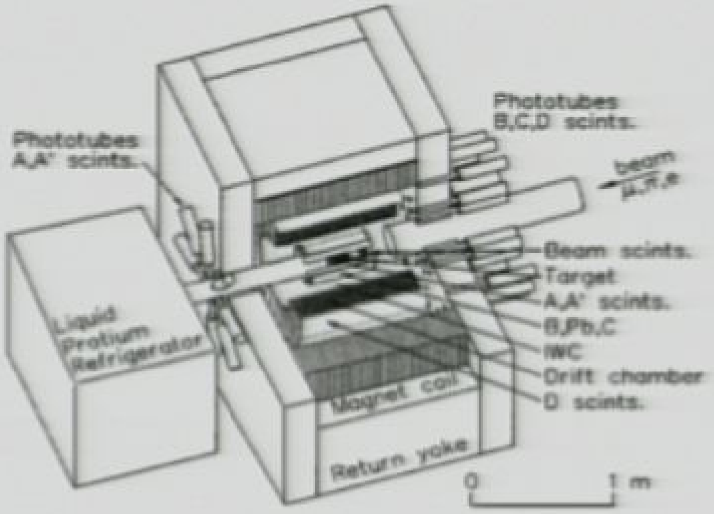

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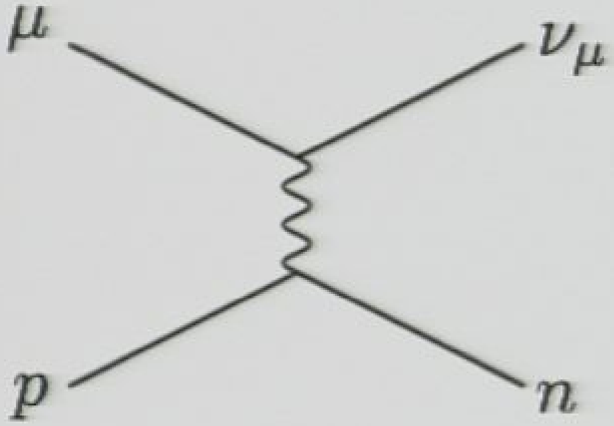
(Radiative) Muon Capture



OMC: $\mu p \to \nu n$

RMC: $\mu p \to \nu n \gamma$

Write the Hadronic portion of the OMC matrix elem. as:

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MC is the best source of info on g_P

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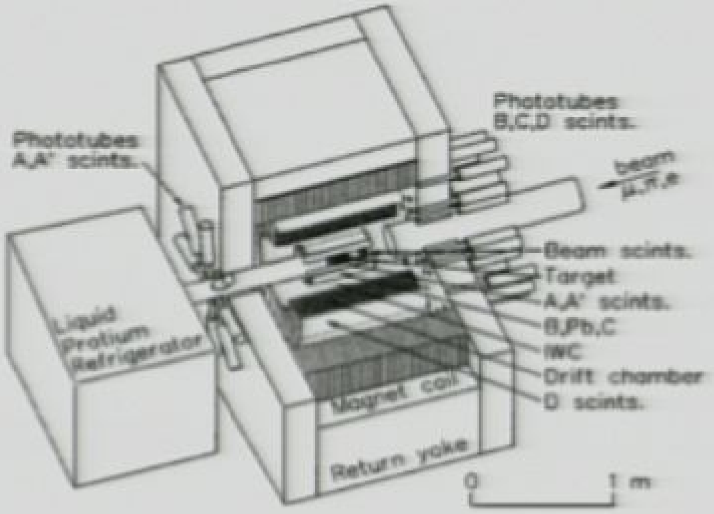

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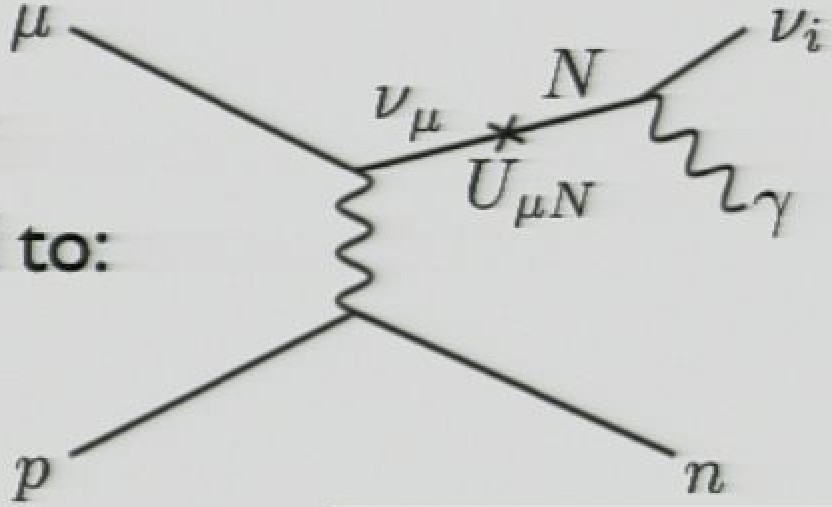

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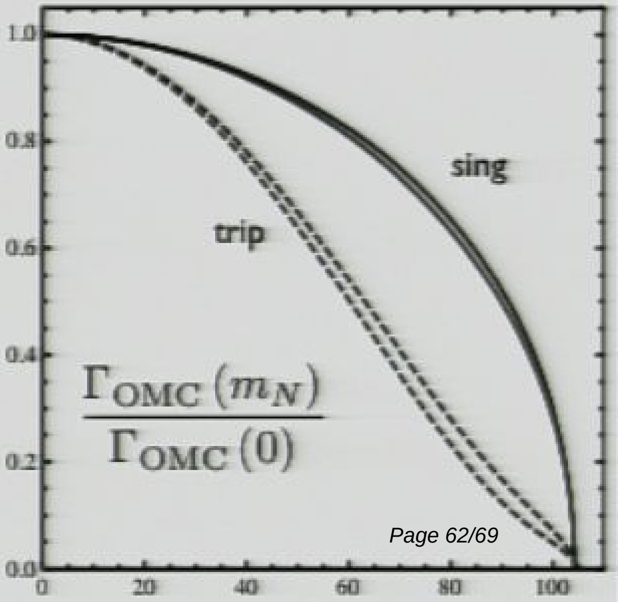

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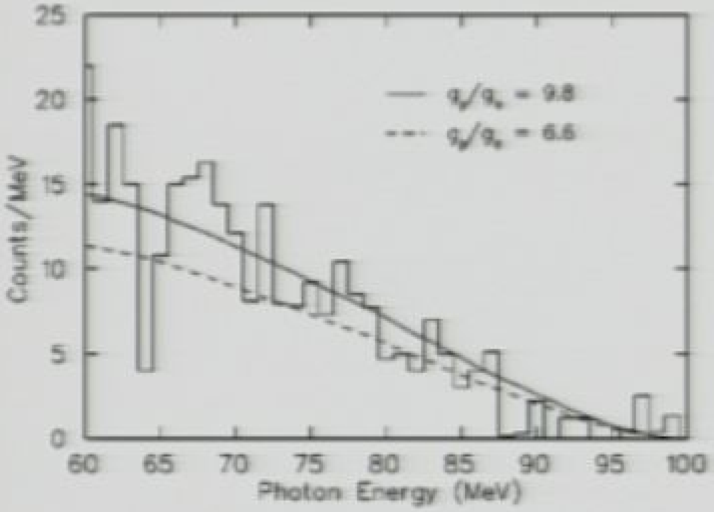

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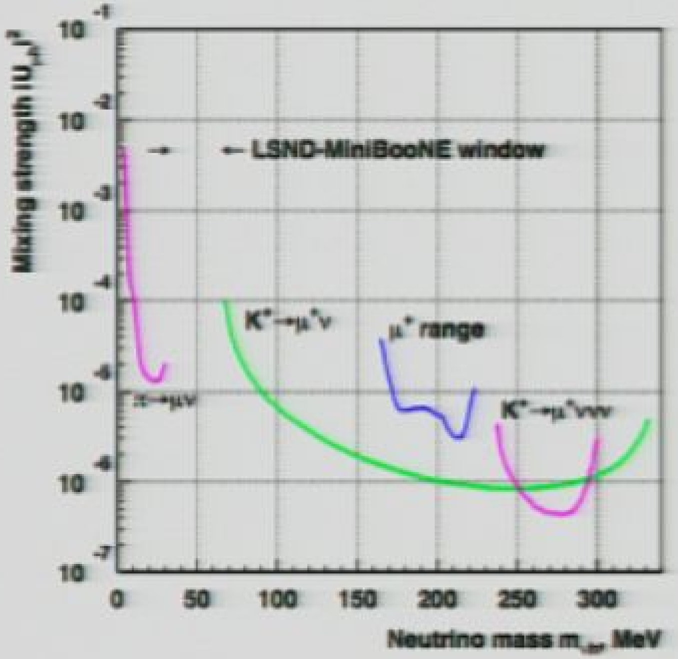

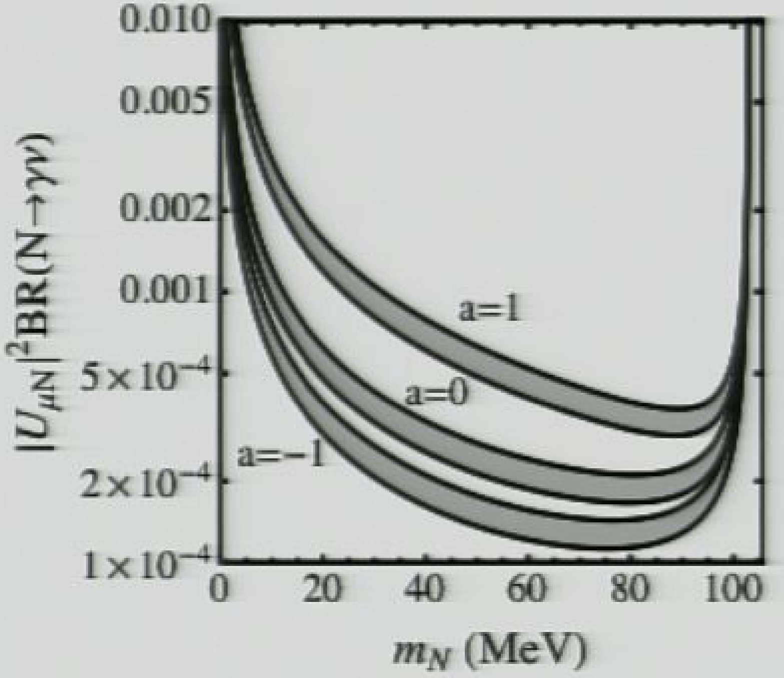

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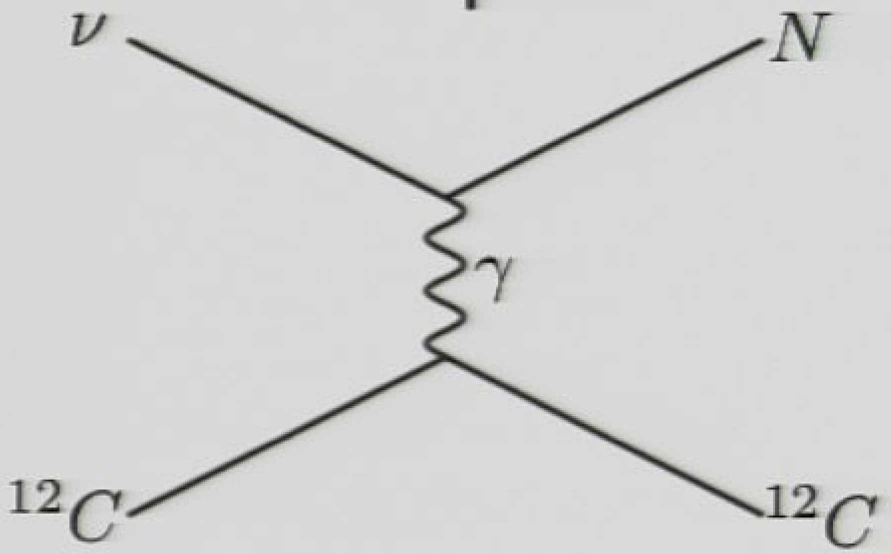

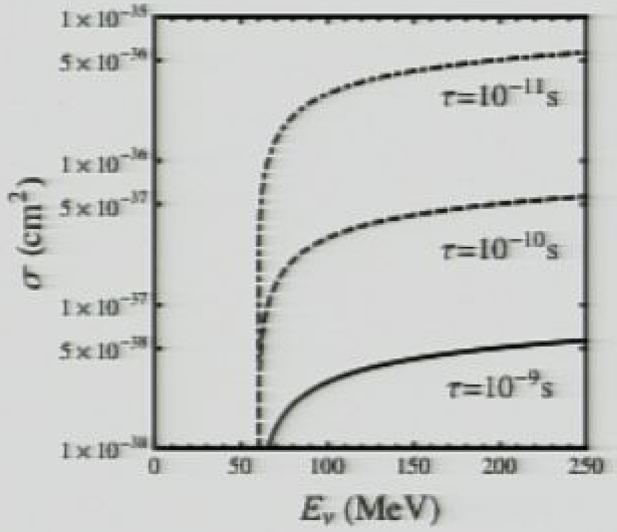

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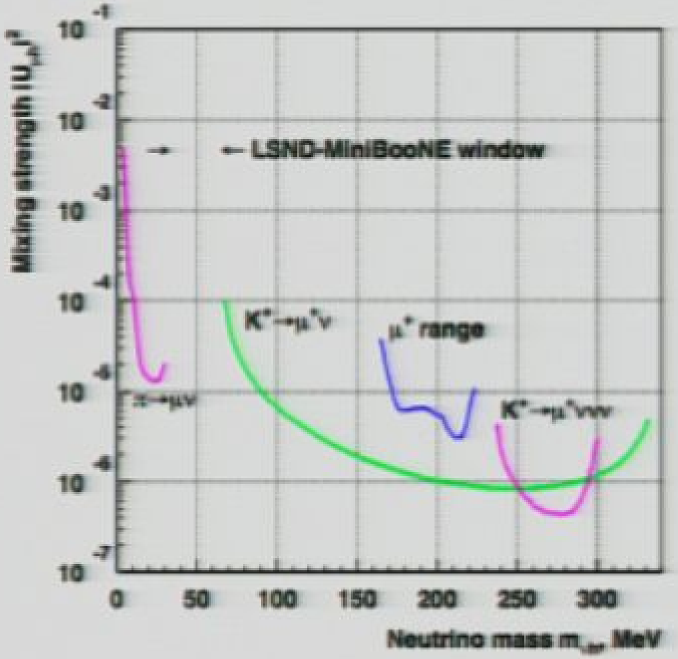

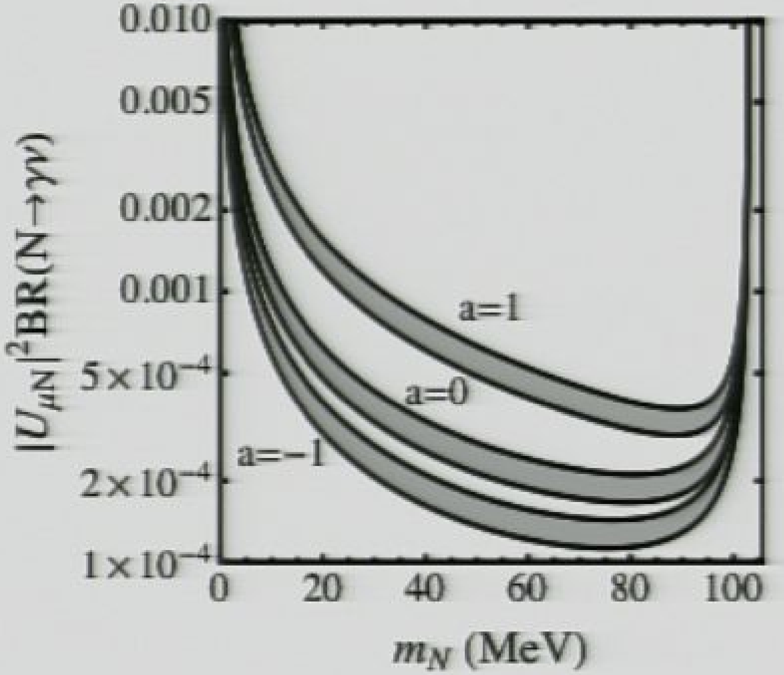

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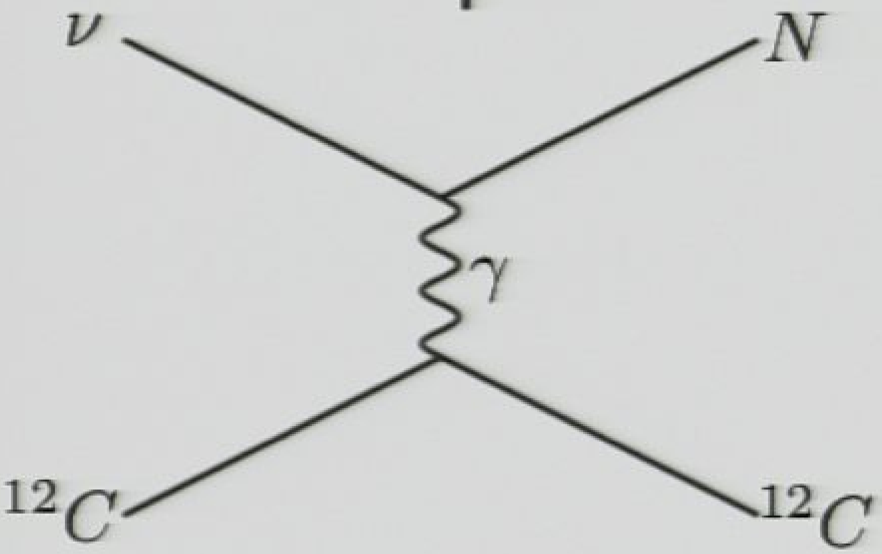

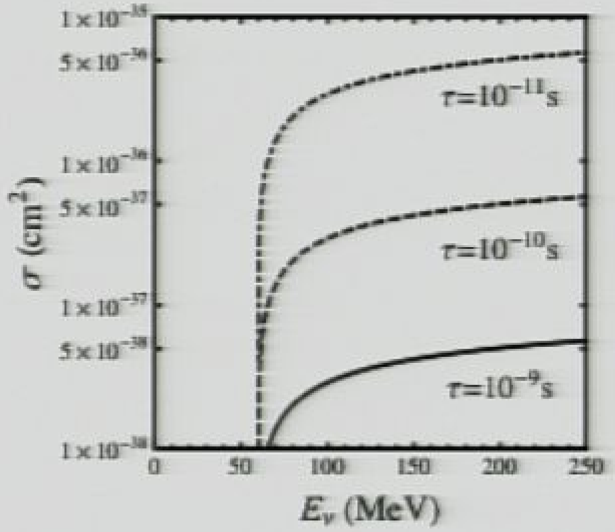

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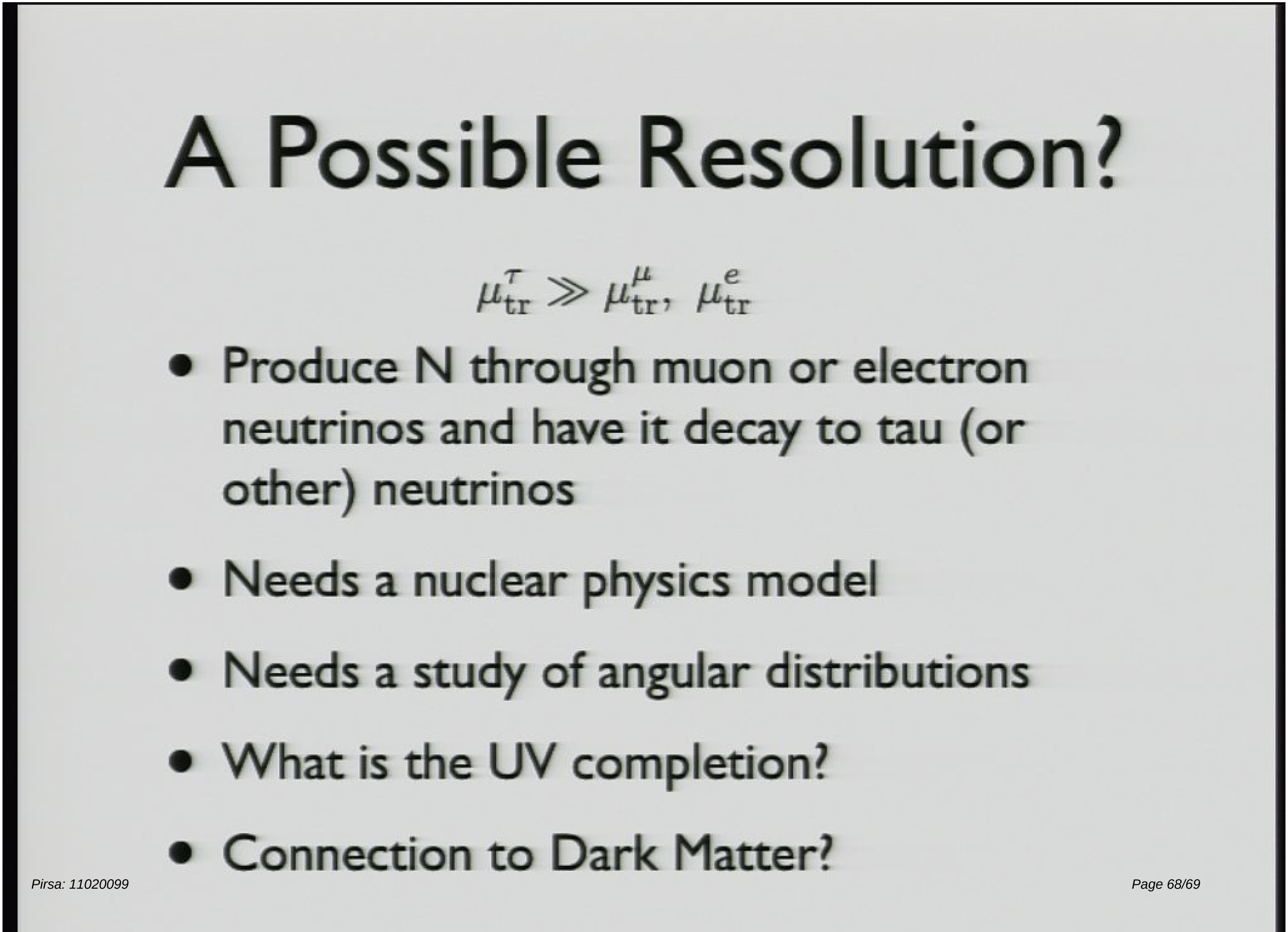

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