I: Non-Standard Neutrino Interactions
II Sterile neutrinos and Short Baseline Anomalies

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"Understanding the Universe through neutrinos"

ICTS, Bengaluru

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Helpful General References on Part I, NSI

Neutrino Non-Standard Interactions: A Status Report, P. S. Bhupal Dev et al, 1907.00991

Neutrino oscillations and Non-Standard Interactions, Y Farzan and M Tortola, 1710.09360

Non standard neutrino interactions: current status and future prospects, O Miranda and H Nunokawa, 1505.06254

Status of non-standard neutrino interactions, T Ohlsson, 1209.2710

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2(\theta_{23}) = 0.539 \pm 0.022 \quad (S = 1.1) \quad$ (Inverted order)

$\sin^2(\theta_{23}) = 0.546 \pm 0.021 \quad$ (Normal order)

$\Delta m^2_{32} = (-2.536 \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Inverted order)

$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Normal order)

$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

δ, CP violating phase $= 1.36^{+0.20}_{-0.16}\ \pi$ rad

★ Atmospheric, solar, reactor, accellerator based neutrino experiments have helped us determine neutrino mass and mixing parameters to within uncertainties.

★ While it is fairly clear that oscillations are dominantly responsible for observed excesses and deficits seen in the neutrino fluxes in these experiments, subdominant effects that have not yet been ruled out include NSI, decoherence and neutrino decay.

★ Are neutrinos Dirac or Majorana particles?

★

★ Is there CP violation in the leptonic sector?

★

★ Is the neutrino mass hierarchy normal or inverted?

★

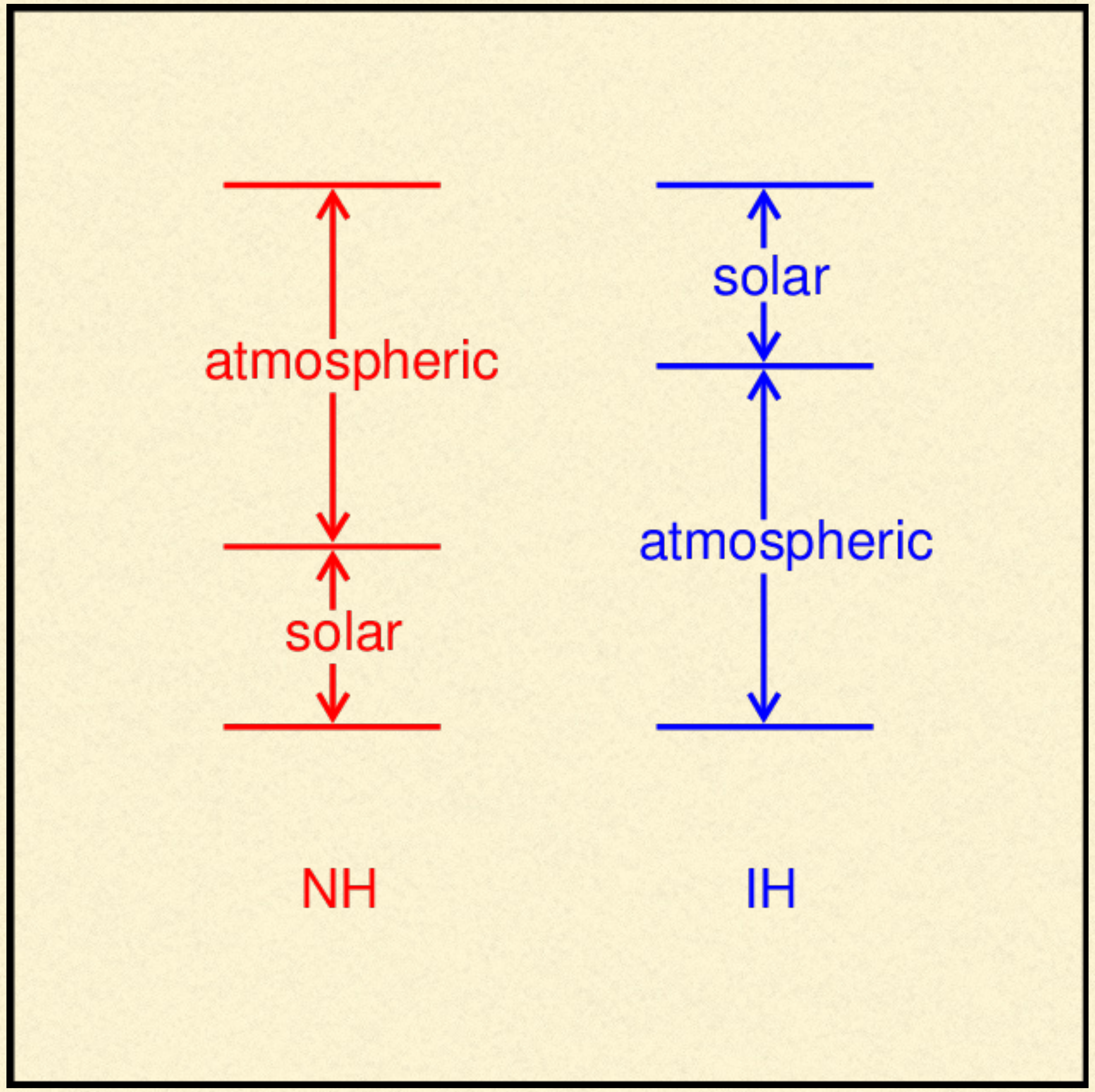
★ What are the absolute masses of neutrinos?

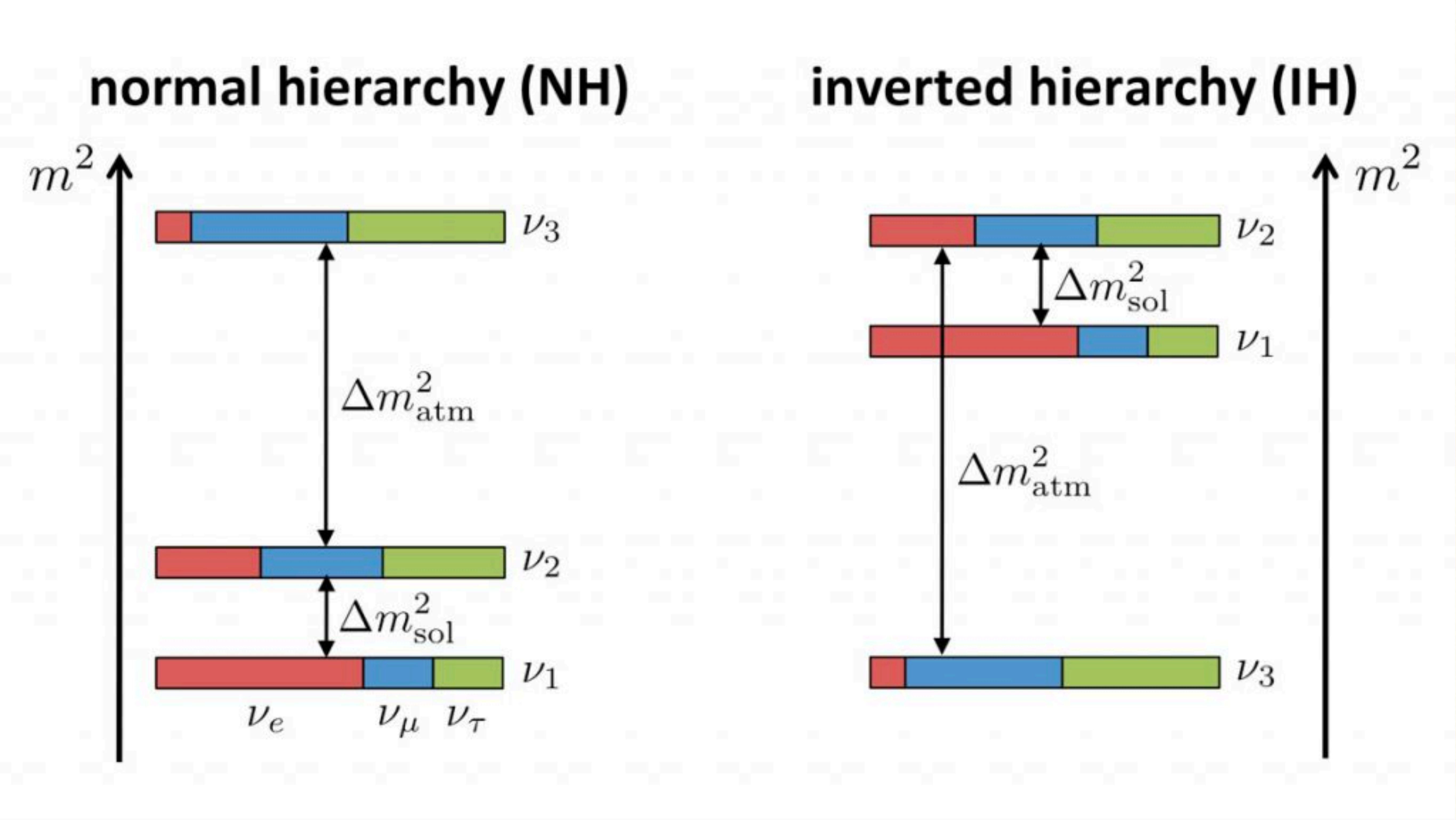
★

★ Are there additional light sterile neutrinos?

★

Mass hierarchy of neutrinos





Decoherence

One of the most essential ingredients in making the oscillation scenario work is that the spread in energy ΔE of the neutrino "beam" is not too wide.

If ΔE of the neutrino "beam" is wide then by the time the neutrinos arrive at the detector the oscillation patterns for neutrinos of different energies get sufficiently out of phase to dampen potentially observable oscillations

Decay

In transit, a neutrino may decay invisibly, e.g into sterile neutrinos which do not produce a signal in a detector.

It could decay visibly, say to another SM neutrino, which gets picked up in a downstream detector.

Both these "non-oscillation" mechanisms could modify neutrino signatures in oscillation experiments

Motivations for studying NSI.......

Generically, new interactions and couplings of neutrinos beyond those in the SM are termed and "Non-Standard Interactions" (NSI).

Such interactions could be present in the production, propagation and detection of neutrinos.

They could affect oscillation probability predictions and measurements made by existing and future experiments.

They could impact our efforts to answer the important unanswered questions about neutrinos listed earlier..

Motivations for studying NSI…….

It is important to emphasize that NSI are not necessarily some strange new beasts, but may very well arise from known BSM physics theories, like supersymmetry, GUT models, left-right models, compositeness, extra dimensional theories…….The term "NSI" is thus an umbrella categorization

It is also important to realise that existing neutrino data are quite well-described by the standard 3 family oscillation picture and the currently measured mass-squared differences and mixings. Hence additional interactions are very likely small effects, sub-dominant to the present understanding of SM interactions of neutrinos.

Despite their smallness and sub-dominance, it is important to study them because they could point towards physics beyond the SM.

Standard Neutrino oscillations…….in matter

E is the neutrino energy,

$$i\frac{d\nu}{dt} = \frac{1}{2E}\left[MM^\dagger + \mathrm{diag}(A,0,0)\right]\nu \equiv H\nu\,,$$

A = 2√ 2EGFNe is the effective matter potential

GF = (1.1663787 ± 0.0000006) × 10−5 GeV−2

N_e is the electron number density in matter

M = U Diag {m1,m2,m3) U^T is the neutrino mass matrix,

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix},$$

U relates the weak interaction eigenstates and the mass eigenstates through the leptonic mixing parameters θ_{12}, θ_{13}, θ_{23}, δ (the Dirac CP-violating phase)

Adding NSI……. (3 flavours)

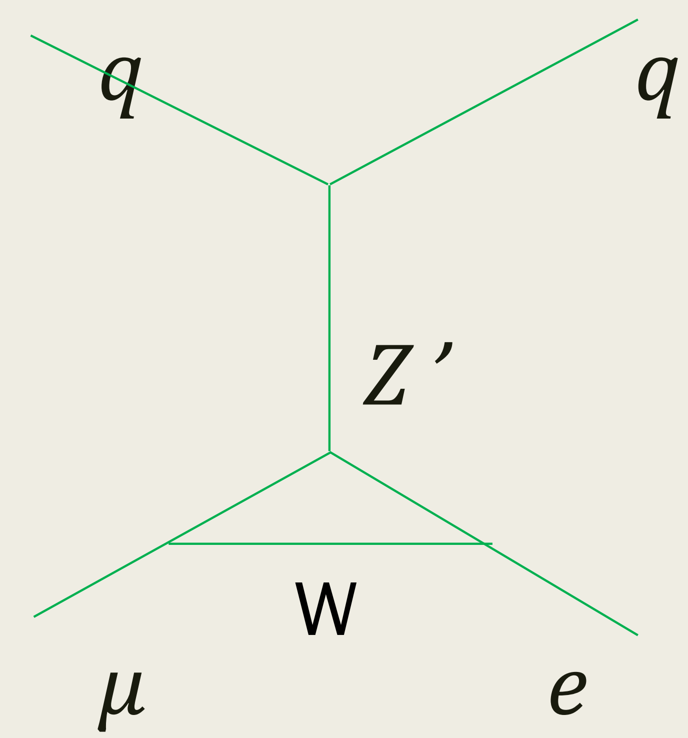
$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon^{fX}_{\alpha\beta}\,(\bar\nu_\alpha\gamma^\mu P_L\nu_\beta)\,(\bar f\gamma_\mu P_X f)$$

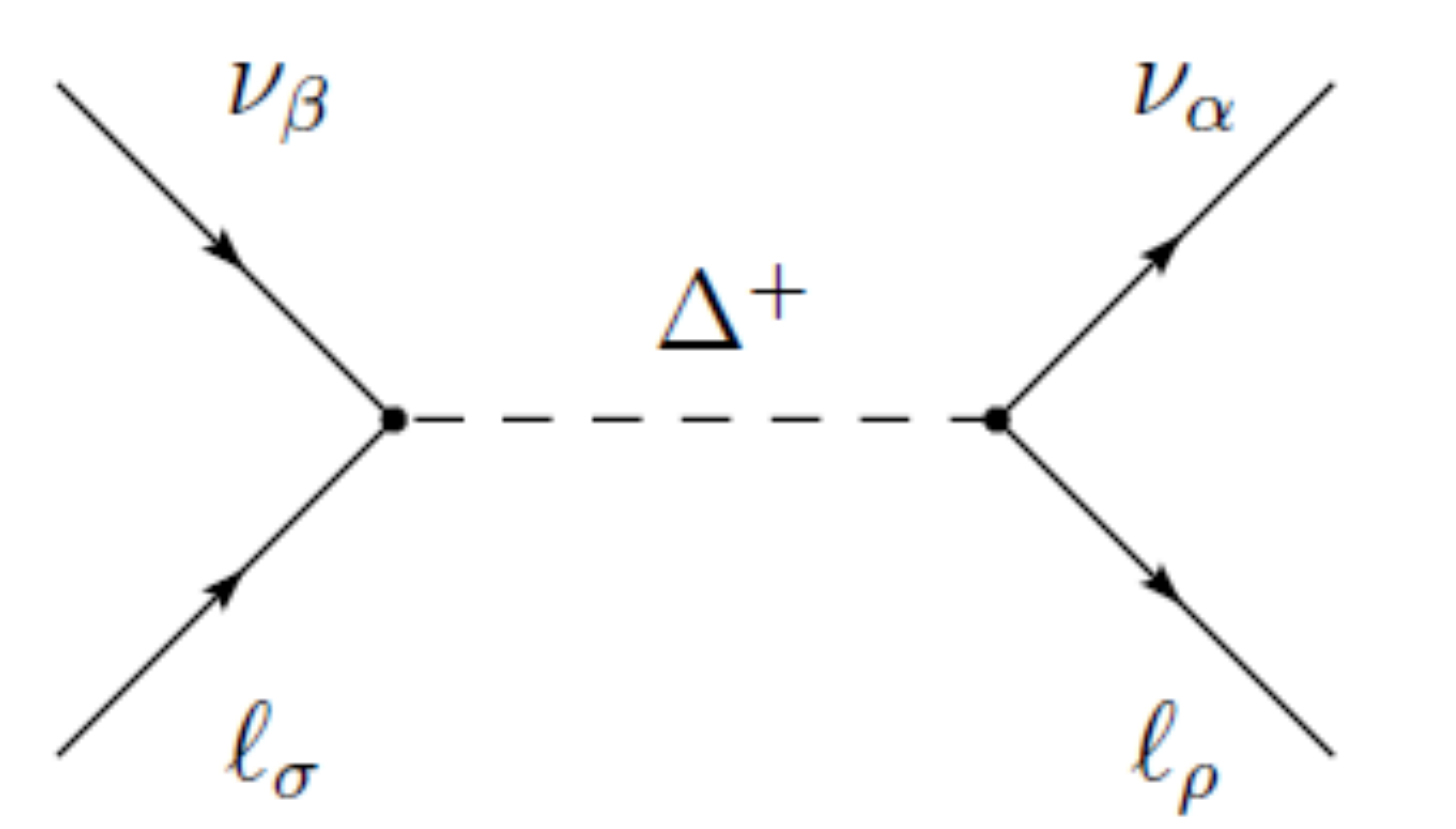
Neutral current NSI with matter fields

$$\mathcal{L}_{\mathrm{CC-NSI}} = -2\sqrt{2}G_F\,\epsilon^{ff'X}_{\alpha\beta}\,(\bar\nu_\alpha\gamma^\mu P_L\ell_\beta)\,(\bar f'\gamma_\mu P_X f)$$

Charged current NSI with matter fields f,f′

$$P_{R,L} = (1\pm\gamma_5)/2.$$





$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0&0&0\\0&\Delta m^2_{21}&0\\0&0&\Delta m^2_{31}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee}&\varepsilon_{e\mu}&\varepsilon_{e\tau}\\ \varepsilon^*_{e\mu}&\varepsilon_{\mu\mu}&\varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau}&\varepsilon^*_{\mu\tau}&\varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}.$$

Standard Two flavour oscillations in matter

$$P_M(\nu_e \to \nu_\mu) = \sin^2 2\theta^M \sin^2\left(\Delta m^2_M \frac{L}{4E}\right) .$$

$$\Delta m^2_M \equiv \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

$$\sin^2 2\theta^M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2} ,$$

$$\mathcal{H}_M = \frac{\Delta m^2_M}{4E}\begin{pmatrix} -\cos 2\theta^M & \sin 2\theta^M \\ \sin 2\theta^M & \cos 2\theta^M \end{pmatrix} .$$

Standard Two flavour oscillations in matter with NSI

$$P(\nu_e \to \nu_\tau) = \sin^2 2\theta_M \ \sin^2\left(\frac{\Delta m^2_M L}{4E}\right)$$

$$\left(\frac{\Delta m^2_M}{2EA}\right)^2 \equiv \left(\frac{\Delta m^2}{2EA}\cos 2\theta - (1 + \epsilon_{ee} - \epsilon_{\tau\tau})\right)^2 + \left(\frac{\Delta m^2}{2EA}\sin 2\theta + 2\epsilon_{e\tau}\right)$$

$$\sin 2\theta_M \equiv \frac{\Delta m^2 \sin 2\theta + 4EA\epsilon_{e\tau}}{\Delta m^2_M}$$

$\varepsilon_{ee}, \varepsilon_{e\tau}, \varepsilon_{\tau\tau} \to 0,$ Gives us back the standard matter oscillations

We thus see that measurements of mass-squared differences and mixing angles can be affected by the presence of NSI when we study neutrino oscillations in matter.

Three flavour oscillations in matter with NSI

$$P(\nu_\alpha \to \nu_\alpha; L) = 1 - 4\sum_{i>j} |\tilde{U}_{\alpha i}\tilde{U}^*_{\alpha j}|^2 \sin^2\left(\frac{\Delta\tilde{m}^2_{ij}L}{4E}\right) ,$$

$$P(\nu_\alpha \to \nu_\beta; L) = -4\sum_{i>j} \mathrm{Re}\left(\tilde{U}^*_{\alpha i}\tilde{U}_{\beta i}\tilde{U}_{\alpha j}\tilde{U}^*_{\beta j}\right) \sin^2\left(\frac{\Delta\tilde{m}^2_{ij}L}{4E}\right) - 8\mathcal{J}\prod_{i>j}\sin\left(\frac{\Delta\tilde{m}^2_{ij}L}{4E}\right)$$

$$\mathcal{J}^2 = |\tilde{U}_{\alpha i}|^2|\tilde{U}_{\beta j}|^2|\tilde{U}_{\alpha j}|^2|\tilde{U}_{\beta i}|^2 - \frac{1}{4}\Big(1 + |\tilde{U}_{\alpha i}|^2|\tilde{U}_{\beta j}|^2 + |\tilde{U}_{\alpha j}|^2|\tilde{U}_{\beta i}|^2 - |\tilde{U}_{\alpha i}|^2 - |\tilde{U}_{\beta j}|^2 - |\tilde{U}_{\alpha j}|^2 - |\tilde{U}_{\beta i}|^2\Big)^2 .$$

D. Meloni, T. Ohlsson, and H. Zhang, arXiv:0901.1784
T Ohlsson, 1209.2710

Three flavour oscillations in matter with NSI

$$\tilde{U}_{e2} \simeq \frac{\alpha s_{12} c_{12}}{\hat{A}} + c_{23}\varepsilon_{e\mu} - s_{23}\varepsilon_{e\tau}\,,$$

$$\tilde{U}_{e3} \simeq \frac{s_{13} \mathrm{e}^{-\mathrm{i}\delta}}{1-\hat{A}} + \frac{\hat{A}(s_{23}\varepsilon_{e\mu} + c_{23}\varepsilon_{e\tau})}{1-\hat{A}}\,,$$

$$\tilde{U}_{\mu 2} \simeq c_{23} + \hat{A} s_{23}^2 c_{23} \left(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}\right) + \hat{A} s_{23} \left(s_{23}\varepsilon_{\mu\tau} - c_{23}^2 \varepsilon_{\mu\tau}^*\right)\,,$$

$$\tilde{U}_{\mu 3} \simeq s_{23} + \hat{A}\left[c_{23}\varepsilon_{\mu\tau} + s_{23} c_{23}^2 \left(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}\right) - s_{23}^2 c_{23} \left(\varepsilon_{\mu\tau} + \varepsilon_{\mu\tau}^*\right)\right]\,,$$

$$\tilde{m}_1^2 \simeq \Delta m_{31}^2 \left(\hat{A} + \alpha s_{12}^2 + \hat{A}\varepsilon_{ee}\right)\,,$$

$$\tilde{m}_2^2 \simeq \Delta m_{31}^2 \left[\alpha c_{12}^2 - \hat{A} s_{23}^2 \left(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}\right) - \hat{A} s_{23} c_{23} \left(\varepsilon_{\mu\tau} + \varepsilon_{\mu\tau}^*\right) + \hat{A}\varepsilon_{\mu\mu}\right]\,,$$

$$\tilde{m}_3^2 \simeq \Delta m_{31}^2 \left[1 + \hat{A}\varepsilon_{\tau\tau} + \hat{A} s_{23}^2 \left(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}\right) + \hat{A} s_{23} c_{23} \left(\varepsilon_{\mu\tau} + \varepsilon_{\mu\tau}^*\right)\right]\,,$$

D. Meloni, T. Ohlsson, and H. Zhang, arXiv:0901.1784
T Ohlsson, 1209.2710

NSI at production at the neutrino source.......

$$\pi^+ \to \mu^+ + \nu_\mu , \quad \mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e , \quad n \to p + e^- + \overline{\nu}_e$$

Examples of standard production,

$$\pi^+ \to \mu^+ + \nu_e , \quad \mu^+ \to e^+ + \overline{\nu}_\mu + \nu_\mu , \quad n \to p + e^- + \overline{\nu}_\mu$$

Examples of non-standard production,

NSI at detection ....

$$\nu_\mu + n \to p + \mu^-$$

Example of standard detection

$$\nu_e + n \to p + \mu^-$$

Example of non-standard detection

Such interactions, which lead to non-standard effects during the production or the detection of a neutrino involve charged current processes, and may arise from a term such as

$$\mathcal{L}_{\mathrm{CC-NSI}} = -2\sqrt{2}G_F\,\epsilon^{f f' X}_{\alpha\beta}\,(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta)\left(\bar{f}'\gamma_\mu P_X f\right)$$

Here f and f' are different fermions

On the other hand, coherent effects over long baselines which affect oscillation probabilities stem from a term that produces NSI in neutral currents,

$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon^{f X}_{\alpha\beta}\,(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)$$

$$P_{R,L} = (1 \pm \gamma_5)/2.$$

Examining NSI parameters as stemming from an underlying gauge theory

$$H = \frac{1}{2E}\left[U_{\mathrm{PMNS}}\begin{pmatrix}0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger_{\mathrm{PMNS}} + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

$$\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}|e^{i\phi_{\alpha\beta}}\,.$$

While the diagonal terms are real , the off diagonal parameters can be complex, and thus interfere in CP measurements.

One would like to associate an underlying gauge structure for NSIs, as opposed to simply parametrising them effectively as we have done so far.

Example of a simple underlying gauge theory for NSI

$$-2\sqrt{2}G_F\,\epsilon^{fX}_{\alpha\beta}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\,(\bar{f}\gamma_\mu P_X f)$$

Consider a new Z' with mass M_X associated with a new U(1) group with gauge coupling g_X

$$Z'_\mu\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta \qquad Z'_\mu\bar{f}\gamma^\mu P_X f$$

Then $\varepsilon \sim g_X^2 m_W^2/m_X^2.$

Note that if the new gauge boson is much heavier than the electroweak scale, the couplings may become unobservable small.

$m_X \ll m_W$ and $g_X \ll 1$

Where weak couplings and a low mass gauge boson are combined, one may have observability.

$$\varepsilon \sim g_X^2 m_W^2/m_X^2.$$

Hence, for new physics appearing at 1 (10)TeV, one expects $\varepsilon_{\alpha\beta} \sim 10^{-2}(10^{-4})$

Putting constraints on NSI…………

Requiring that the new theory preserve $SU(2)_L \times U(1)$ gauge invariance at high energies immediately leads to strong constraints

Consider the 6-dimensional operator in effective theory which yields an effective NSI parameter leading to, say $\varepsilon^{ee}_{e\mu}$

$$\frac{1}{\Lambda^2}(\bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta)\,(\bar{\ell}_\gamma \gamma_\rho \ell_\delta)$$

To preserve gauge invariance, this must be part of a general SU(2) x U(1) operator

$$\frac{1}{\Lambda^2}(\bar{L}_\alpha \gamma^\rho L_\beta)\,(\bar{L}_\gamma \gamma_\rho L_\delta\,)$$

Applying this to an interaction with 4 charged leptons, where constraints are tight,

$$\mu \to 3\,e: \quad \mathrm{BR}(\mu \to 3e) < 10^{-12}$$

$\Rightarrow$

$$\varepsilon^{ee}_{e\mu} < 10^{-6}$$

Putting constraints on NSI…………atmospheric neutrinos

Atmospheric neutrinos are very sensitive to matter NSIs, since they travel over long distances inside the Earth before being detected, and $\nu_\mu \leftrightarrow \nu_\tau$ oscillations are important.

Further, a two flavour approximation can be made,

$$i\frac{d}{dL}\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 \\ 0 & \Delta m^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix} .$$

$$P(\nu_\mu \to \nu_\mu; L) = 1 - P(\nu_\mu \to \nu_\tau; L) = 1 - \sin^2(2\Theta)\sin^2\left(\frac{\Delta m^2 L}{4E}R\right) ,$$

$$\sin^2(2\Theta) = \frac{1}{R^2}\left[\sin^2(2\theta) + R_0^2\sin^2(2\xi) + 2R_0\sin(2\theta)\sin(2\xi)\right] ,$$
$$R = \sqrt{1 + R_0^2 + 2R_0\left[\cos(2\theta)\cos(2\xi) + \sin(2\theta)\sin(2\xi)\right]}$$

$$R_0 = \sqrt{2}G_F N_e \frac{4E}{\Delta m^2}\sqrt{|\varepsilon|^2 + \frac{\varepsilon'^2}{4}} ,$$
$$\xi = \frac{1}{2}\arctan\left(\frac{2\varepsilon}{\varepsilon'}\right) .$$

Putting constraints on NSI…………atmospheric neutrinos

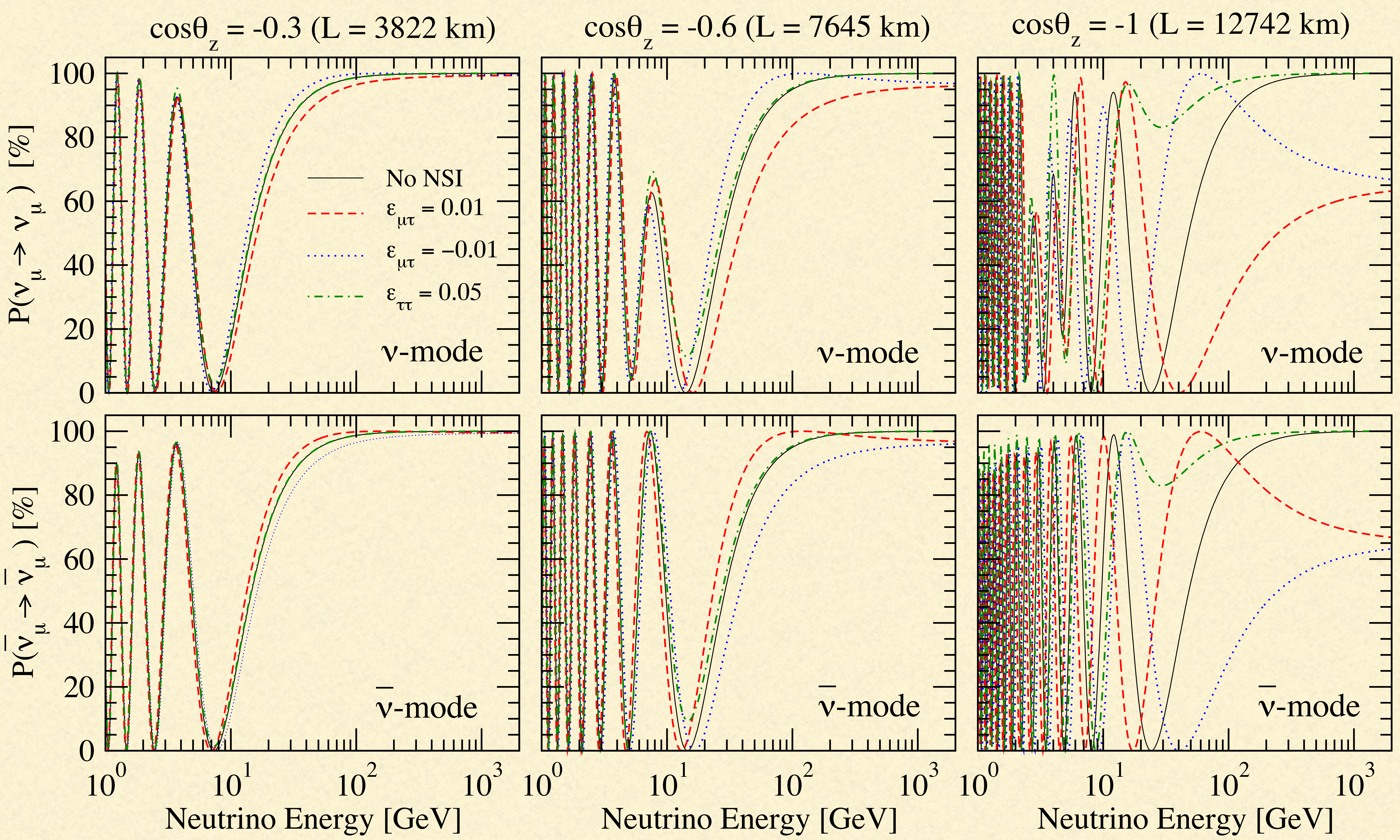
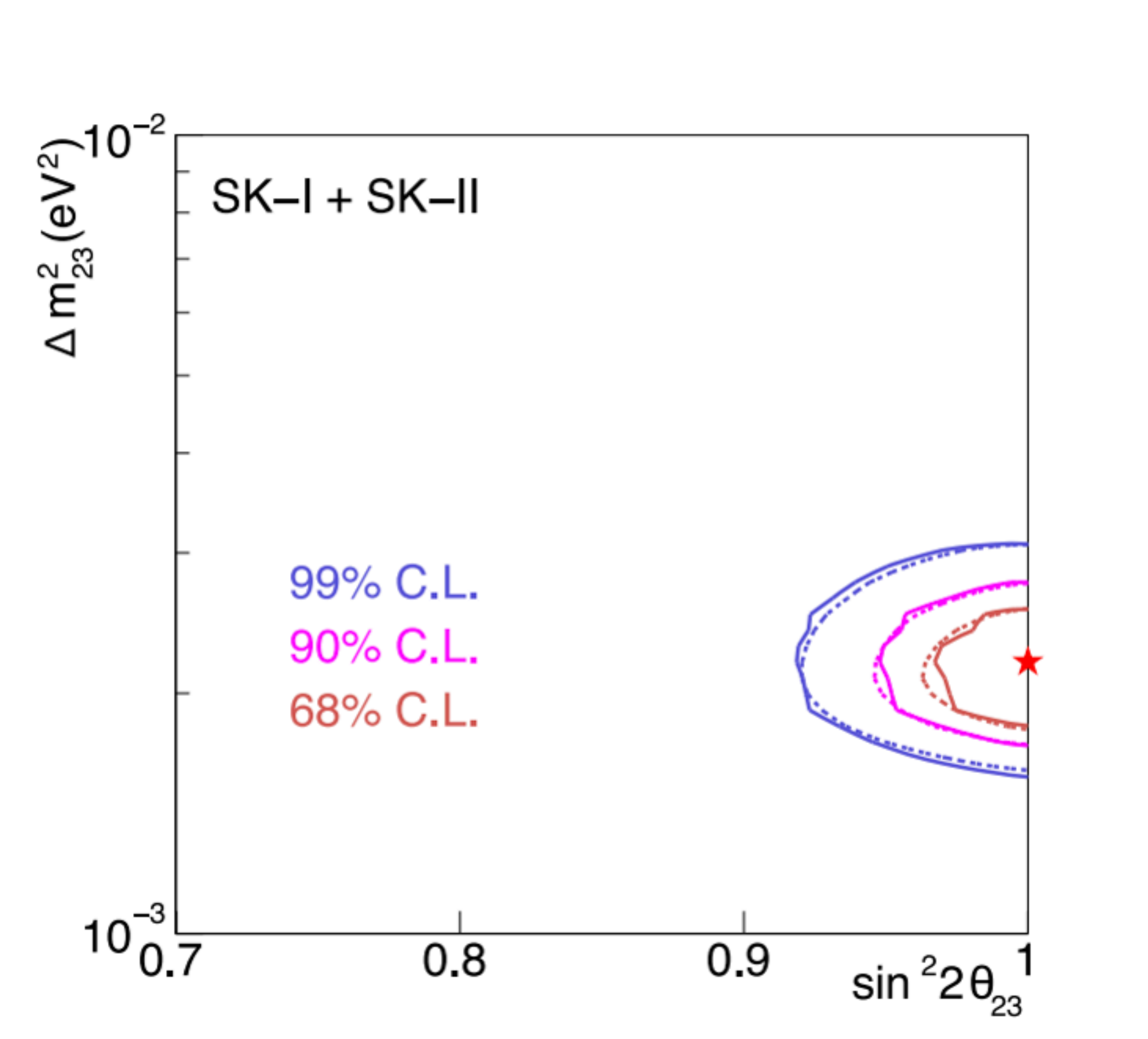


Figure 1. Survival probabilities of $\nu_\mu \to \nu_\mu$ (upper panels) and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ (lower panels) as a function of the neutrino energy for different zenith angle of incoming neutrinos, $\cos\theta_z = -0.3$ (left panels), -0.6 (middle panels) and -1 (right panels). The corresponding distances traveled by neutrinos are indicated in the plots. The normal mass ordering was assumed.



Solid lines: with NSI
Dashed lines: Normal oscillations

Miranda and Nunokawa, 1505.06254

Putting constraints on NSI…………detection of reactor neutrinos

Nuclear reactor experiments usually have short or medium baselines, and hence effects of matter and NSI in propagation can be neglected.

Their energy is around a few MeV,

NSI may thus arise only at source (production) or in the detector.

Constraints will arise based on the deviation in the survival probability standard (known) reactor flux and standard oscillations, i.e. measurements of $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ are done at source (LHS) and detector (RHS) and compared to expectations.

Thus at reactors, the relevant NSI parameters which can be constrained are $\varepsilon^f_{e\mu}$ $\varepsilon^f_{e\tau}$ ε^f_{ee}

Putting constraints on NSI………..detection of reactor neutrinos $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$

$T_e \equiv E_e - m_e$

$$\frac{d\sigma}{dT_e} = \frac{2G_F^2 m_e}{\pi}\Bigg[(g_R+\varepsilon^R_{ee})^2 + \sum_{\alpha\neq e}|\varepsilon^R_{\alpha e}|^2 + \left\{(g_L+\varepsilon^L_{ee})^2 + \sum_{\alpha\neq e}|\varepsilon^L_{\alpha e}|^2\right\}\left(1-\frac{T_e}{E_\nu}\right)^2 - \left\{(g_L+\varepsilon^L_{ee})(g_R+\varepsilon^R_{ee}) + \sum_{\alpha\neq e}|\varepsilon^L_{\alpha e}||\varepsilon^R_{\alpha e}|\right\} m_e\frac{T_e}{E_\nu^2}\Bigg]. \quad (26$$

Flavour diagonal NSI give linear corrections,

Flavour changing NSI give quadratic corrections,

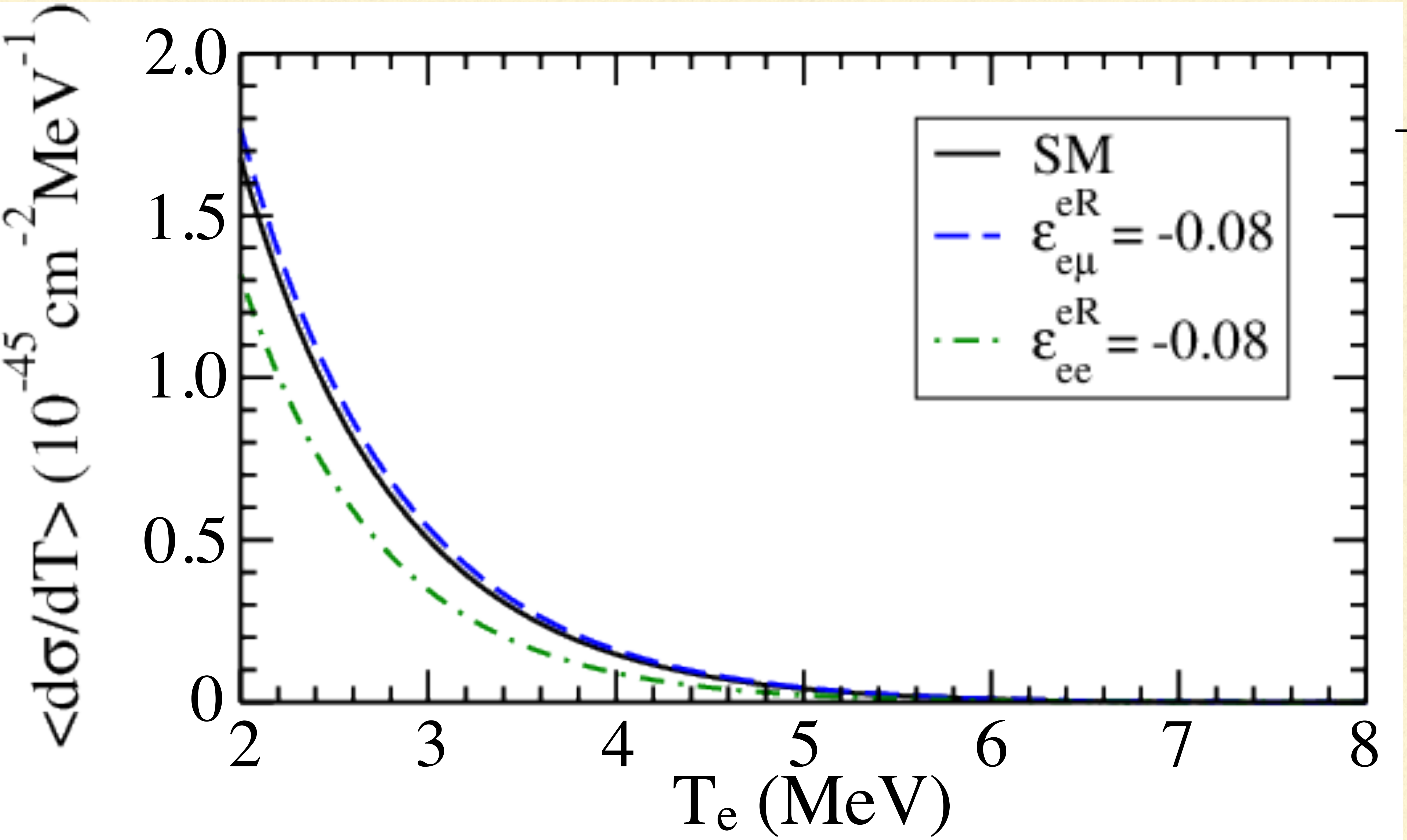


Figure 4. Averaged differential cross section for the electron anti-neutrino scatterin off electrons for the SM case (black solid line), for a flavor changing NSI (blue dashe line), and for a flavor conserving NSI (green dashed dotted line). The reactor ant neutrino flux has been considered in order to integrate the anti-neutrino cross sectio over the appropriate neutrino energy range

Miranda and Nunokawa, 1505.06254

Putting constraints on NSI…………detection of reactor neutrinos

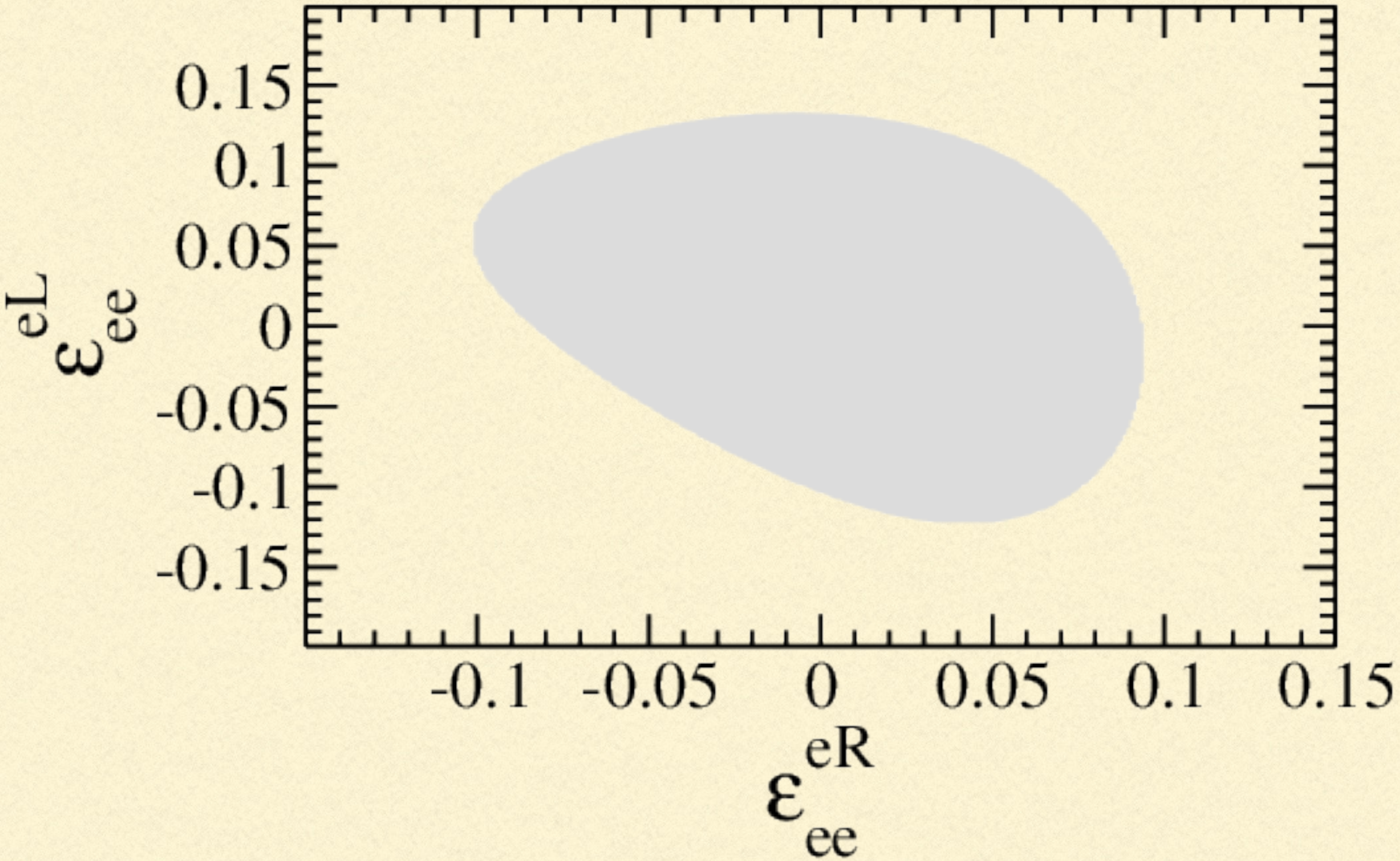


Figure 5. Allowed region, at 90 % CL, for diagonal NSI parameters, $\varepsilon_{ee}^{L,R}$, from a combined analysis of TEXONO reactor anti-neutrino and LSND neutrino electron scattering off electrons.

The NSI parameters for this reaction can be constrained by considering, for example, the data from the TEXONO collaboration, which use $\bar{\nu}$ee scattering as the detection signal

Usually one combines more than one experiment to get better constraints

NSI at low energies……..

The conventional formalism studied so far mainly looks at new physics in neutrinos at high energies.

It assumes heavy particles and loop contributions which can be integrated out and cast in the form $\varepsilon \sim g_X^2 m_W^2 / m_X^2$.

The absence of new physics discoveries at the LHC have spiked interest in searching for new physics at low energies. Such physics must be weakly (feebly) coupled . It could involve Low energy NSI of neutrinos and may show itself in anomalies at neutrino and DM detectors.

Such NSI of neutrinos may not be easily cast into the formalism studied here……

Conclusions………..

Among anomalous observations at neutrino experiments, their flavour transitions are the most studied, using oscillations and matter effects.

At present, a fairly accurate picture of SM neutrino interactions explains all the oscillation data well across many experiments, giving us a handle on their mixings and mass-squared differences.

Given the uncertainties, however, NSI could be playing a subdominant role in oscillations and neutrino scattering. Exploring NSI thus opens a window to new physics at high energy scales.

It could play a subdominant role in the physics of production, detection and propagation of neutrinos in matter.

Conclusions………..cont'd

Analytic expressions for both 2 and 3 flavour standard oscillations in matter can be recast to include NSI. This underlines the fact that measurements made in experiments may hide subdominant effects of new physics.

Unravelling these effects would require the help of multiple experiments due to degeneracies.

Existing neutrino experiments can be used to constrain NSI parameters, e.g data from atmospheric, reactor, coherent elastic neutrino-nucleus scattering long-baseline accelerator experiments etc.

If BSM physics resides at low energies, a somewhat different approach from the standard NSI parameters discussed here may be necessary.

Short Baseline Anomalies and Sterile Neutrinos:

Status and Perspectives

Initial remarks.......

Generically, any neutral lepton that is a singlet under the gauge groups of the Standard Model (SM) is loosely referred to as a sterile neutrino. Their mass can range from light to very heavy. Heavier ones are generically called HNLs (heavy neutral leptons)

Sterile neutrinos have come to play an increasingly important role in present-day attempts to take our current understanding beyond the standard model (BSM).

Sterile neutrinos which are heavy (~>> GeV or more) have been invoked to explain the smallness of neutrino masses via the seesaw mechanism.

Over the past couple of decades, a number of anomalous results have been observed in experiments which involve the production and detection of neutrinos over short baselines (< 1 km). Sterile neutrino oscillations of mass ~ eV have been invoked to understand them and comprise a major proposed solution to resolve them.

Initial remarks……. (Contd)

Sterile neutrinos which are heavy (mass >> 100 GeV) have been invoked to explain the baryon asymmetry of the Universe.

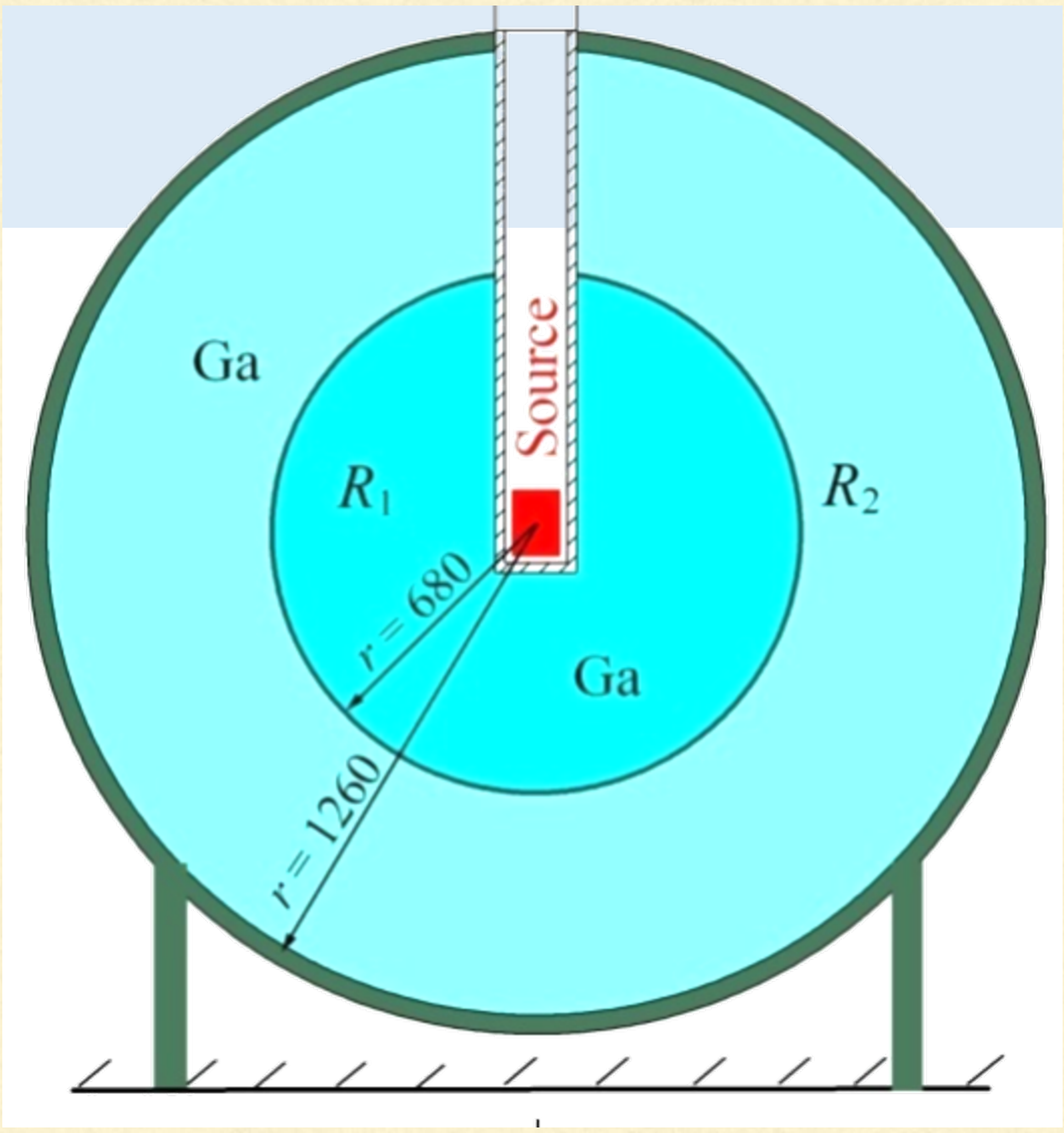
Sterile neutrinos which have masses in ~keV or higher range have also been considered as dark matter candidates. (e.g Dodelson-Widrow mechanism)

Finally, most recently, HNLs play an important role in explaining the short baseline anomalies via new physics (non-oscillation) mechanisms.

Anomalies at Short Baselines…….1) The Gallium source Anomaly

Intense radioactive sources (e.g. Cr, Ar) with well-determined neutrino spectra are used. These neutrinos are captured by $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

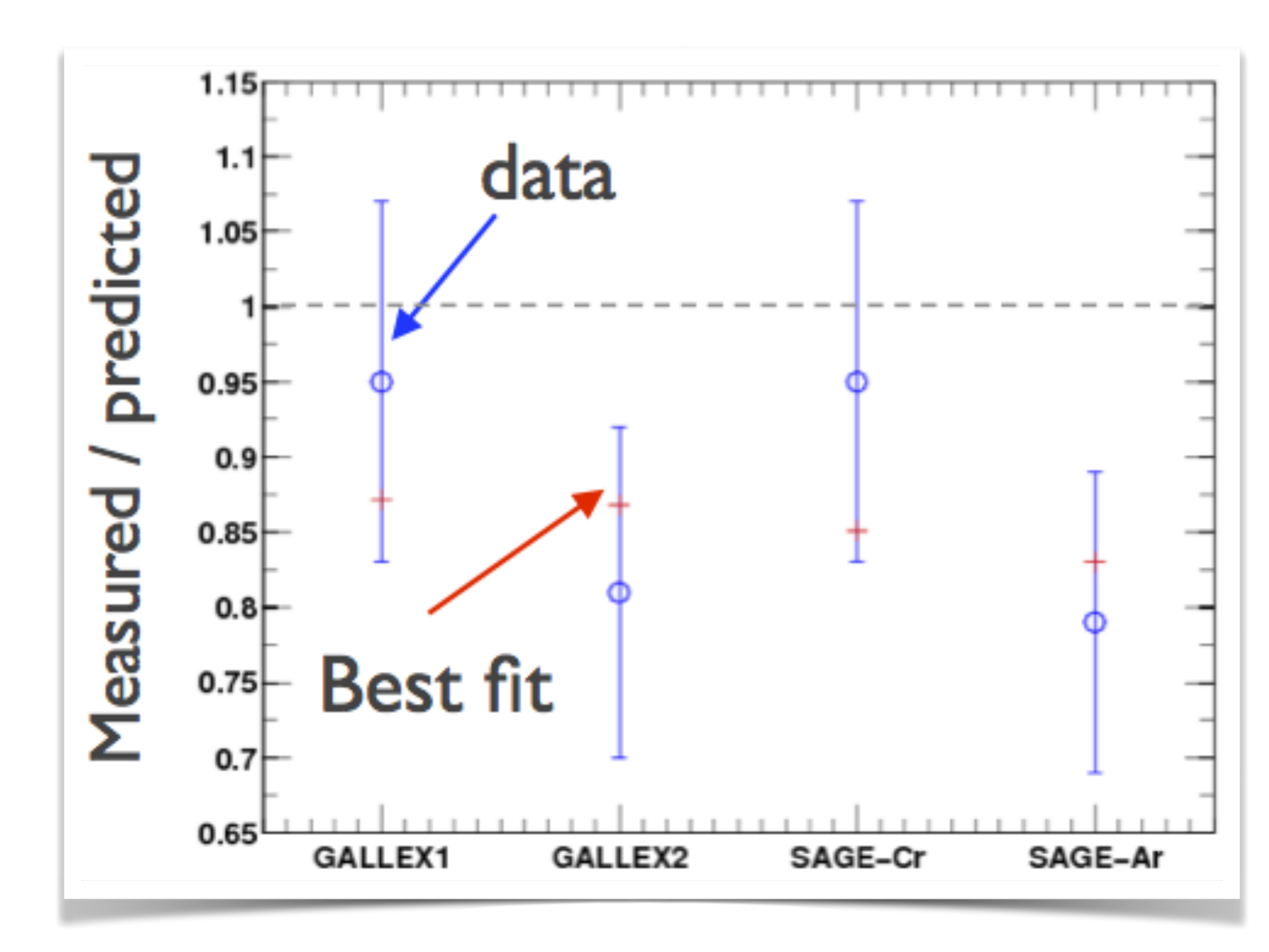
Baselines over which the decay neutrinos propagate are very short, ~ 1 m. However, in the latest experiment (BEST) 2 target zones are created, to see evidence of oscillations.



- Radio chemistry for extraction and counting of the ^{71}Ge was developed in SAGE solar measurements. and is well understood

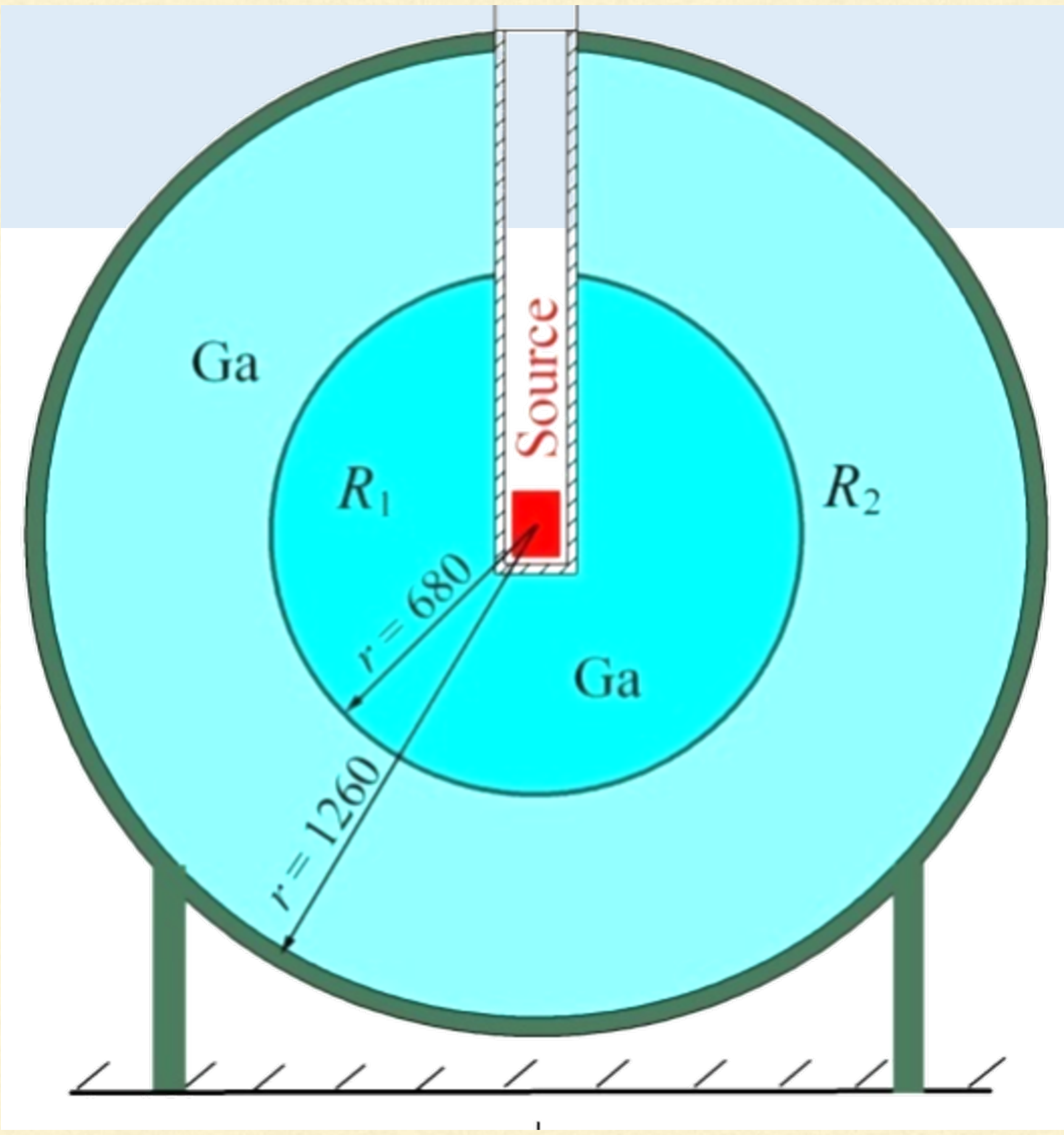
Anomalies at Short Baselines…….2) The Gallium source Anomaly

Earlier experiments, SAGE and Gallex, had reported a deficit in the neutrino flux. (R = 0.87 \pm 0.05)



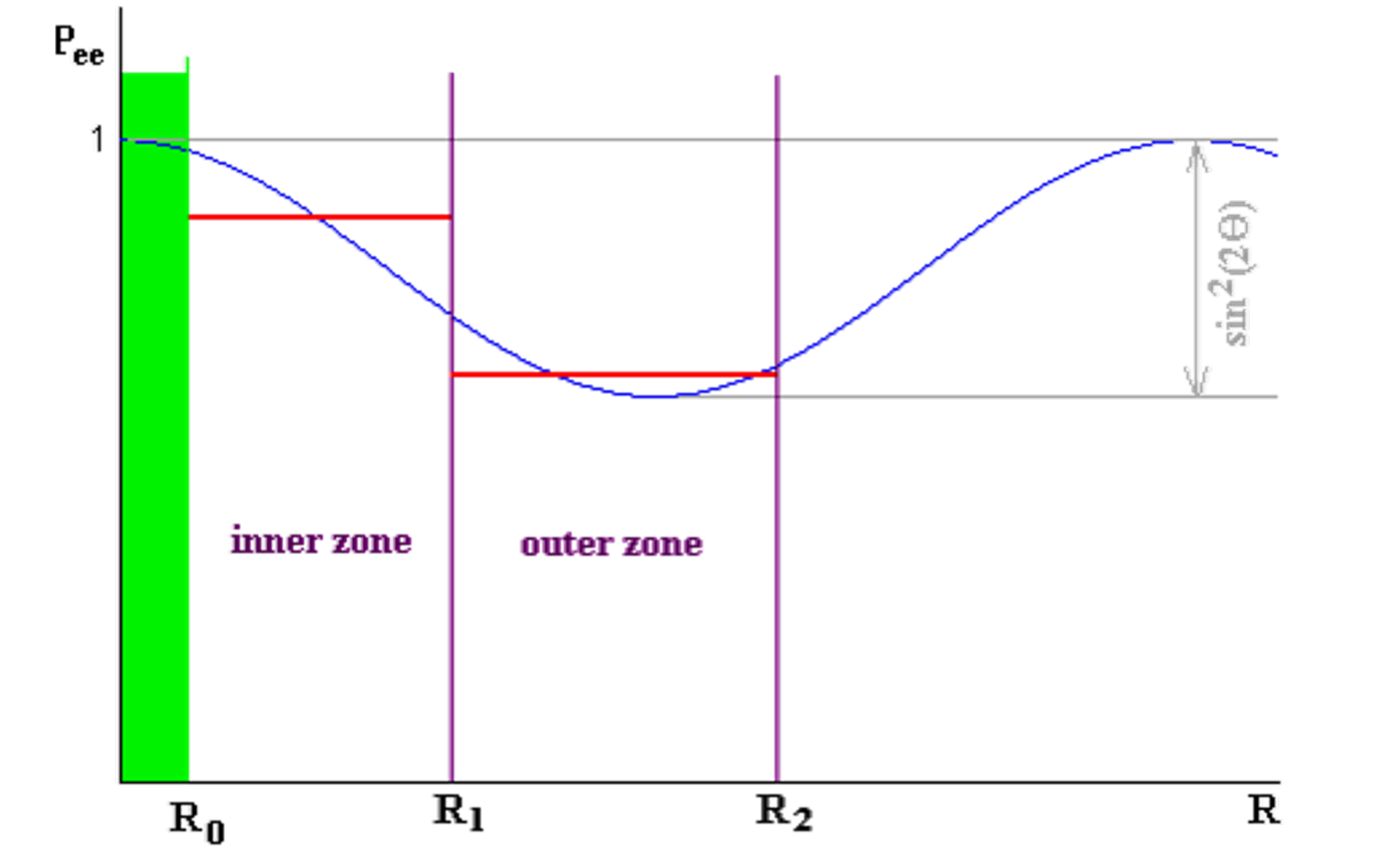
Giunti and Laveder, 1006.3224

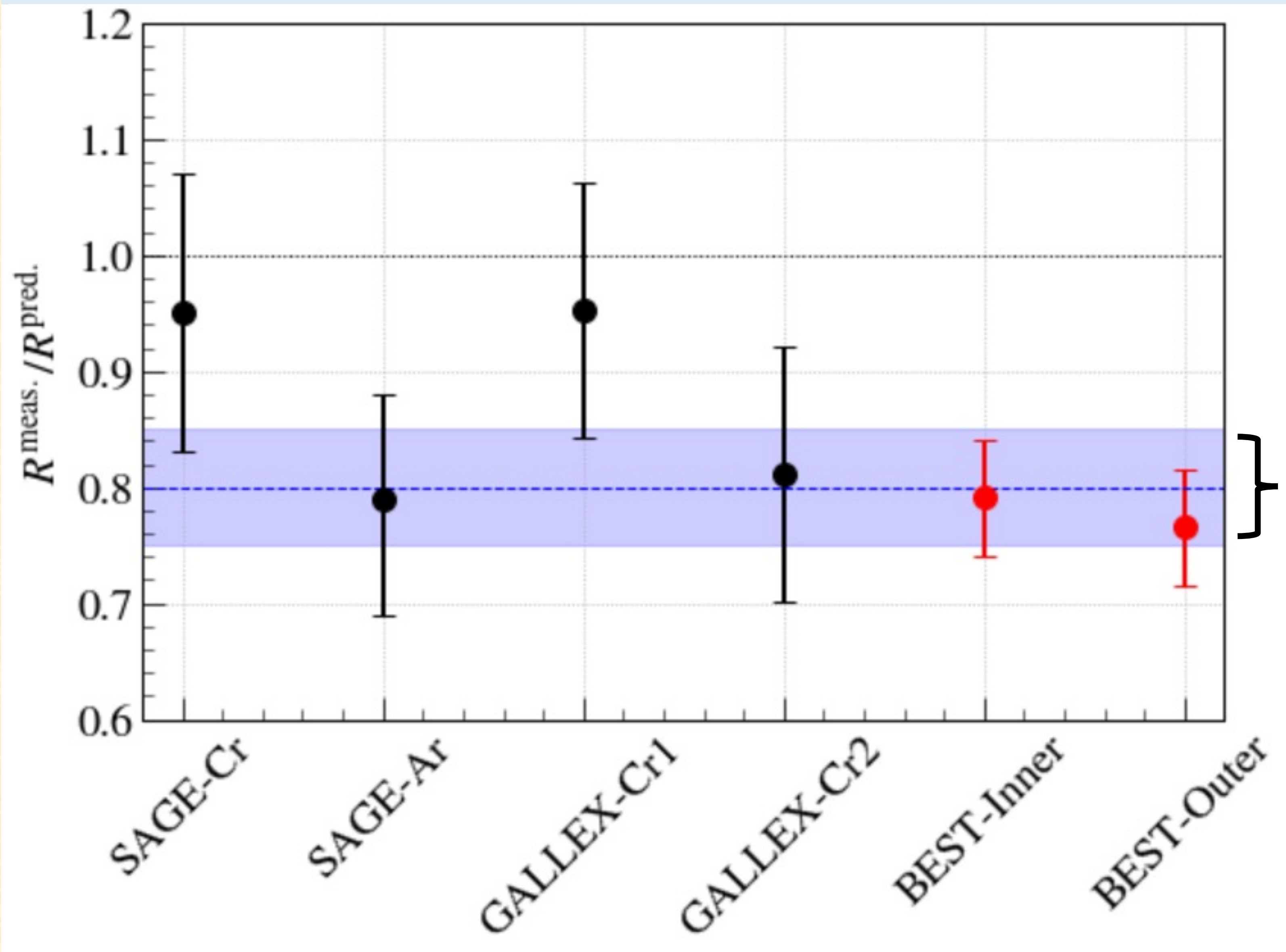
More recently, the BEST experiment was conducted to test this anomaly (2011-2021)



Anomalies at Short Baselines…….1) The Gallium source Anomaly

If one were to understand the SAGE and Gallex results in terms of sterile neutrino oscillations, one would expect these results (shown adjacent) in BEST →





Combined result:

$R_0 = 0.80 \pm 0.05$

← BEST confirms (with higher statistical precision) (4σ) the presence of a deficit in overall flux consistent with earlier SAGE/GALLEX results

arXiv:2109.11482, PRL arXiv:2201.07364, PRC

Anomalies at Short Baselines…….1) The Gallium source Anomaly

However, while results can be accommodated in the sterile/active oscillation space, BEST did not observe any variation with distance.

Smoking gun for oscillations is missing

Note that large mixing is required →

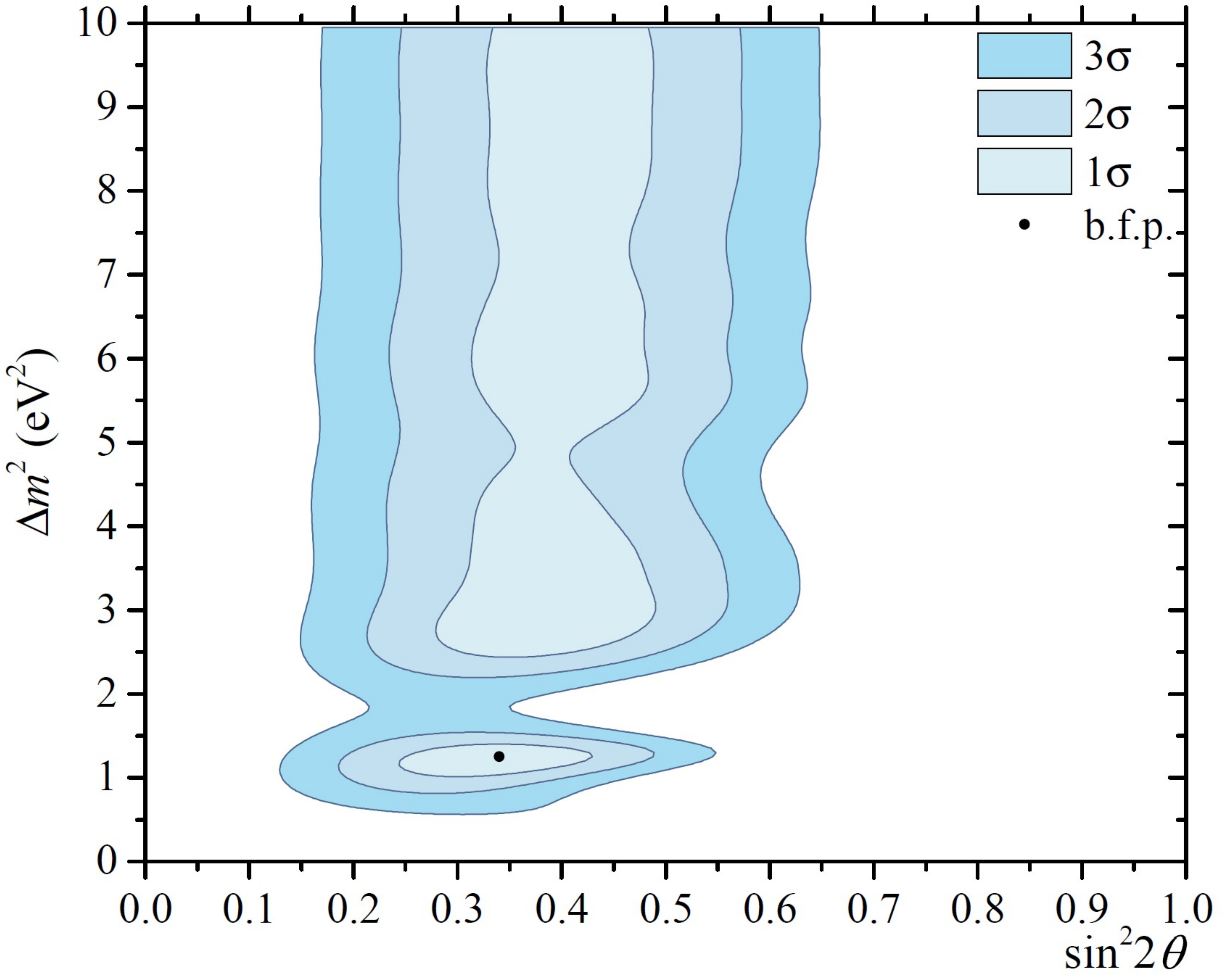


FIG. 8. Allowed regions for two GALLEX, two SAGE and two BEST results. The best-fit point is $\sin^2 2\theta$=0.33, $\Delta m^2 = 1.25$ eV^2 and is indicated by a point.

Possible non-oscillation reasons for the observed deficit could be inaccuracies in 1) xsecs, 2) source strength, 3) counting efficiency 4) extraction efficiency.

No clear answer at present.

Anomalies at Short Baselines.......Reactor Antineutrino Anomaly (RAA)

Reactor antineutrinos are produced from beta decays of neutron-rich fission fragments generated by the heavy isotopes 235U, 238U, 239Pu, and 241Pu

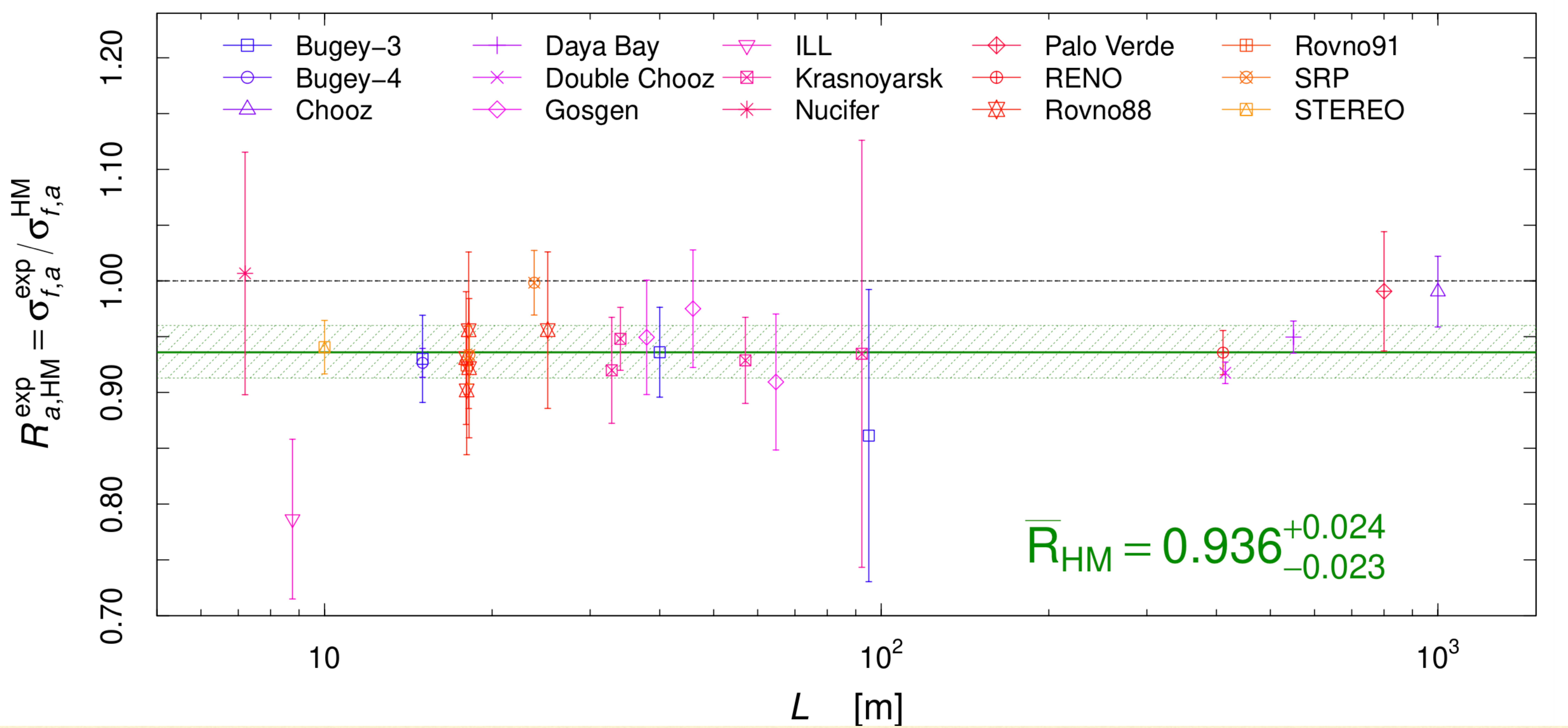
The most important antineutrino fluxes are those produced by the fissions of 235U and 239Pu.

The flux measurement from various reactors, was, until recently, on the average, about 3.5% (~3σ) lower than predicted from careful calculations done by several groups.

Mueller et al. 1101.2663, Huber 1106.0687, Giunti et al. 2110.06820

.

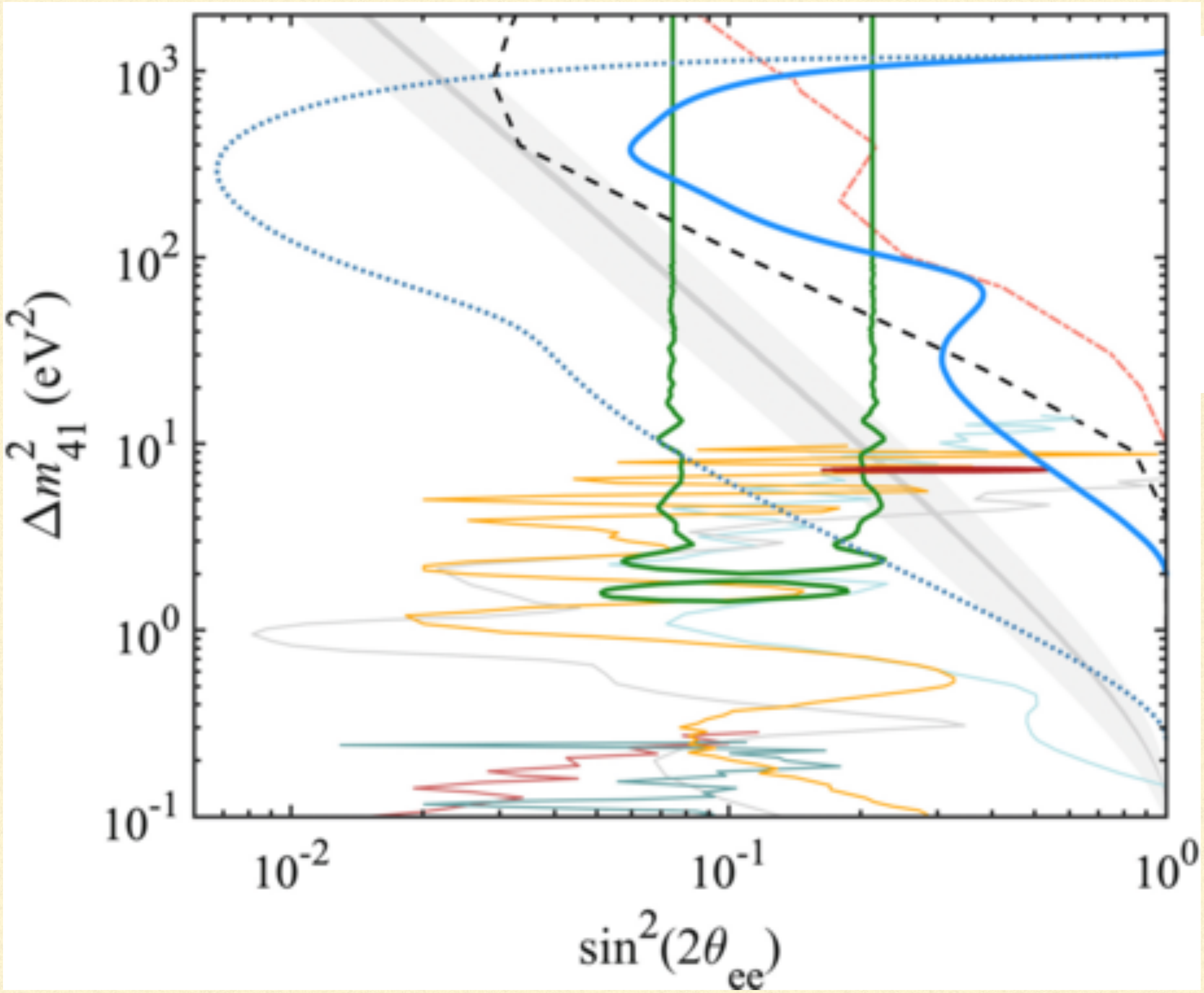
Anomalies at Short Baselines.......Reactor Antineutrino Anomaly (RAA)

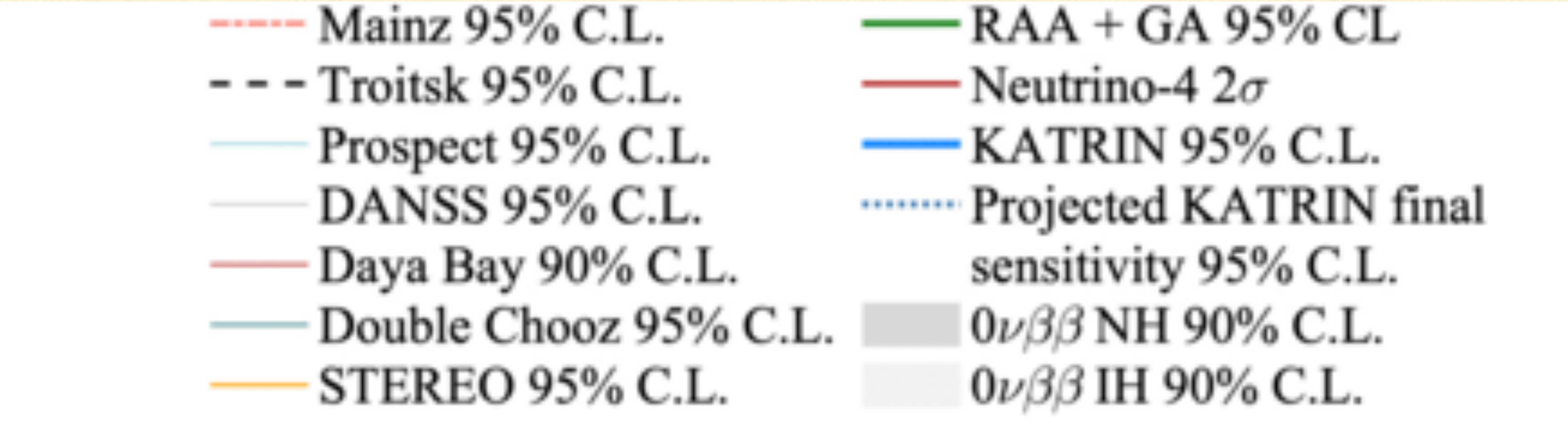


Mueller et al. 1101.2663, Huber 1106.0687, Giunti et al. 2110.06820

This raised the possibility that the deficit was due to active-sterile oscillations .

Anomalies at Short Baselines…….Reactor Antineutrino Anomaly (RAA)





Allowed oscillation regions for RAA in strong tension with many exclusion curves of reactors.

Figure 1. Exclusion contours of all reactor experiments in the plane of $[\sin^2(2\theta_{ee}), \Delta m^2_{41}]$ alongside the allowed contours of the RAA and Gallium anomaly as well as Neutrino-4. KATRIN's current and expected exclusion limits are shown in addition. Reprinted from [29] under CC BY 4.0.

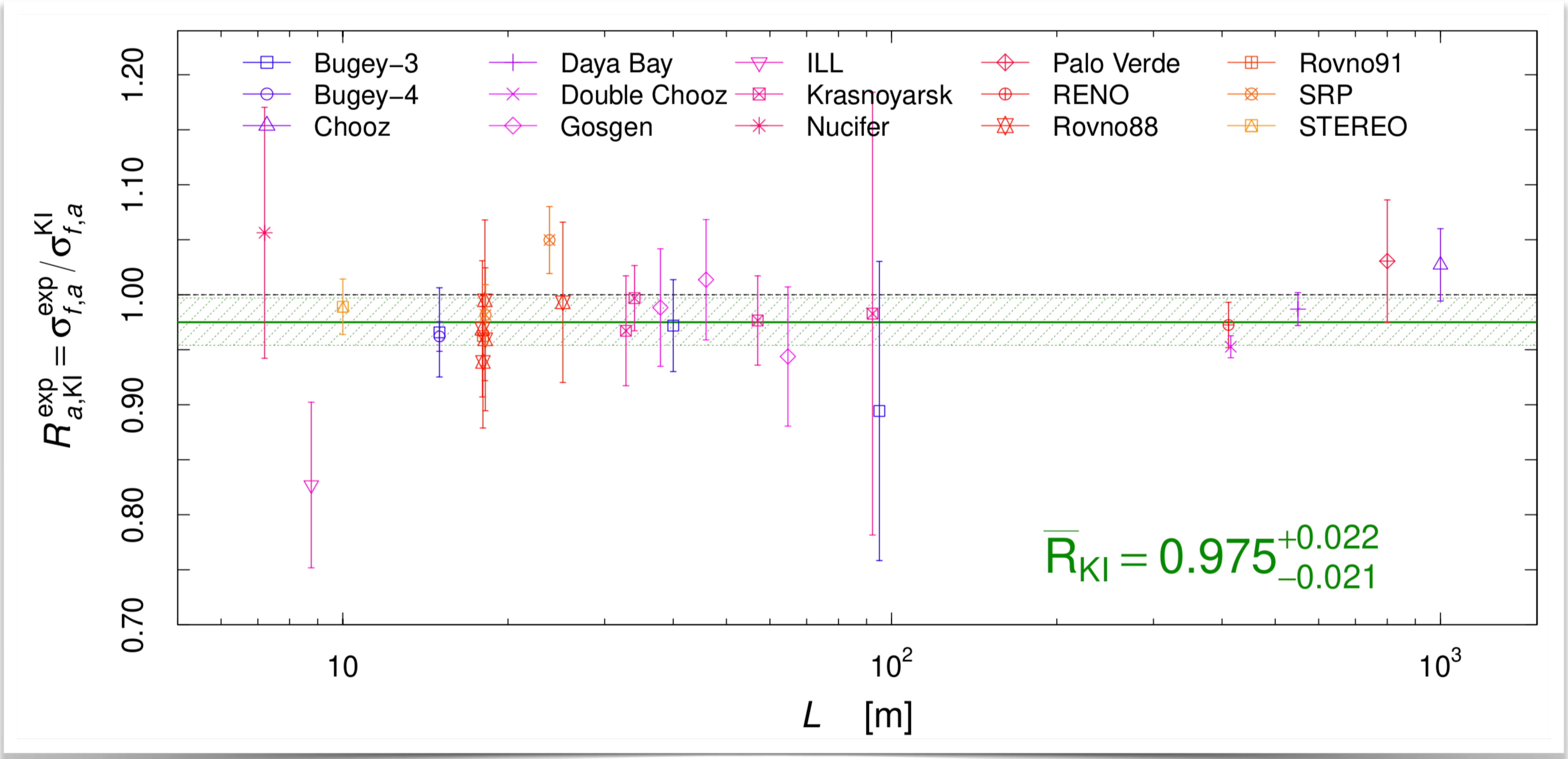
Anomalies at Short Baselines.......Reactor Antineutrino Anomaly (RAA)

Nuclear databases have been improved in recent years, especially through the application of the Total Absorption Gamma-ray Spectroscopy (TAGS) technique for a better identification of the β decay branches.

This new information was used by Fallot et al [18] (EF model) (1904.09358), and Silaeva et al, 2012.09917 to obtain a 235U reactor antineutrino flux that is smaller than that of the earlier models.

This has led to improved agreement with measured fluxes, and there is now a belief in the community that the RAA has been understood to be a flux calculation/data issue (as opposed to a neutrino deficit issue) .

Anomalies at Short Baselines.......Reactor Antineutrino Anomaly (RAA)

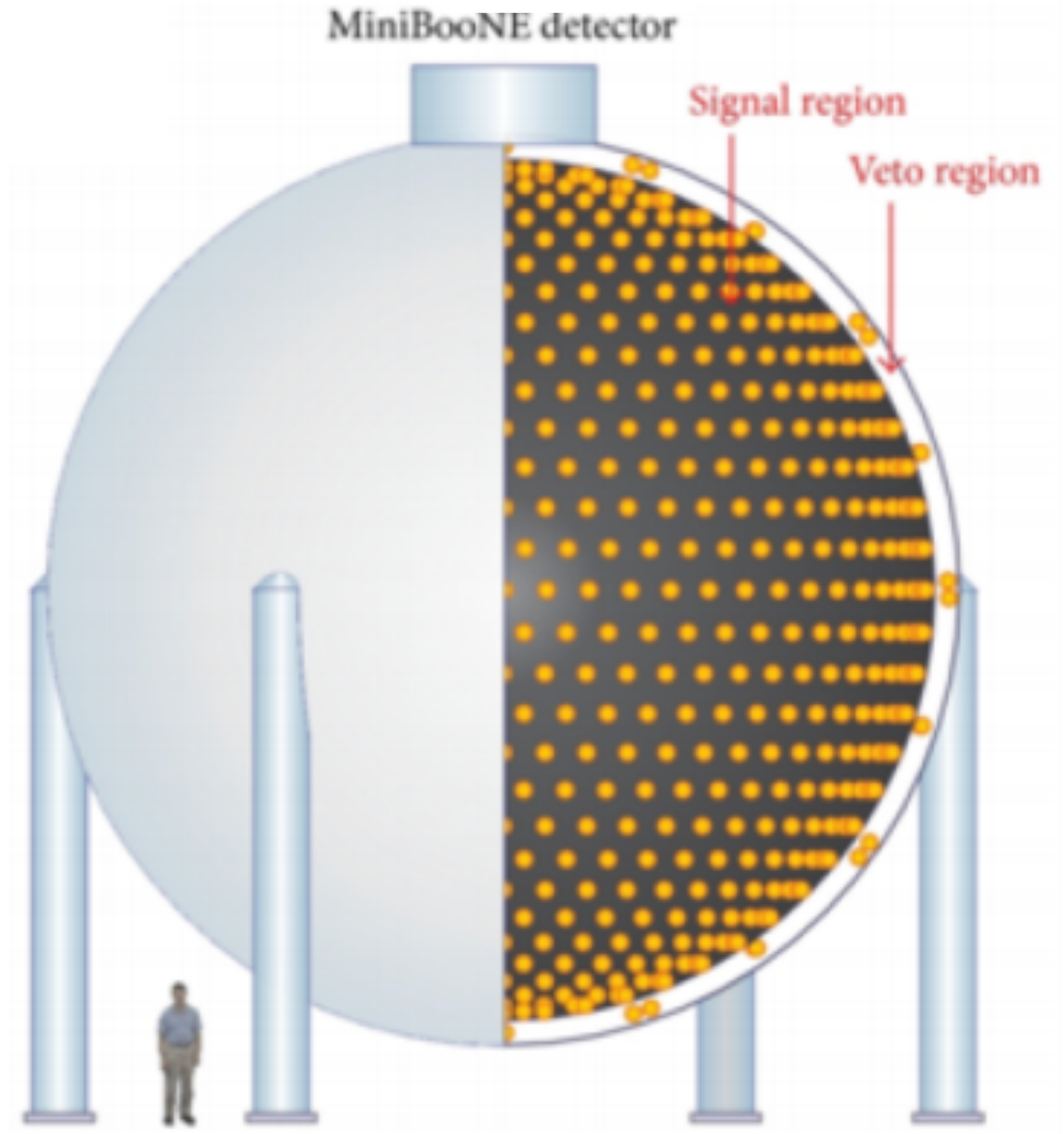


Kopeikin et al 2103.01684, Berryman et al 2005.01756, Giunti et al 2110.06820

Anomalies at Short Baselines…….MiniBooNE (2002-2017)

MiniBooNE

(4.8σ!)

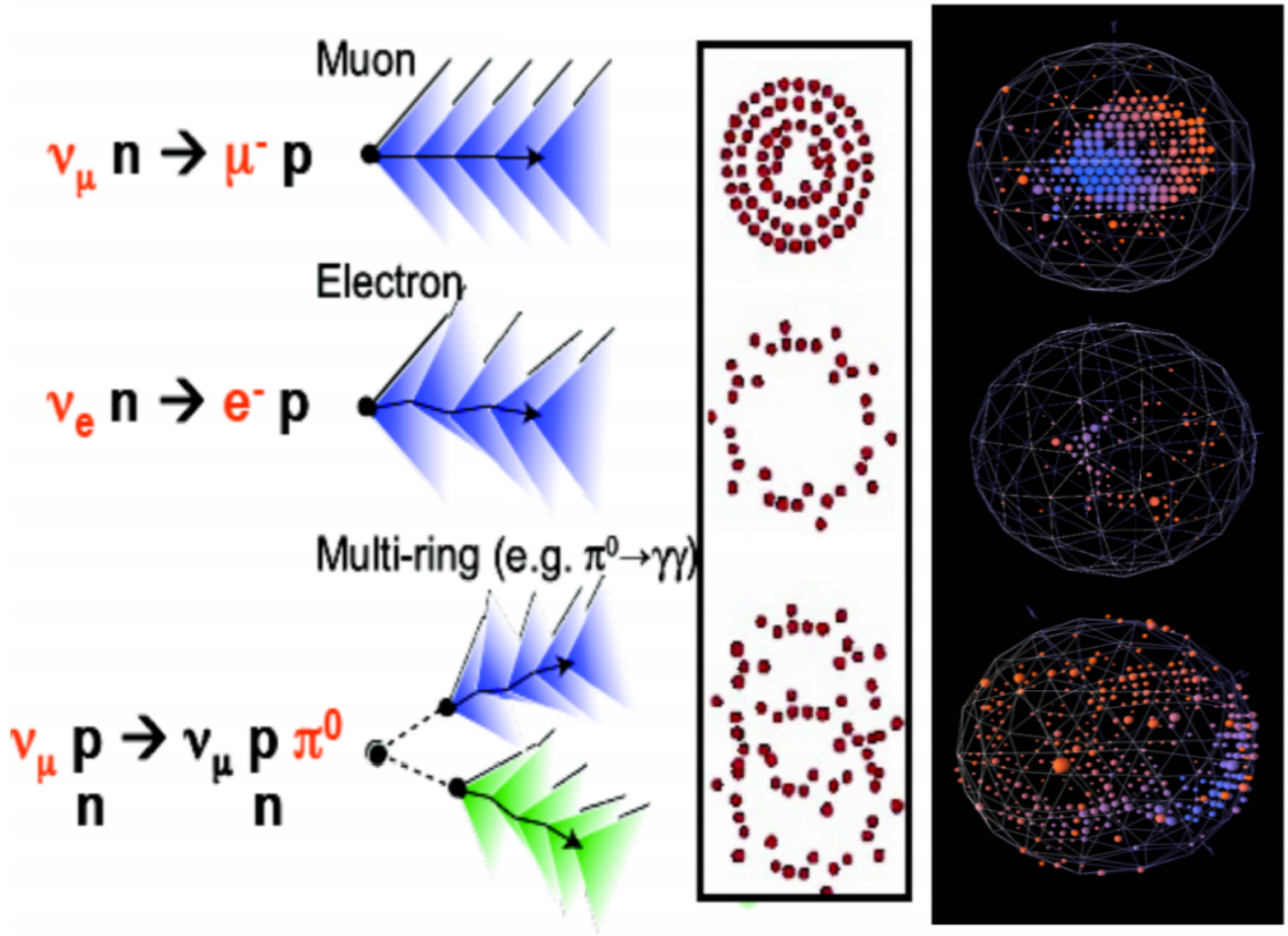


Mineral oil detector, 541 m baseline, 600 MeV ($\nu\mu$) and 400 MeV ($\bar{\nu}\mu$) peak fluxes.

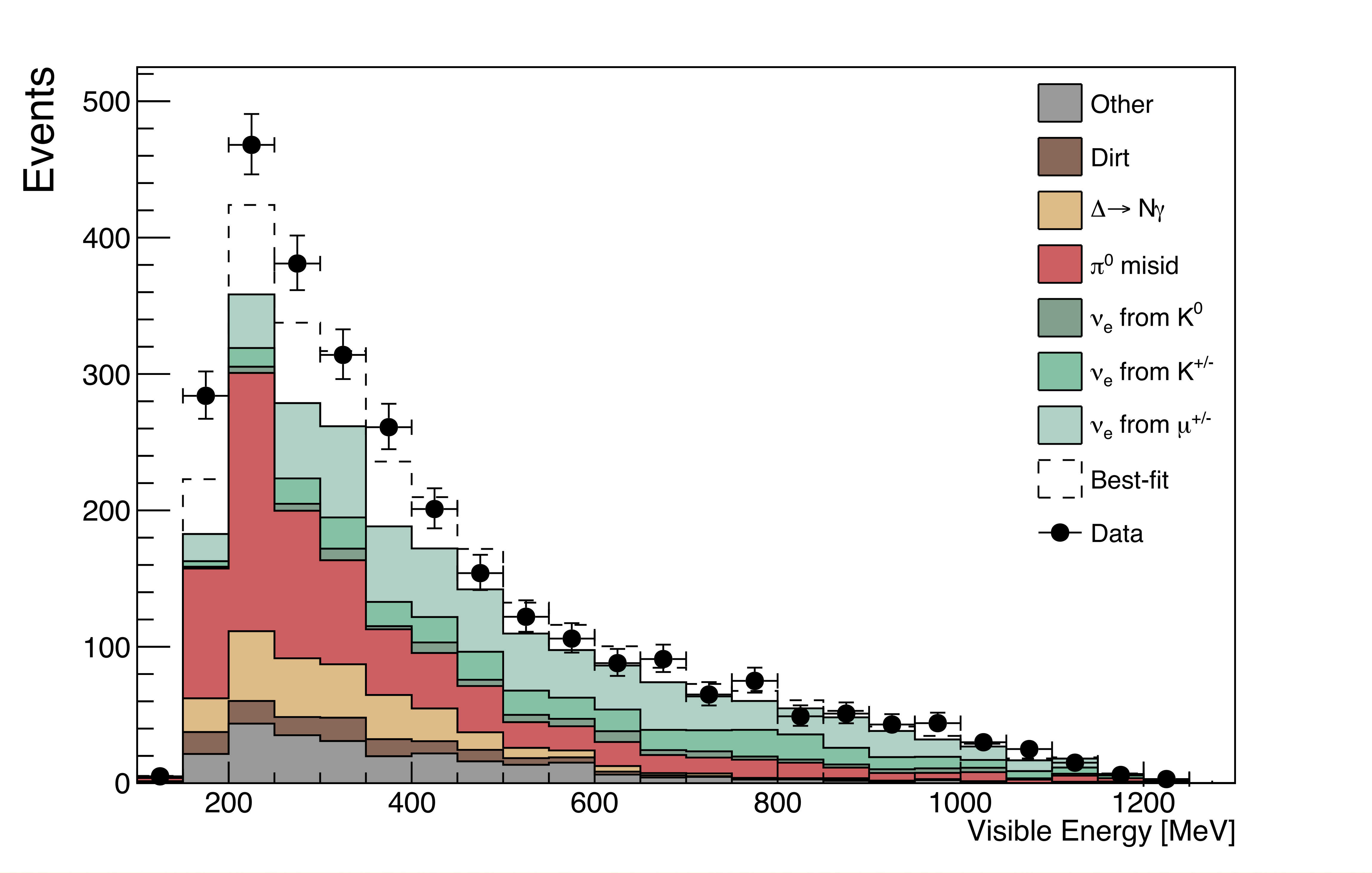
Was specifically built to test the LSND anomaly

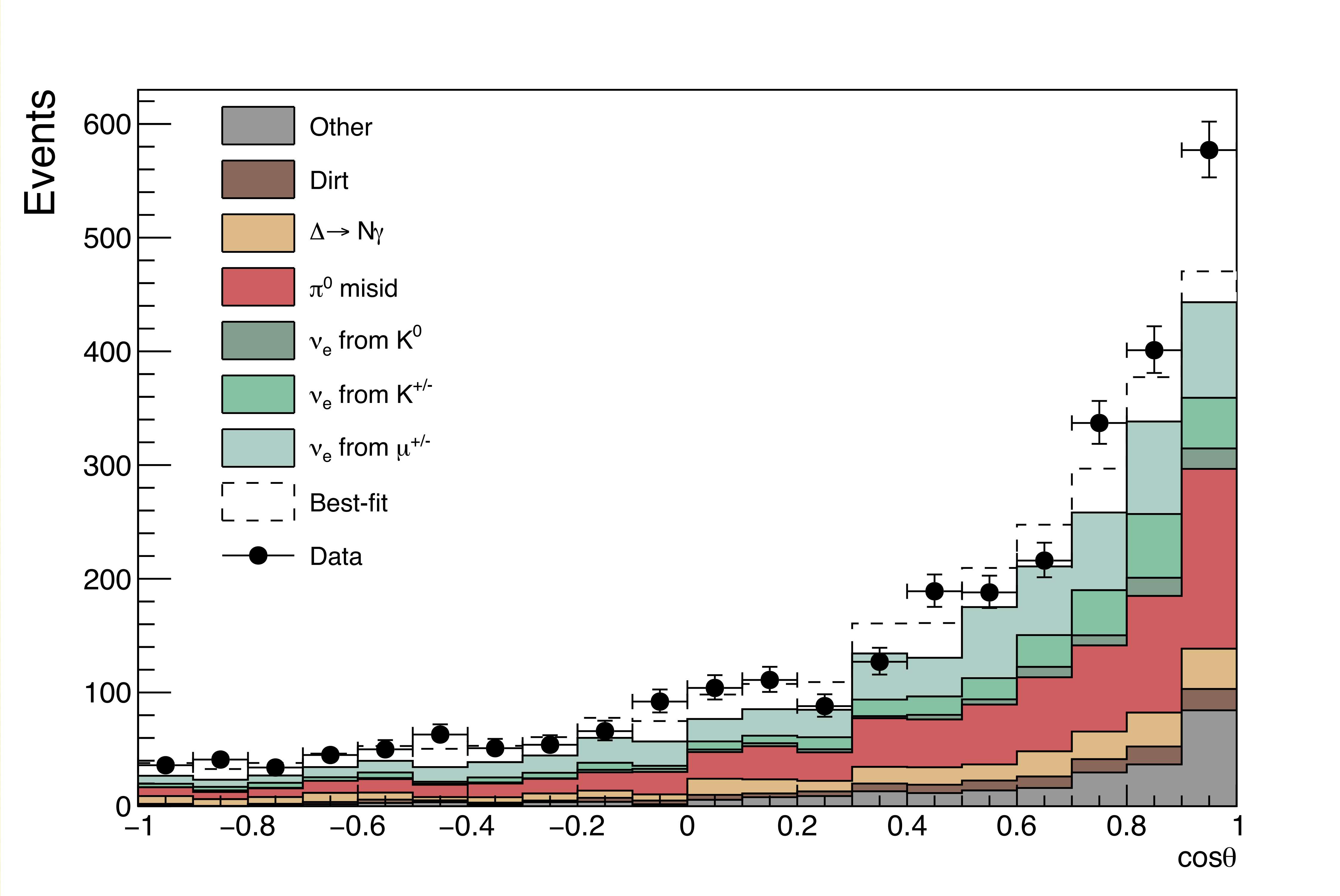
Three typical event signatures:

- Muon-neutrino CCQE produces sharp photon ring on PMTS,
- Electron-neutrino CCQE events produces fuzzy ring,
- Muon-neutrino NC can produce π_0: two gammas -> two fuzzy rings.



Anomalies at Short Baselines.......MiniBooNE





- The observation of a 4.8σ excess in electron-like events for neutrino and antineutrino modes in the MiniBooNE (MB) detector is observed

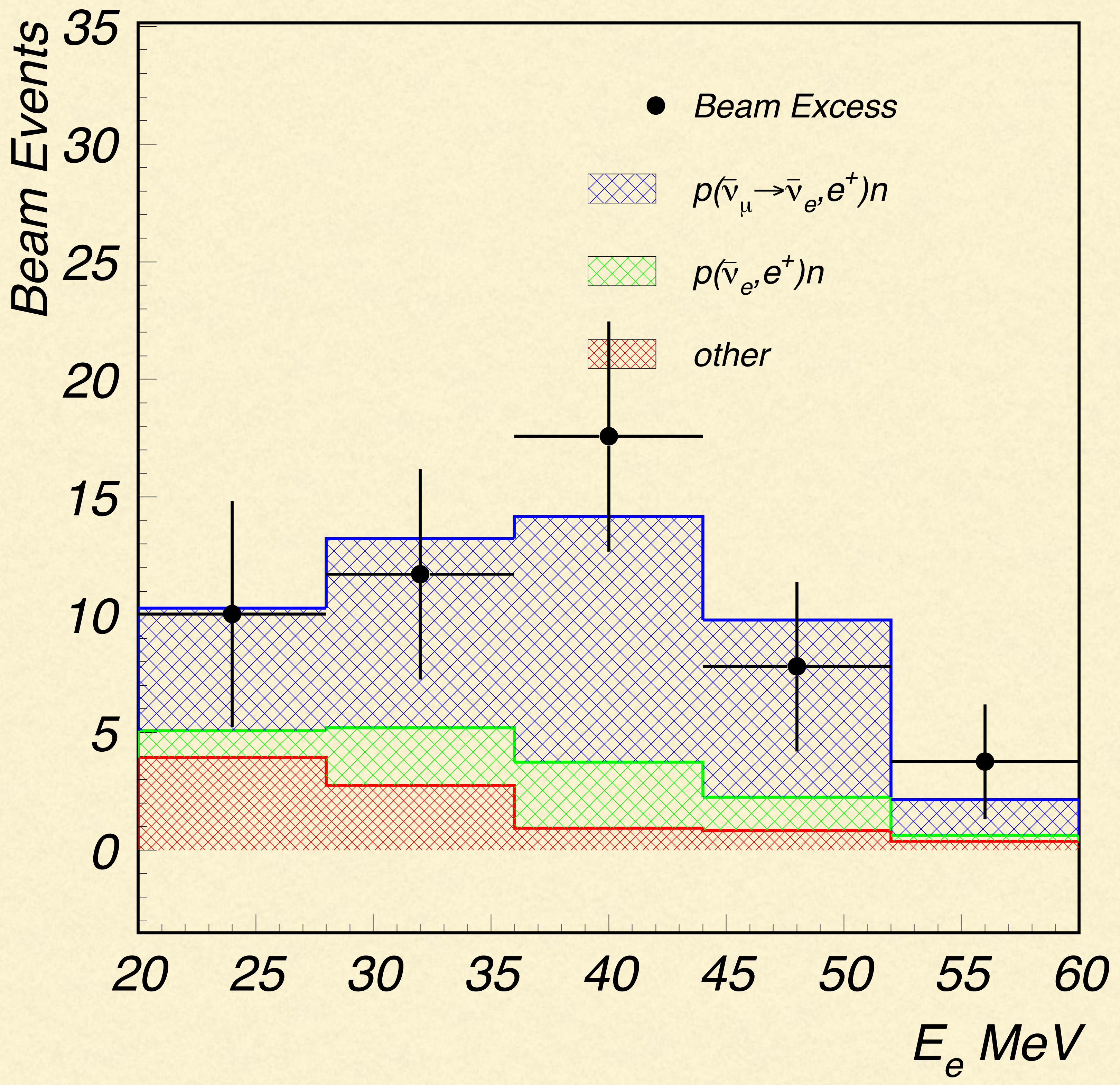
- SM: 2309 events
  Data: 2870
  Excess: 560

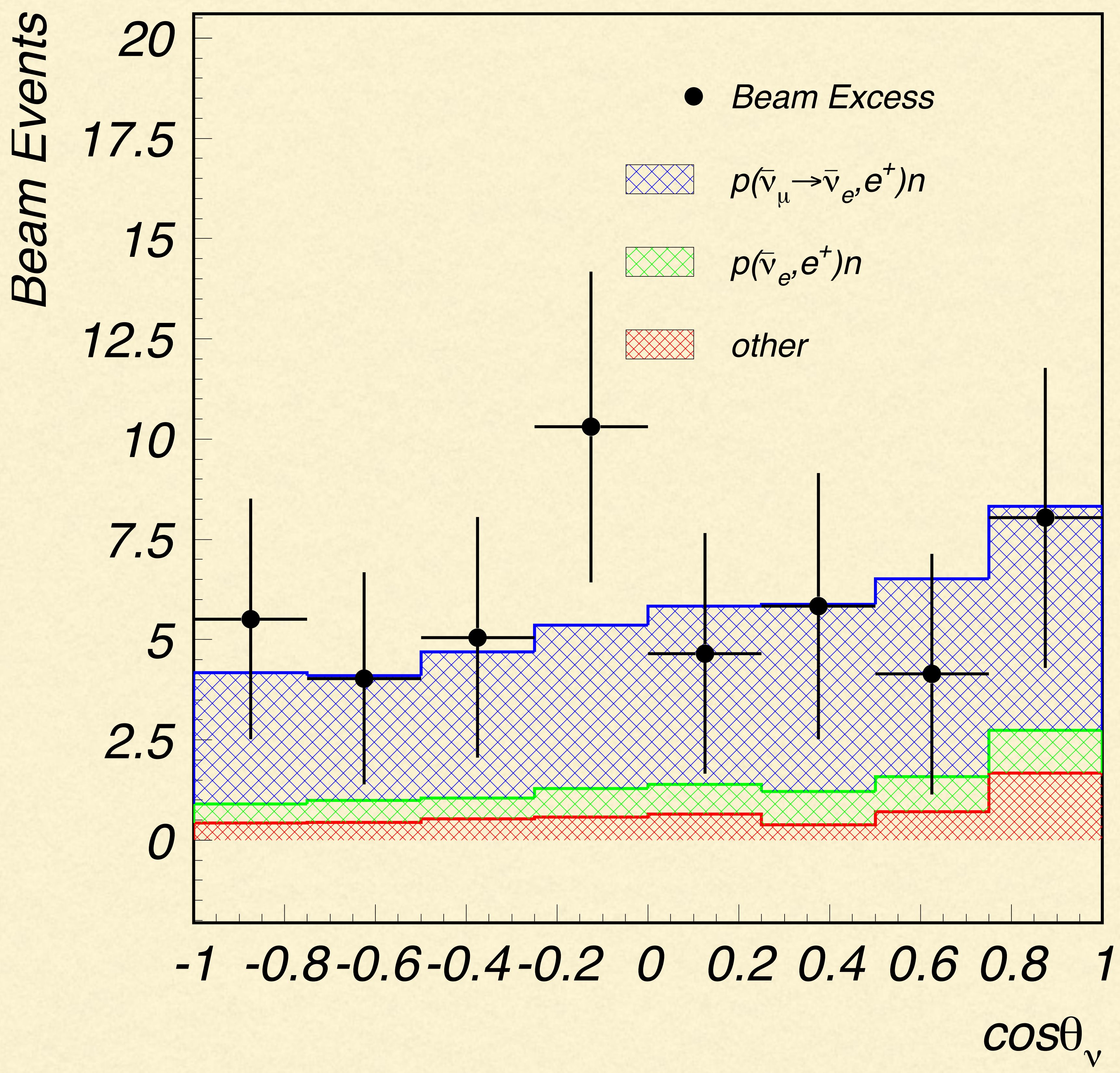
Excess is not small. Note it is at level of important SM backgrounds

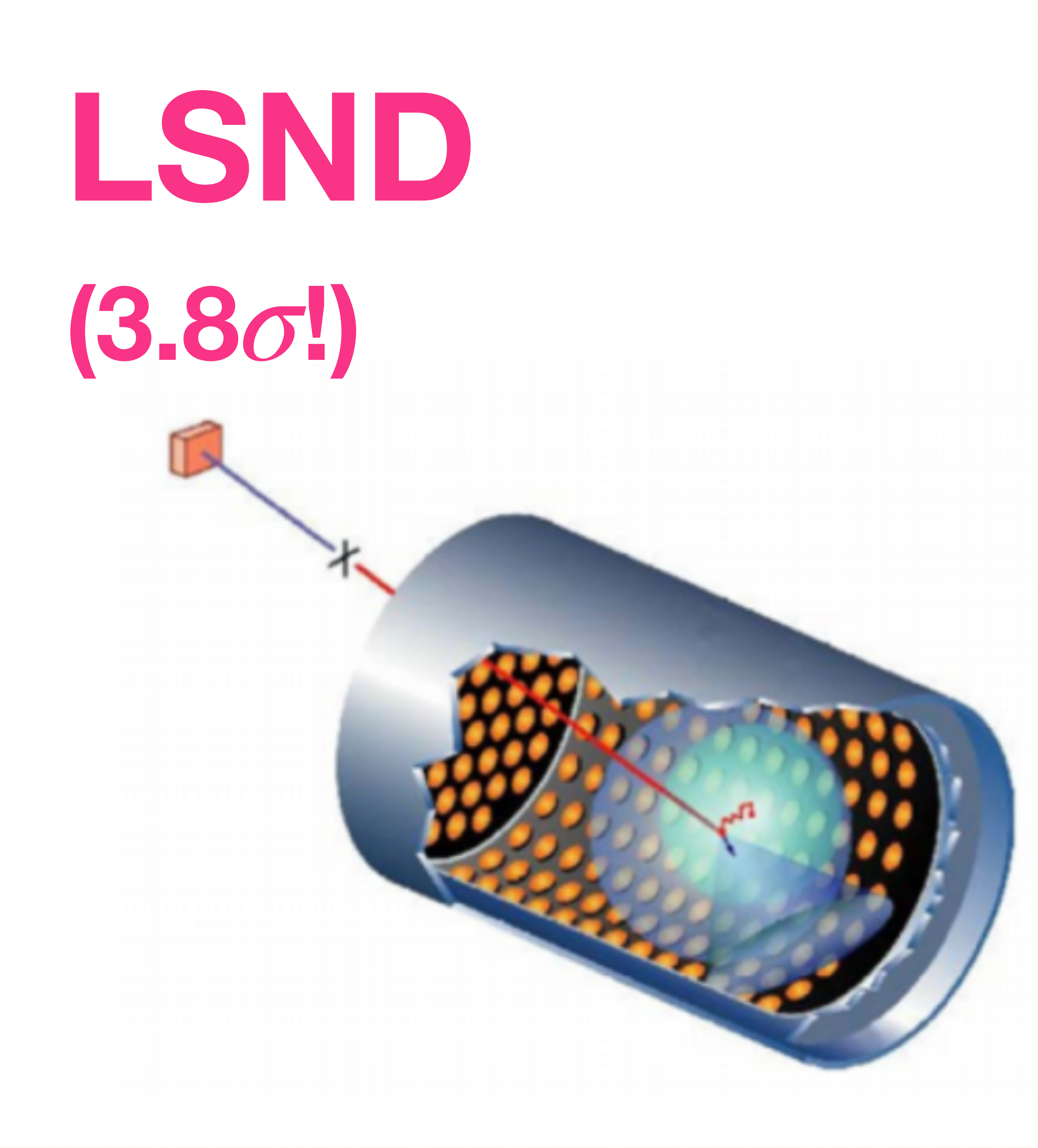
Distinctive energy and angular distribution

Dashed line is oscillation fit. Not a good fit at low energies or forward angles where most events present

Anomalies at Short Baselines.......LSND (1993-1998)







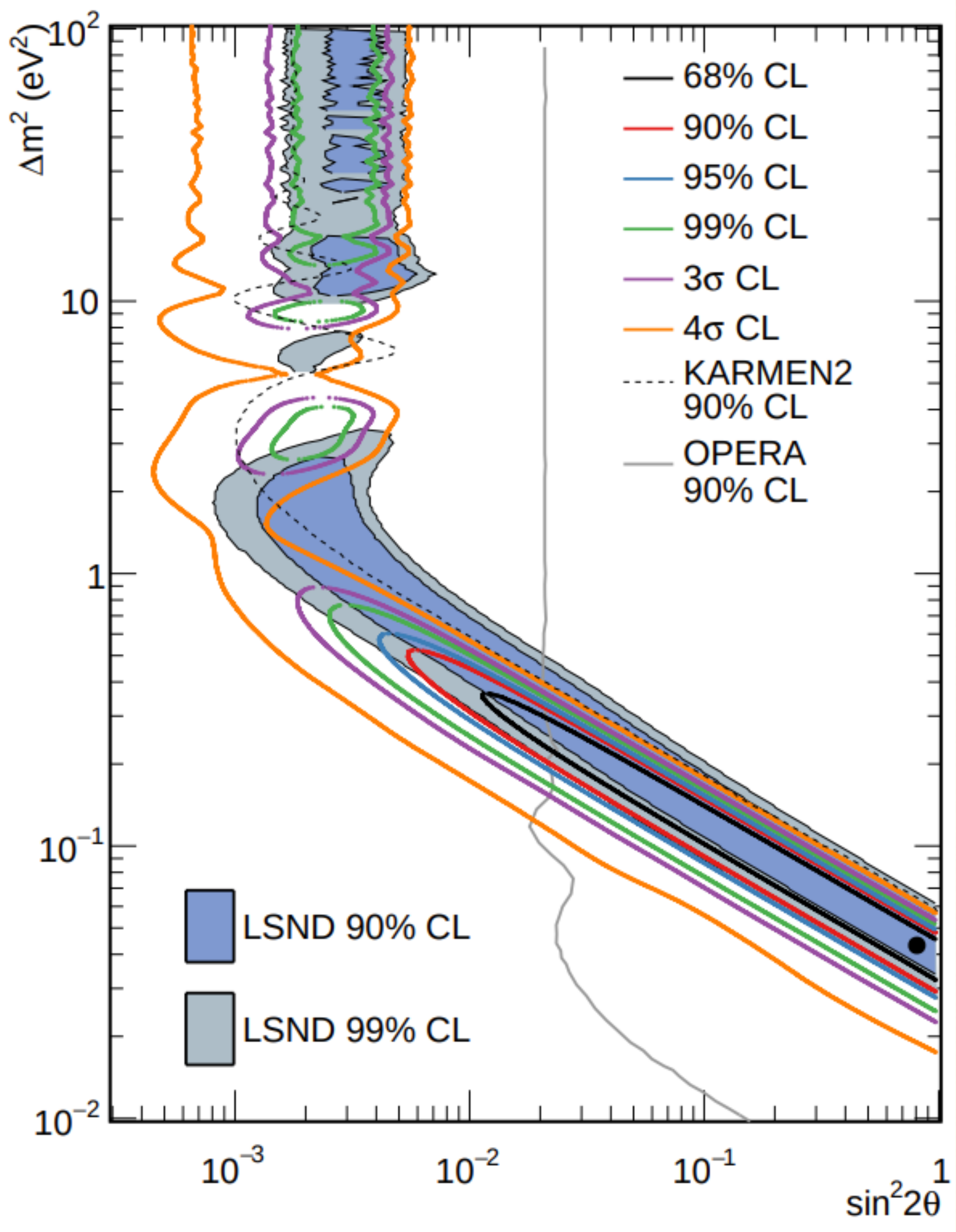
- Observation of unexplained electron-like excesses in the LSND at a level of 3.8σ above SM backgrounds.

Blue hatched region is oscillation fit.

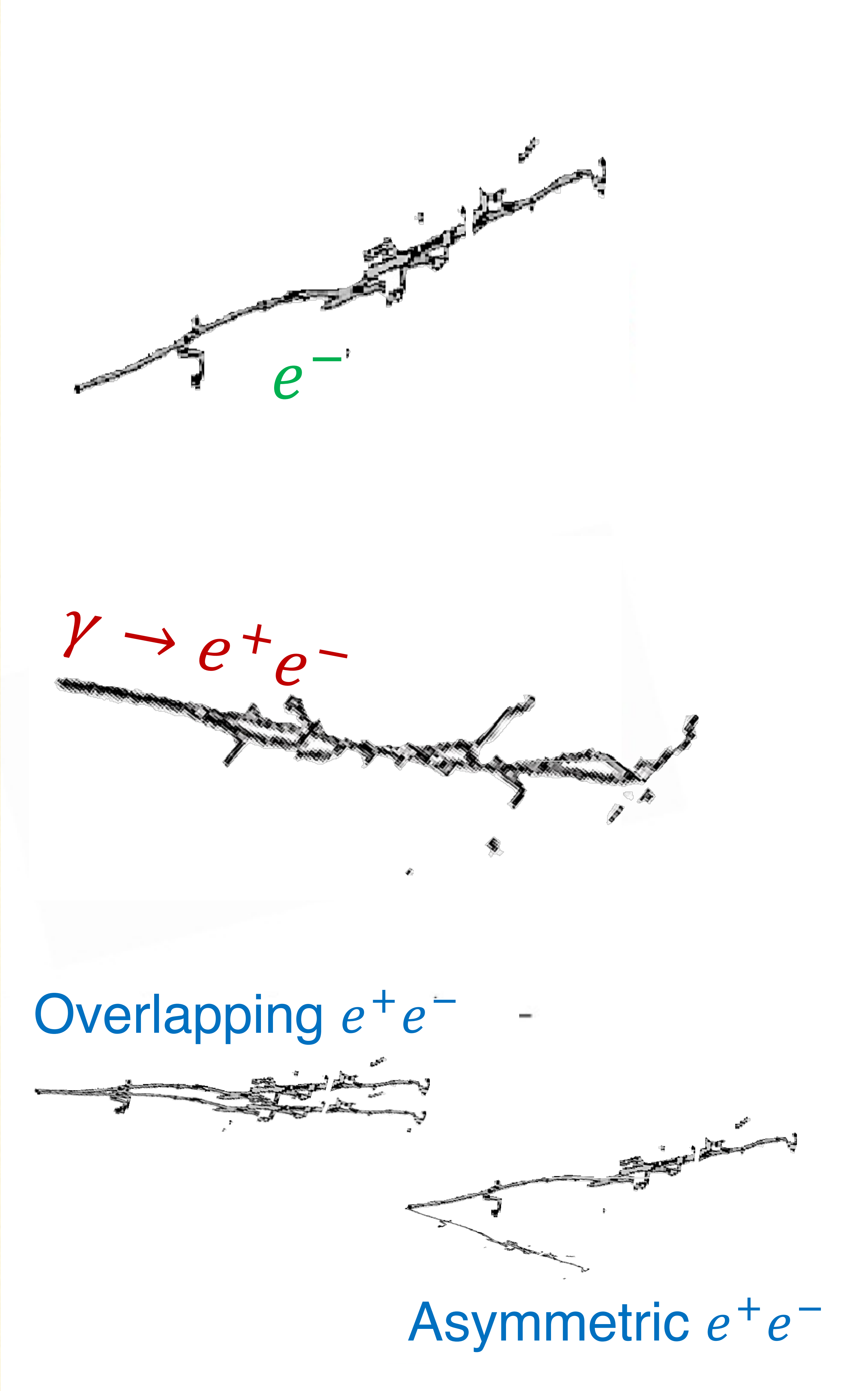
- Note that unlike MB, both energy and angular distributions are relatively flat

•

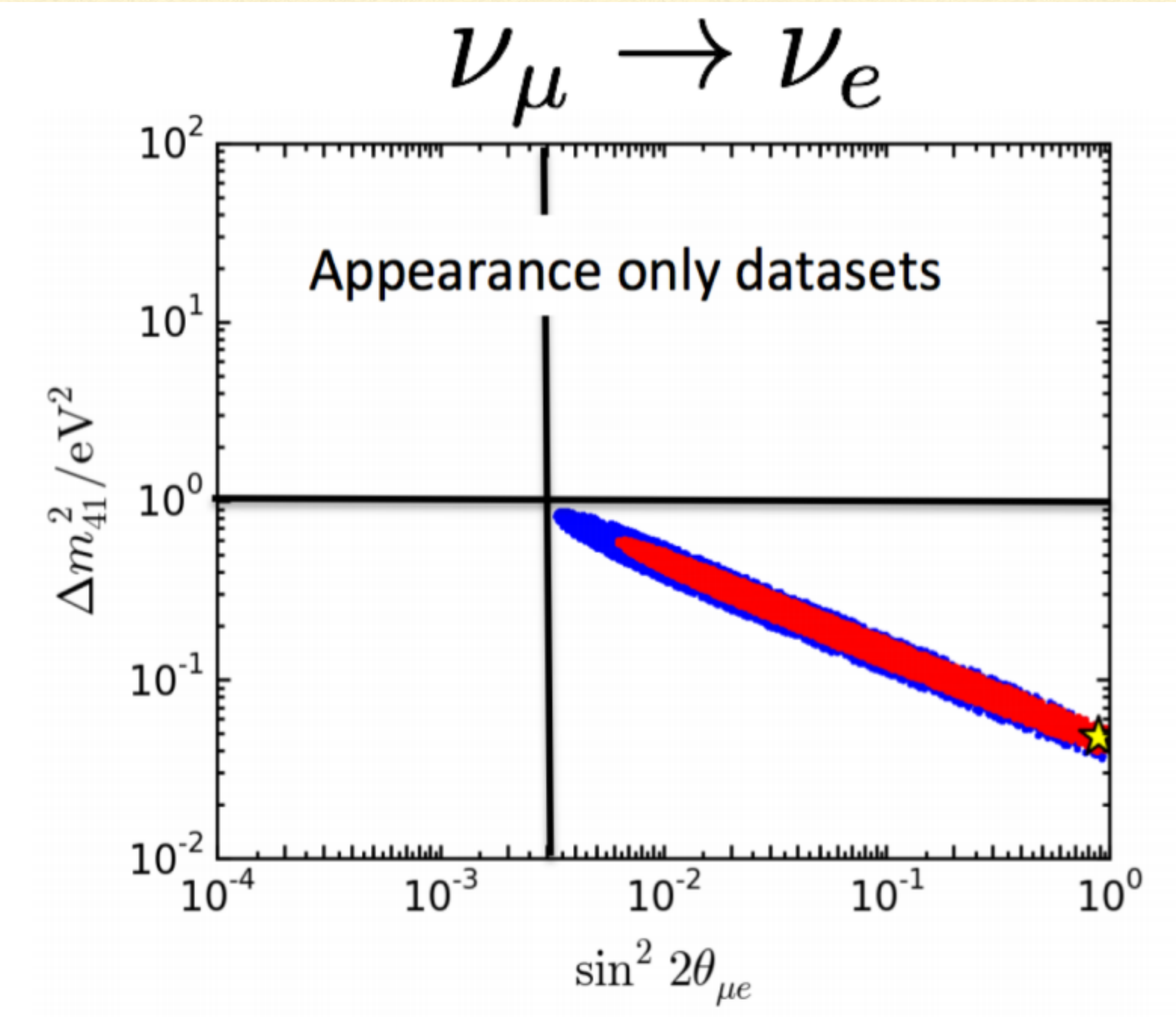
Anomalies at Short Baselines…….LSND and MiniBooNE



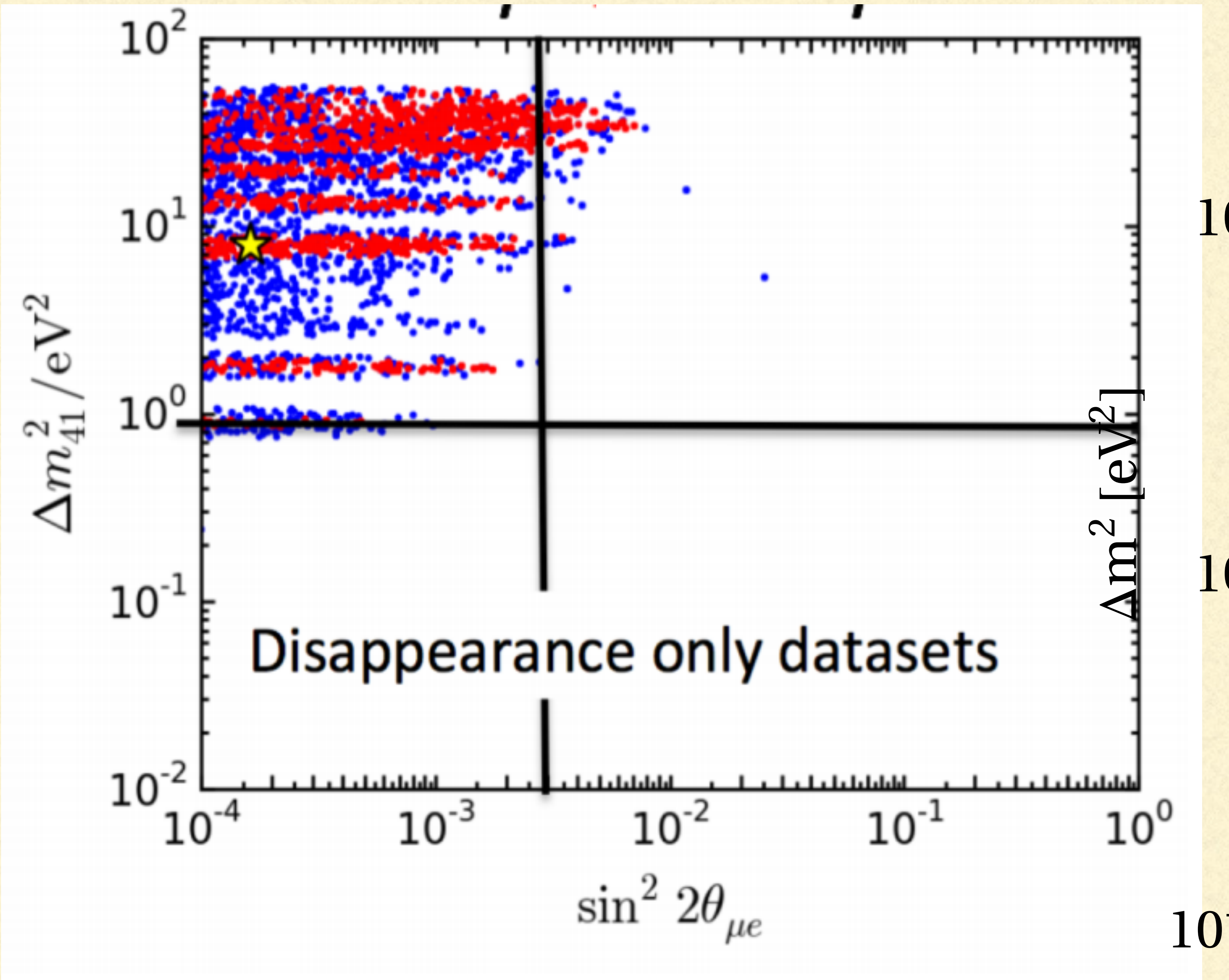
- Elongated bullet shaped regions in the above are MB preferred regions. KARMEN2 and OPERA exclude much of these.



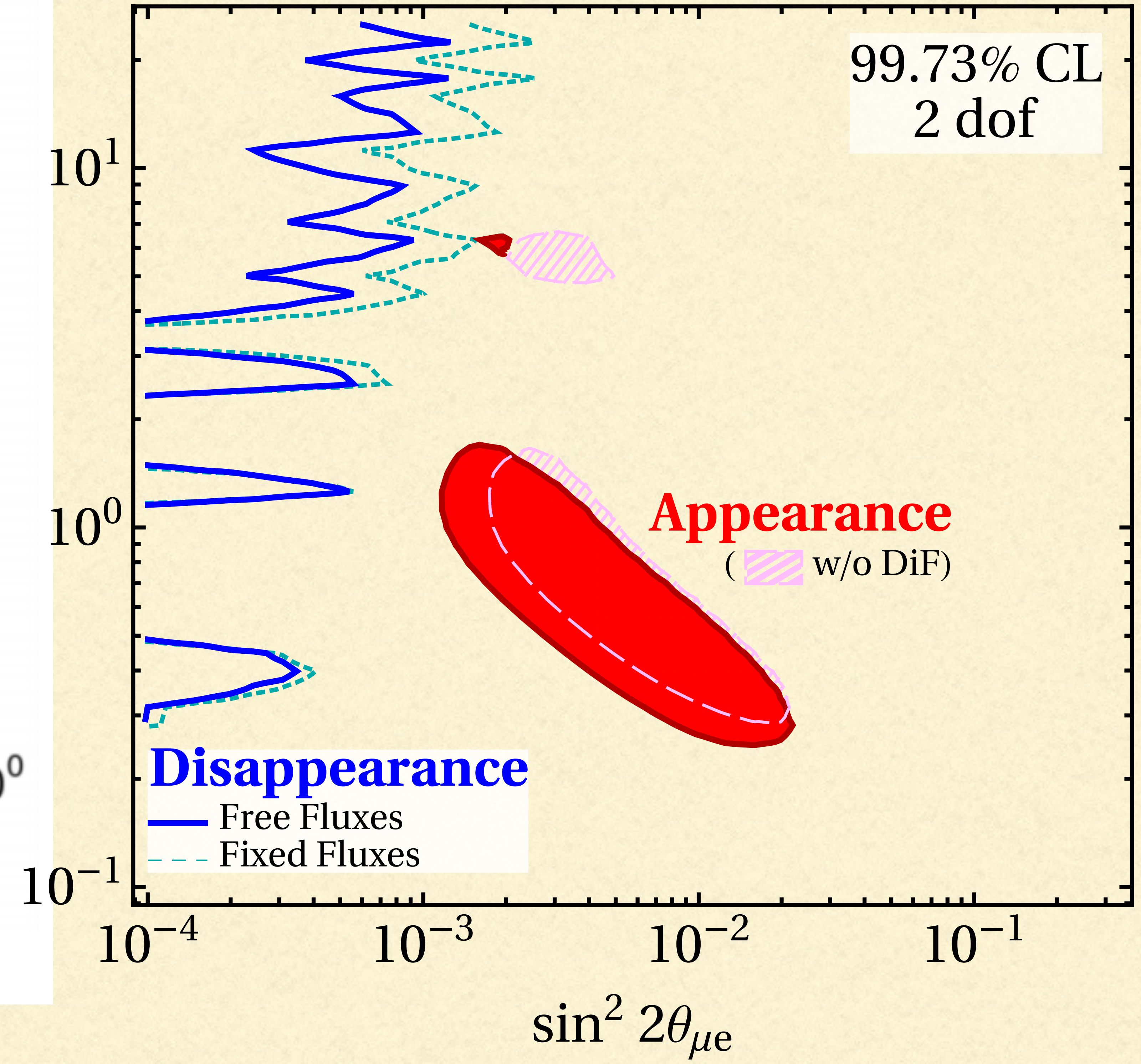
- Oscillations? or new physics?
- An important point: Both are mineral oil detectors, unable to distinguish electrons from photons or e+e- pairs



LSND/MB Driven



Reactor, Long-Baseline Driven



Collin et al 1602.00671

$$\nu_e \to \nu_e$$
$$\nu_\mu \to \nu_\mu$$

Dentler et al 1803.10661

- Combined analyses to test the active-sterile hypothesis for short baseline anomalies by various groups all reveal a common underlying problem: **Strong tension between appearance and disappearance data**

Additionally, eV scale sterile neutrinos are constrained by Cosmology…….

Any relativistic neutrino species will contribute to the energy density of the Universe as radiation. Their total contribution may be parametrised by the parameter N_{eff}

Cosmology is sensitive to neutrinos in a way that is complementary to laboratory searches. It is less sensitive to individual masses and mixings, but is more directly affected by the absolute mass scale,

$$\frac{\rho_r - \rho_\gamma}{\rho_\nu^{\rm std}} = N_{\rm eff}\,,$$

e ρ_r is the total radiation energy density, ρ_γ is the photon contribution

$$\rho_\nu^{\rm std} = 2 \times \frac{7}{8}\,\frac{\pi^2}{30}\left(\frac{4}{11}\right)^{4/3} T^4.$$

However, N_{eff} = 3.044 +- 0005 in the SM, leaving no space for an additional sterile relativistic neutrino species

Also, from PLANCK data,

$$\sum m_\nu < 0.26\,{\rm eV}\ (95\%{\rm CL}).$$

Hence, so far, vis a vis sterile-active oscillations of eV neutrinos,

→ Situation with the Ga anomaly is somewhat unclear, since BEST confirmed earlier deficit seen by SAGE and GALLEX but did not see any variation with L.

→ It is likely that RAA is resolved by the new flux calculations using improved beta decay spectra now available.

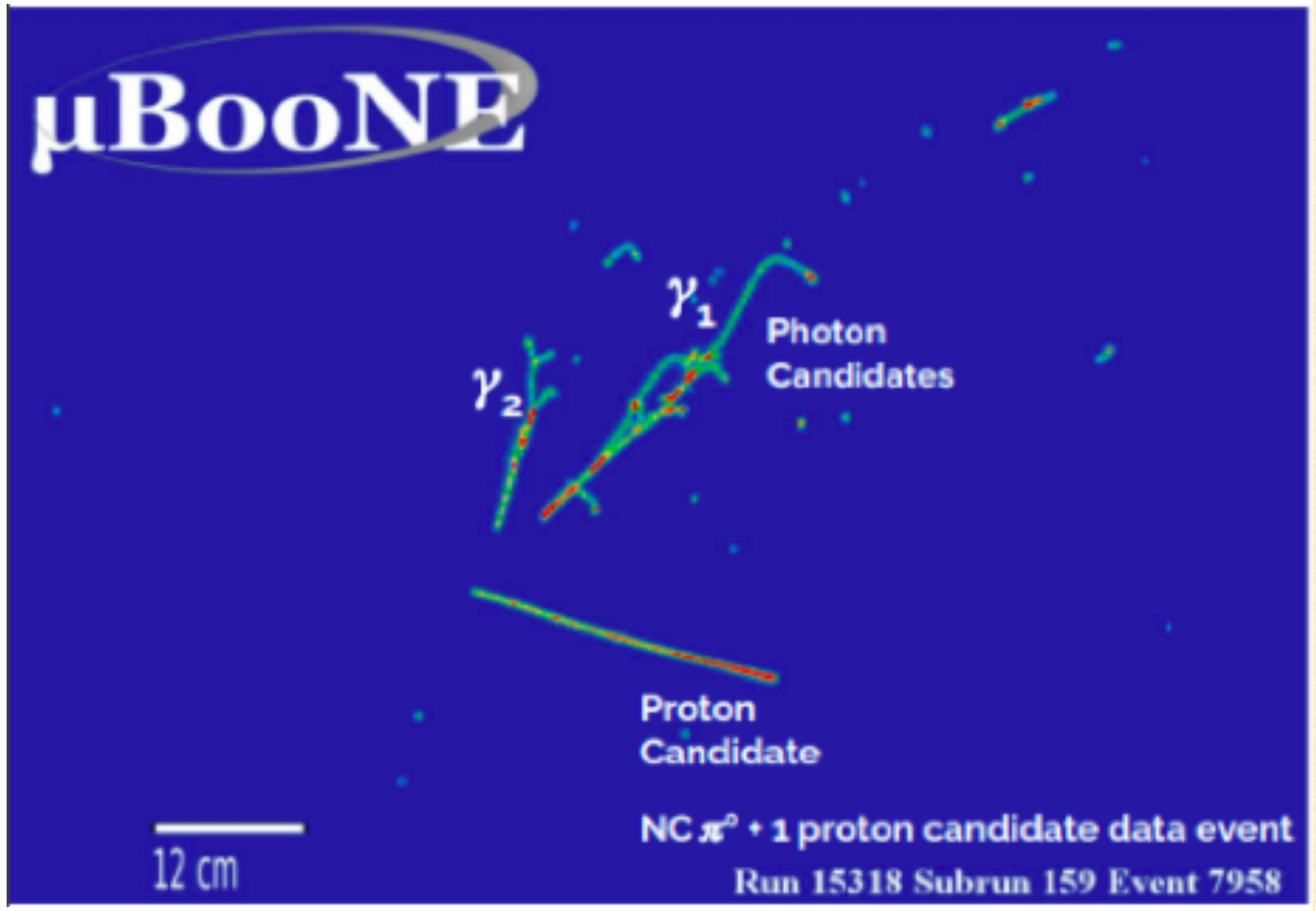
→ Increasingly accurate cosmological observations put strong constraints on the mass and number of eV scale neutrinos, in tension with what is required to explain SBL anomalies by sterile active oscillations.

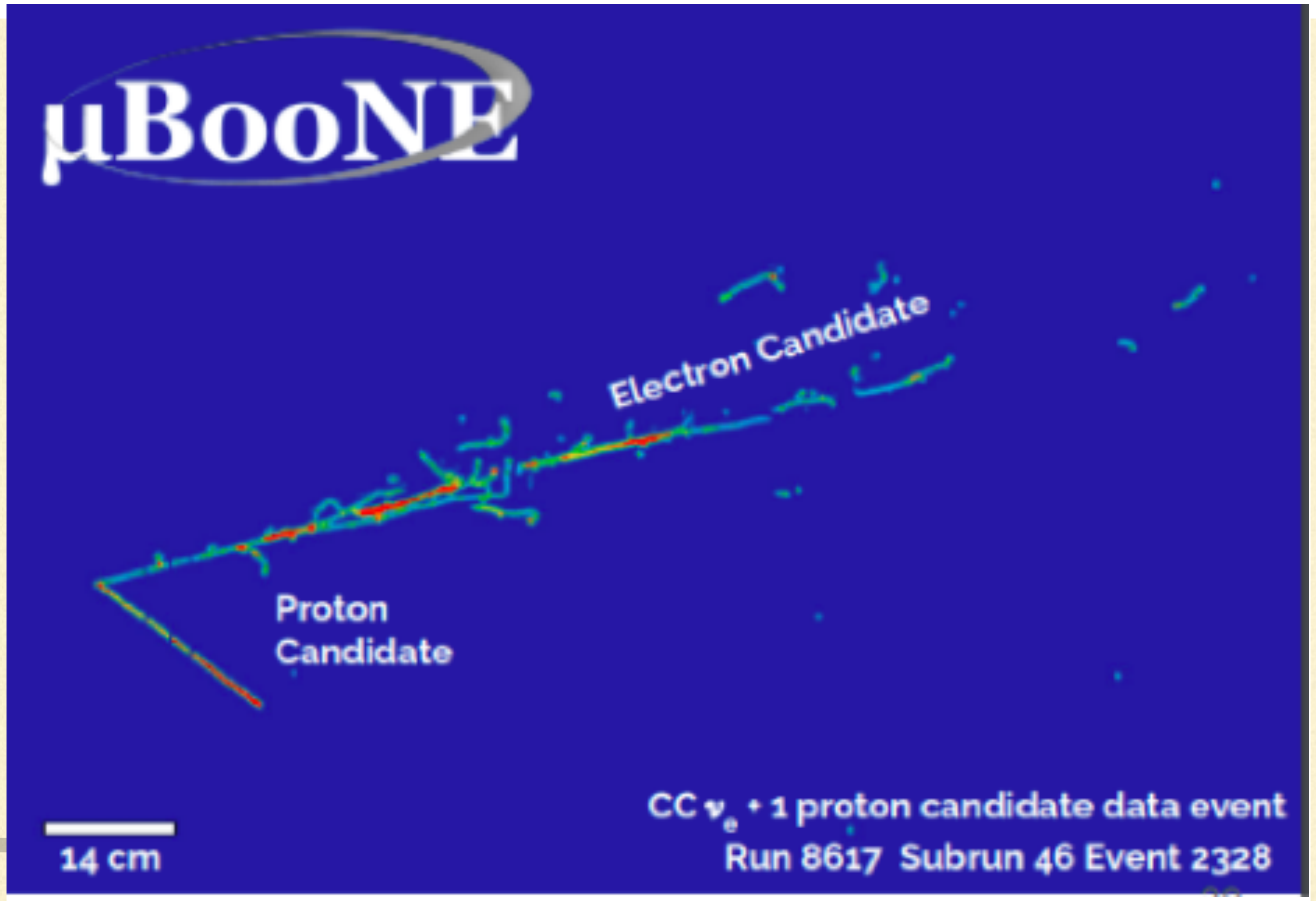
→ MiniBooNE and LSND appear to be statistically strong and long-standing anomalies which, when we try to explain using sterile -active appearance oscillations, are in strong contradiction with disappearance data from reactors and long baseline experiments.

This has led to a lot of efforts to explain MiniBooNE (and in some cases, LSND) by non-oscillation new physics mechanisms.

Many of these efforts also use sterile neutrinos which are significantly heavier than the eV scale.

MicroBooNE (to test MB)





80 ton LAr TPC

Excellent particle identification capabilities.

Can potentially distinguish electrons , protons and photons

- The combined significance of the LSND and MB results is 6.1 σ

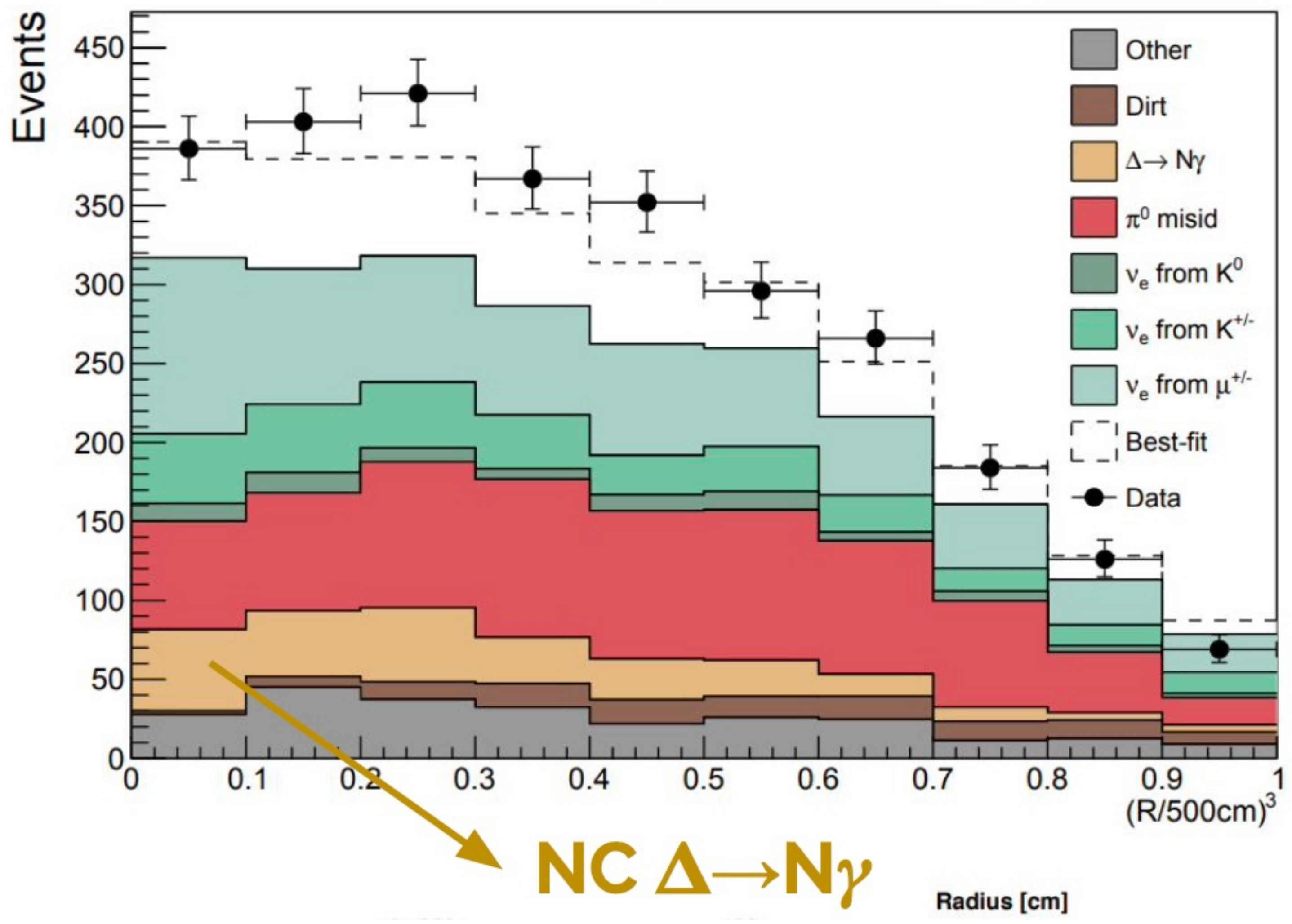
- Both are long-standing anomalies. The community has worked hard to check errors and background estimates over this period. Most recent efforts in this direction come from MicroBooNE

Search for a single-photon excess

Phys. Rev. Lett. **128**, 111801

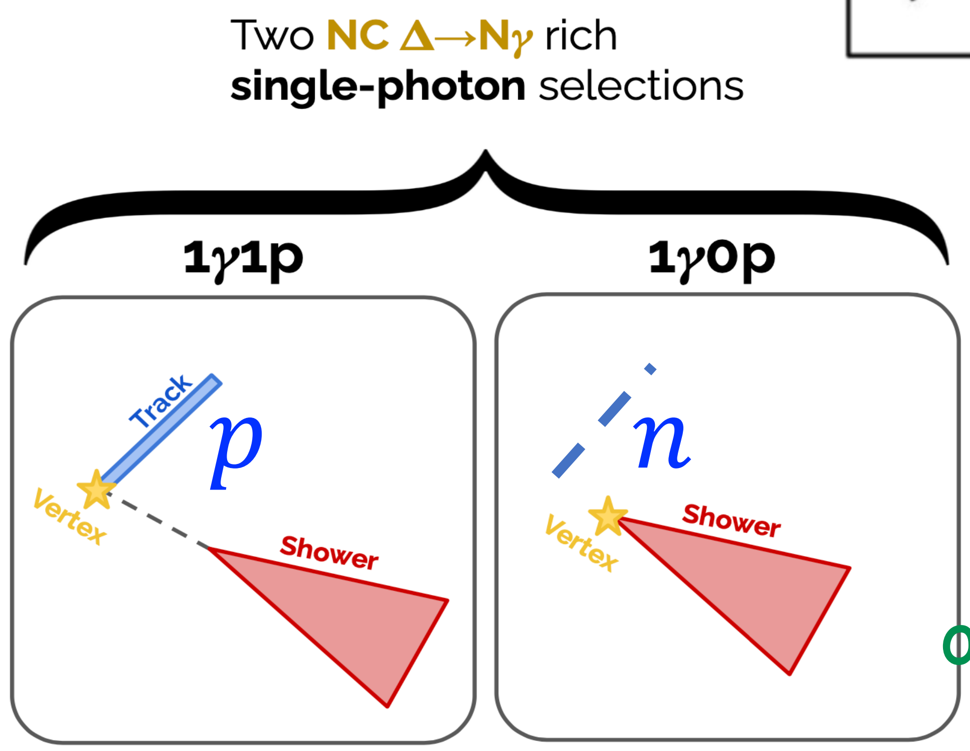
Targeting NC Δ resonance radiative decay ($\Delta \rightarrow N\gamma$)
- Standard model process
- Never been directly observed in neutrino scattering
- Previous best experimental limit at O(1 GeV) is orders of magnitude higher than the prediction

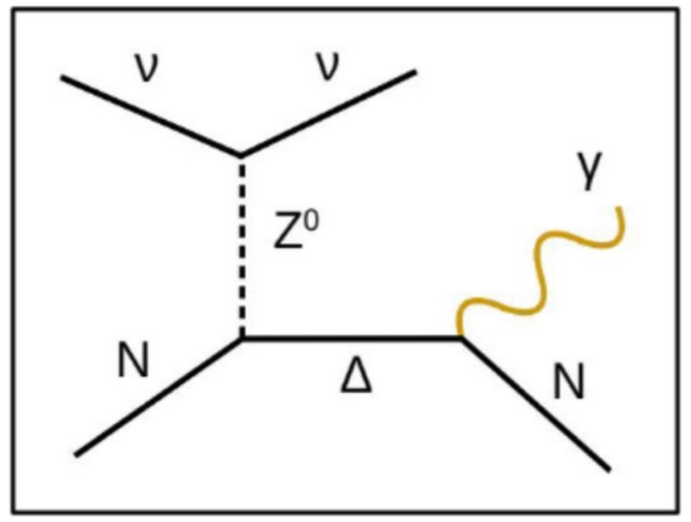
MiniBooNE Collaboration Phys. Rev. D 103, 052002 (2021)



- An enhancement in NC Δ → Nγ with a multiplicative factor of **x3.18** would give good agreement with the observed MiniBooNE LEE

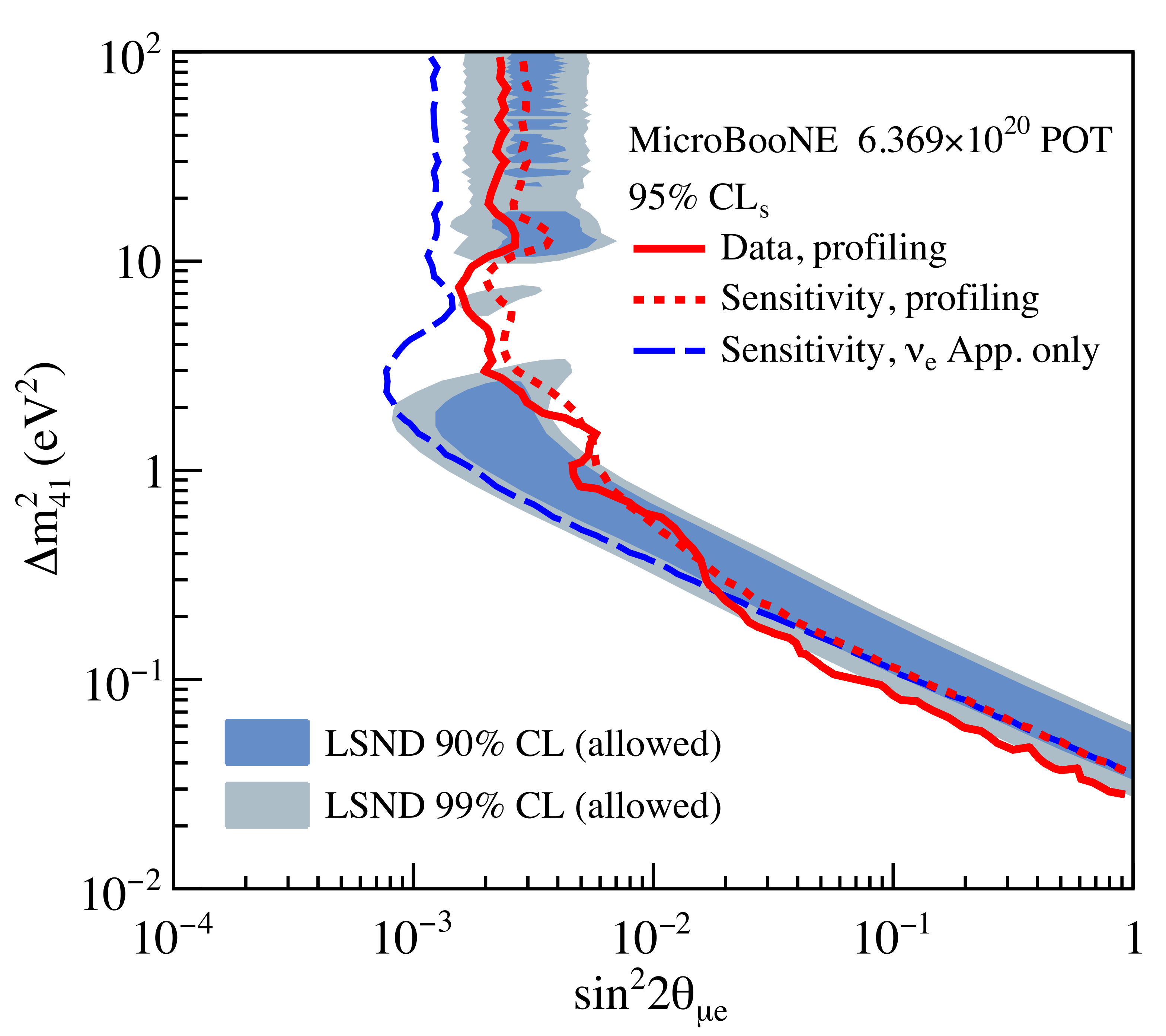
Event topologies

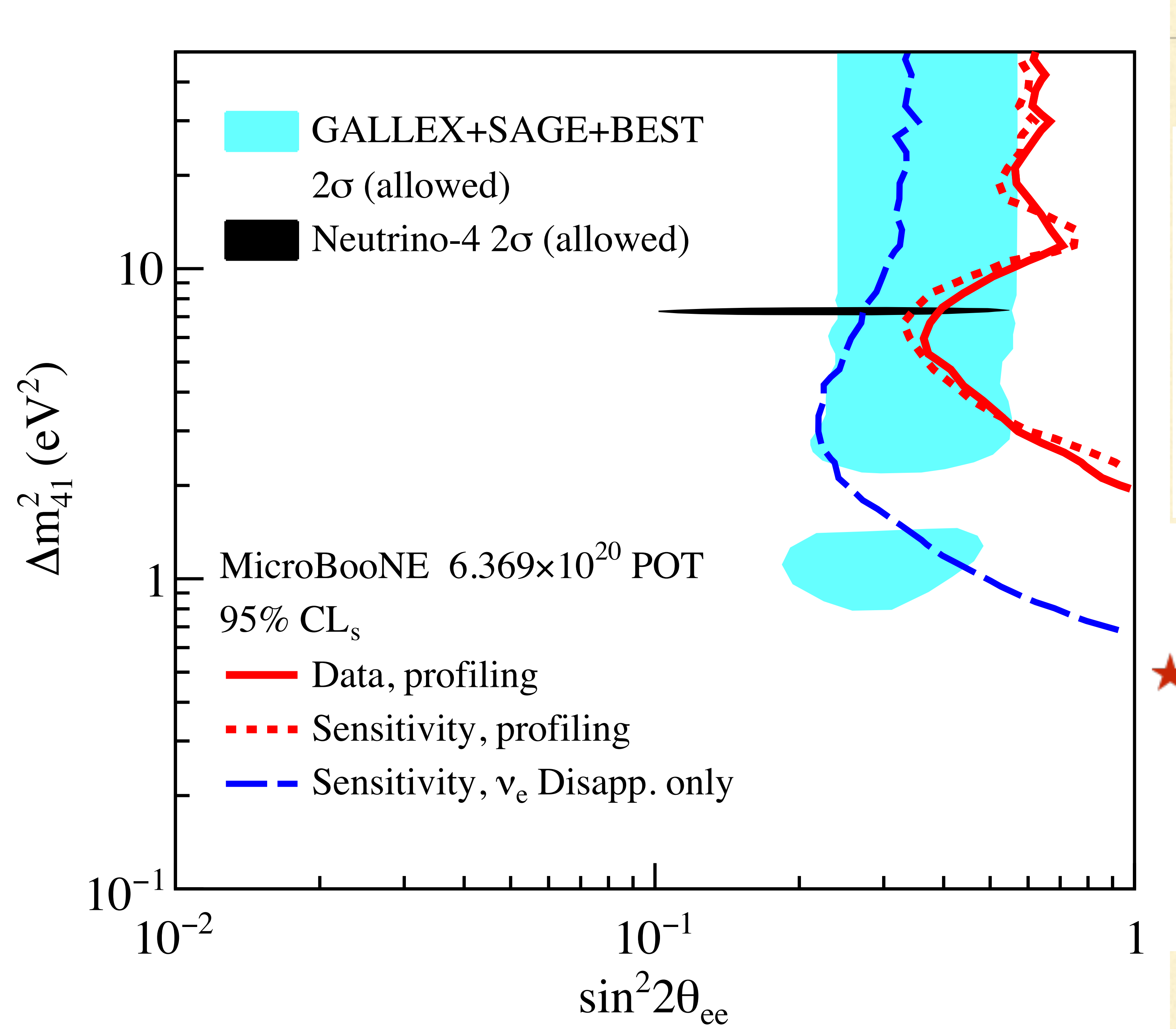


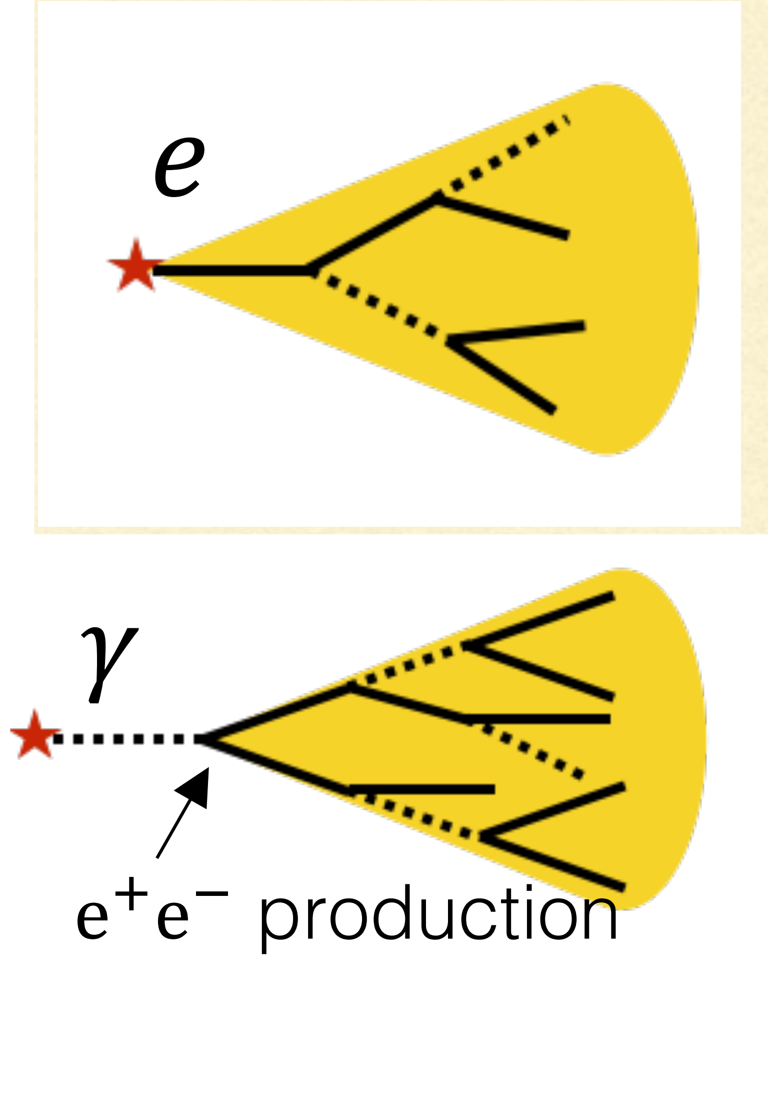


No evidence for any enhancement over SM prediction

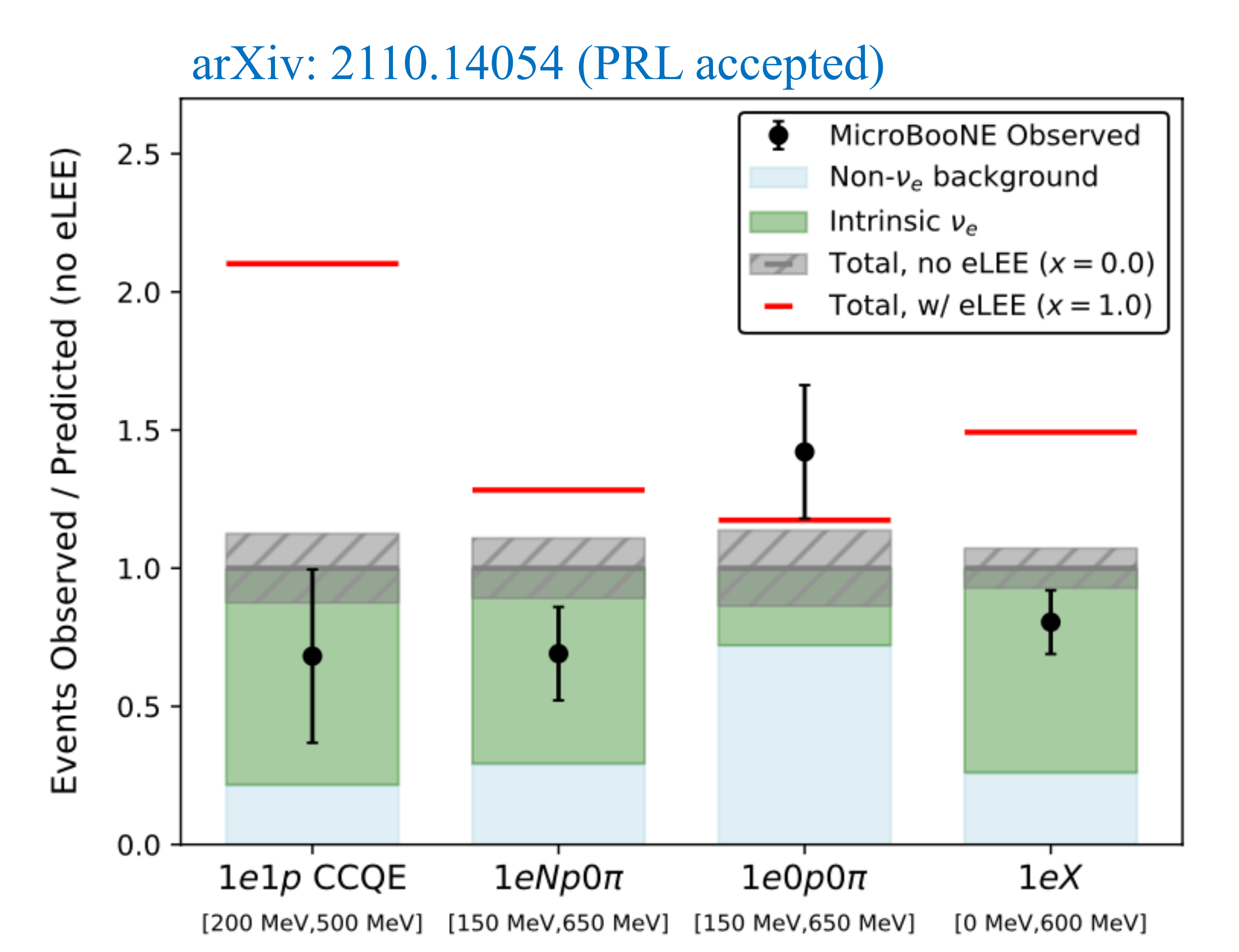
(From Hanyu Wei, Nu 2022 talk)







(MicroBooNE 2210.10216)



- Finally, latest results from the MicroBoone detector strongly disfavour the sterile neutrino hypothesis of electron appearance as a solution to the LSND and MB excesses.

MicroBooNE results……

"These results disfavor the hypothesis that the MiniBooNE low-energy excess originates solely from an excess of ve interactions. Instead, one or more additional mechanisms [45–52] are required to explain the MiniBooNE observations. "

(MicroBooNE Collab, 2210.10216)

- [45] A.de Gouvˆea,O.L.G.Peres,S.Prakash,andG.V. Stenico, arXiv:1911.01447 [hep-ph].

  (Sterile to active decay)
- [46] S. Vergani, N. W. Kamp, A. Diaz, C. A. Argu¨elles, J. M. Conrad, M. H. Shaevitz, arXiv:2105.06470 [hep-ph].

  (Mix of sterile osc and decay to active)
- [47] J. Asaadi, E. Church, R. Guenette, B. J. P. Jones, and A. M. Szelc, arXiv:1712.08019 [hep-ph].

  (New matter resonance effects)
- [48] D. S. M. Alves, W. C. Louis, and P. G. deNiverville, arXiv:2201.00876 [hep-ph].

  (New matter resonance effects)
- [49] E. Bertuzzo, S. Jana, P. A. N. Machado, and R. Zukanovich Funchal, arXiv:1807.09877 [hep-ph].

  (Up-scattering and additional Z')
- [50] P. Ballett, S. Pascoli, and M. Ross-Lonergan, arXiv:1808.02915 [hep- ph].

  (Up-scattering and additional Z')
- [51] W. Abdallah, R. Gandhi, and S. Roy, arXiv:2010.06159 [hep-ph].

  (Up-scattering and additional Z')
- [52] W. Abdallah, R. Gandhi, and S. Roy, arXiv:2006.01948 [hep-ph].

  (Up-scattering and Additional scalars)

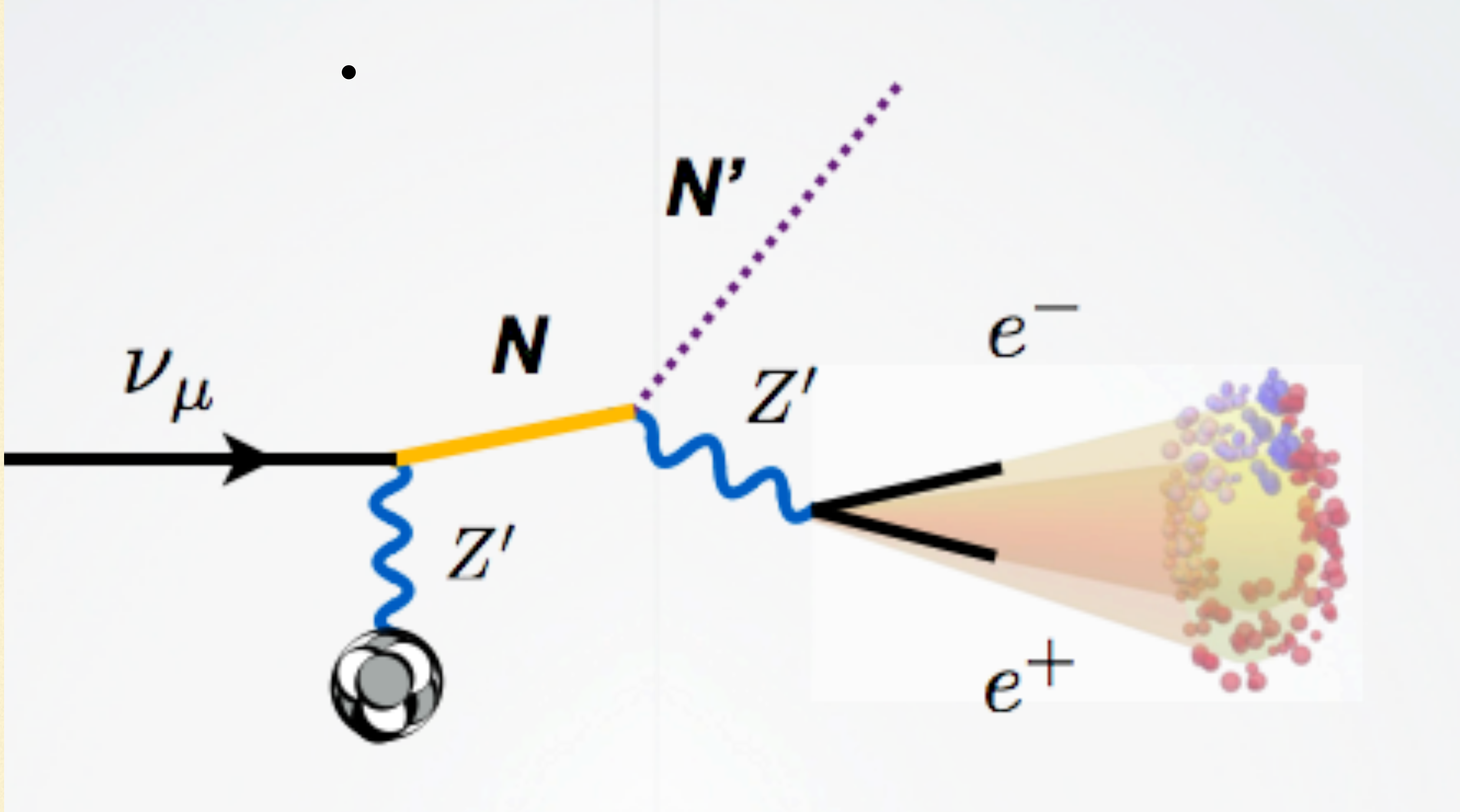
- Given the situation as summarised, it makes sense to consider new physics solutions to MB and LSND which involve sterile neutrinos, but not those at the eV scale and involved in active-sterile oscillations.

-

New Physics solutions to MB and LSND

- Generic new physics process
-

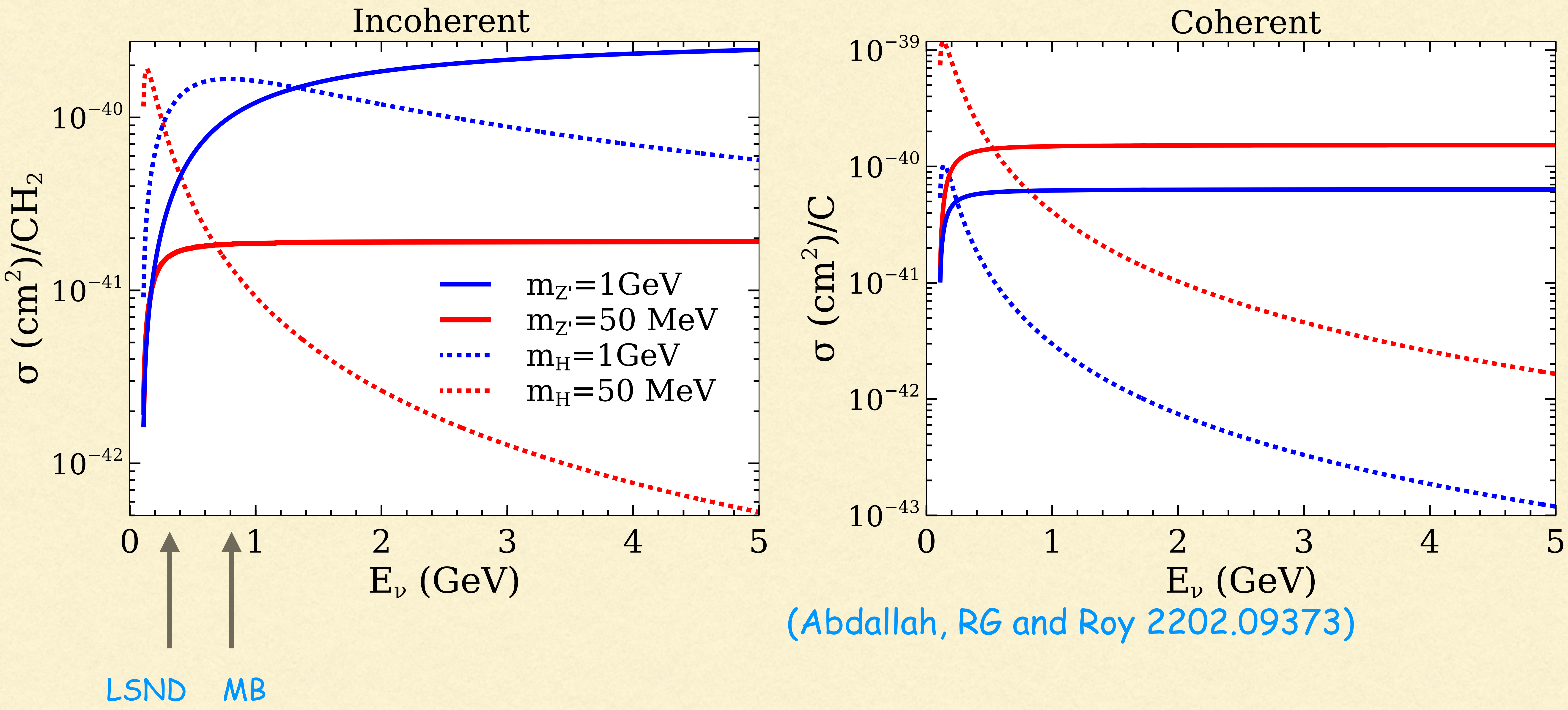
NSI, but at low energies



Using an additional Z' and heavier sterile neutrinos, it is possible to get good fits to the MB data

Bertuzzo, Jana, Machado & Funchal, 1807.09877;
Ballet, Pascoli, Ross-Lonergon 1808.02915;
Abdallah, RG and Roy 2006.01948)

However, it is very difficult to explain both LSND and MB simultaneously using these ingredients, because a vector mediator does not give enough events at LSND

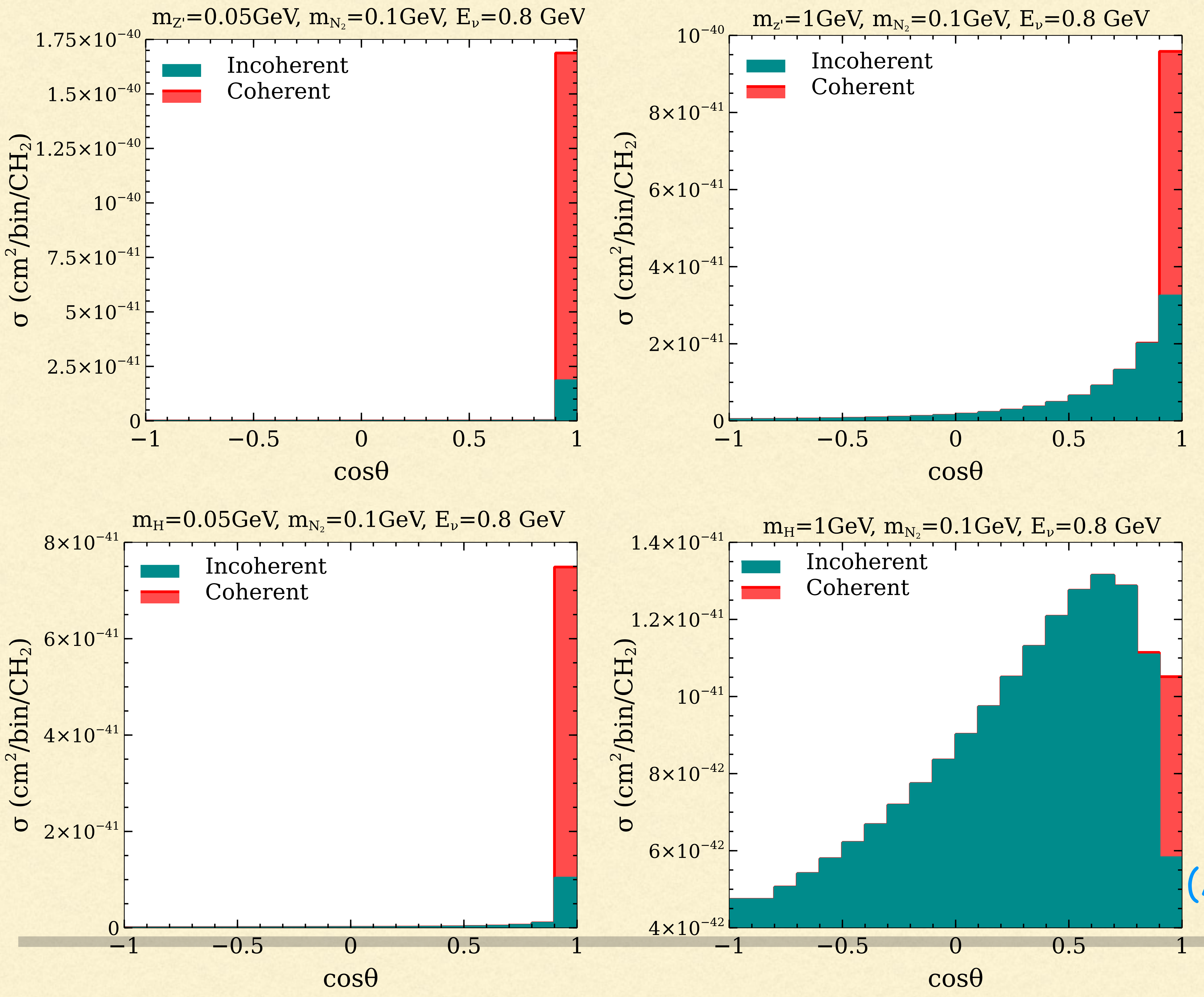


(Abdallah, RG and Roy 2202.09373)

Scalar mediators not only avoid HE constraints that vector mediators have difficulty avoiding, but also give enough events at LSND once you get the required number at MB.

Vector models, given the shape of the xsec, violate constraints by experiments with higher E, e.g. CHARM II (E_nu ~ 20 GeV and MINERvA, E_nu ~ 4-5 GeV

One learns something new if one demands that the new physics resolve both LSND and MB, as opposed to just MB.



By studying the angular distribution at MB for both light and not so light scalar and vector mediators, one discerns the need for both a light and an intermediate mass mediator

(Abdallah, RG and Roy 2202.09373)

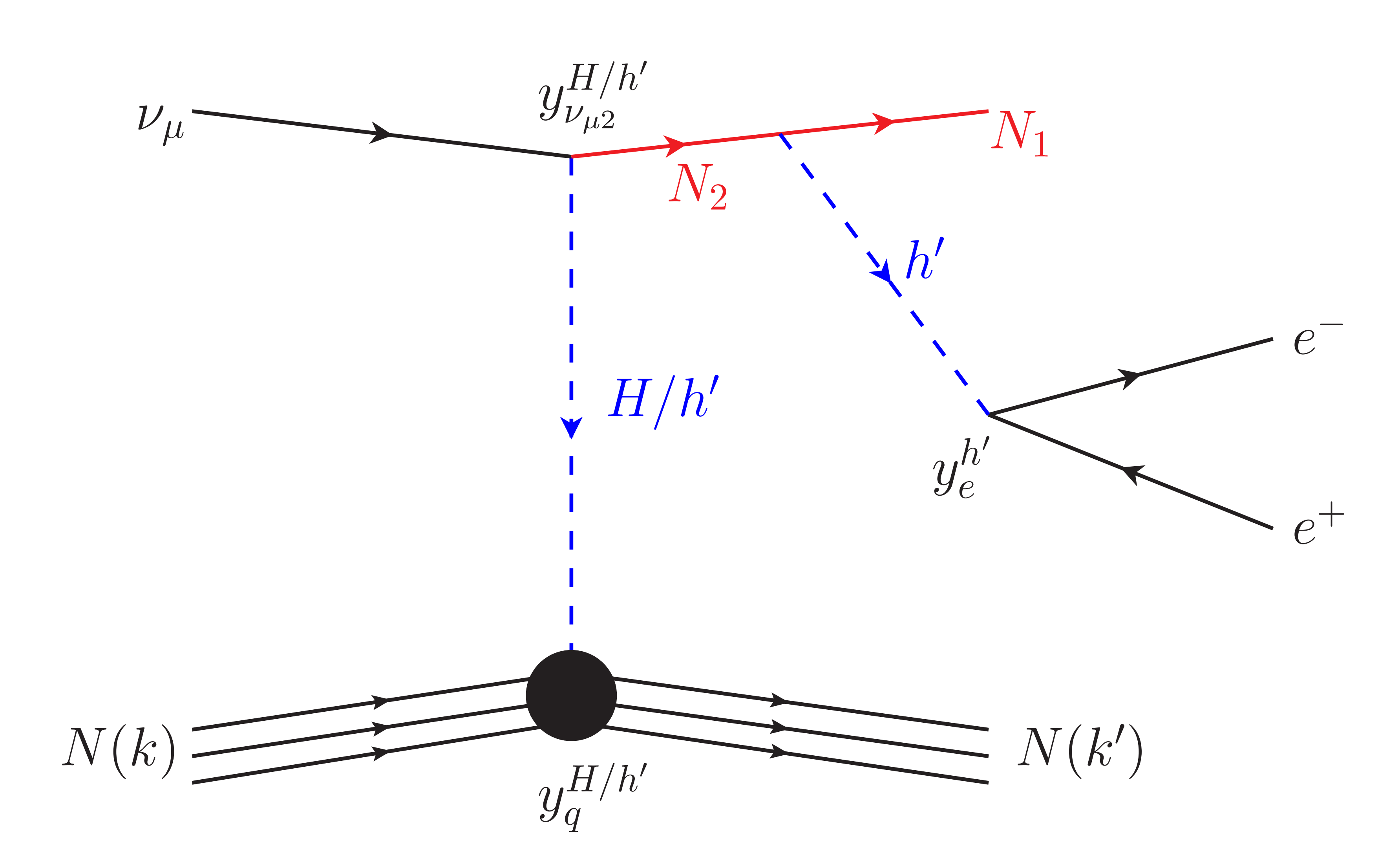
The model, ……

$$
\begin{aligned}
V = & \, |\phi_h|^2 \left(\frac{\lambda_1}{2} |\phi_h|^2 + \lambda_3 |\phi_H|^2 + \mu_1 \right) \\
& + |\phi_H|^2 \left(\frac{\lambda_2}{2} |\phi_H|^2 + \mu_2 \right) + \lambda_4 (\phi_h^\dagger \phi_H)(\phi_H^\dagger \phi_h) \\
& + \phi_{h'}^2 \left(\lambda_2' \phi_{h'}^2 + \lambda_3' |\phi_h|^2 + \lambda_4' |\phi_H|^2 + m' \phi_{h'} + \mu' \right) \\
& + \left[\phi_h^\dagger \phi_H \left(\frac{\lambda_5}{2} \phi_h^\dagger \phi_H + \lambda_6 |\phi_h|^2 + \lambda_7 |\phi_H|^2 + \lambda_5' \phi_{h'}^2 - \mu_{12} \right) \right. \\
& \left. + \phi_{h'} (m_1 |\phi_h|^2 + m_2 |\phi_H|^2 + m_{12} \phi_h^\dagger \phi_H) + h.c. \right], \qquad (1)
\end{aligned}
$$

$(\phi_h, \phi_H, \phi_{h'})$

Ingredients :

2nd Higgs doublet + one dark singlet , and 3 RH neutrinos

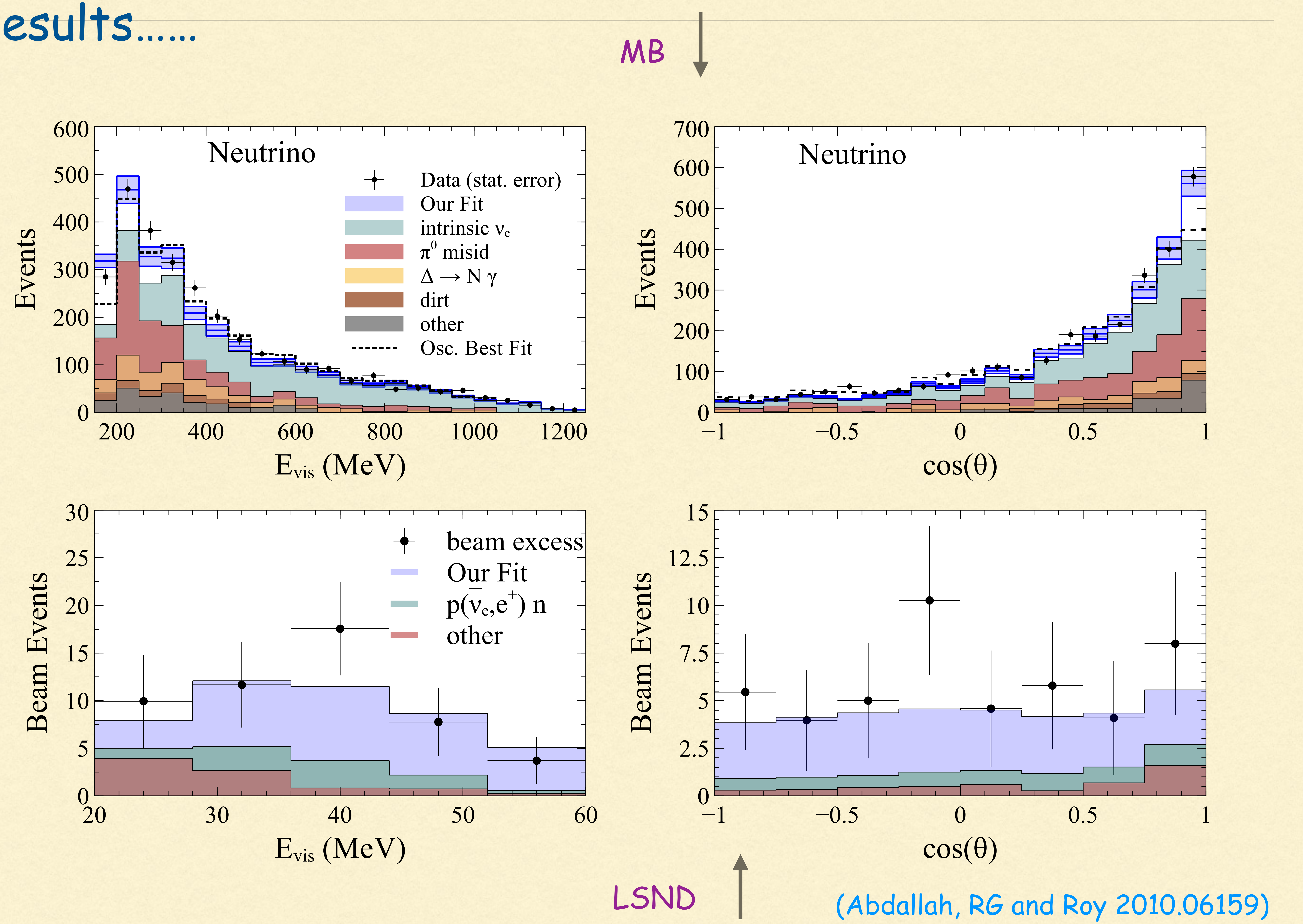


m_{N_1}	m_{N_2}	m_{N_3}	$y_u^{h'(H)}\times 10^6$	$y_{e(\mu)}^{h'}\times 10^4$	$y_{e(\mu)}^{H}\times 10^4$
85 MeV	130 MeV	10 GeV	0.8(8)	0.73(1.6)	7.25(15.9)
$m_{h'}$	m_H	$\sin\delta$	$y_d^{h'(H)}\times 10^6$	$y_{\nu_{i2}}^{h'(H)}\times 10^3$	$\lambda_{N_{12}}^{h'(H)}\times 10^3$
15 MeV	750 MeV	0.1	0.8(8)	1.3(12.4)	7.5(74.4)

TABLE I: Benchmark parameter values used for event generation in LSND, MB and for calculating the muon $g-2$.

(Abdallah, RG and Roy 2010.06159)

Results……



(Abdallah, RG and Roy 2010.06159)

Conclusions……

- Short baseline anomalies like the Ga source anomaly, the RAA, LSND and MB have reached a stage where a host of complementary experiments and theoretical inputs have helped gradually clarify the situation. No clear resolution has yet emerged, however.

- The situation with the Ga anomaly is unclear, given that the most recent experiment, BEST, verifi the presence of the deficit but could not detect any L variation, which would have signalled active sterile oscillations

- Improved data on beta spectra and consequent improved flux calculations point to a disappearance the RAA.

- Attempts to understand the anomalies using oscillations with eV scale neutrinos show a very strong tension between appearance and disappearance data.

The MB and LSND anomalies persist with a high combined statistical significance of 6.1 sigma

Conclusions……

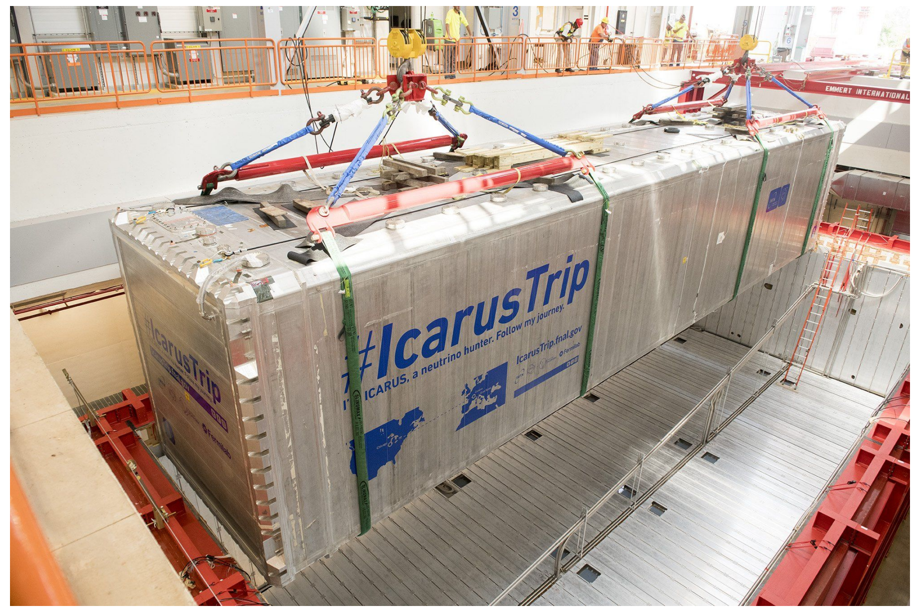
MicroBooNE has recently made important (but not conclusive) strides in helping establish that SM backgrounds are unlikely to be responsible for the MB signal, strengthening the case that MB and possibly LSND could be signals for new physics.

It is significant that sterile neutrinos (much) heavier than ~eV play a role in most new physics proposals put forward to explain the anomaly (anomalies)

A definitive resolution must await results from the Fermilab Short Baseline Program, with its 3 detectors , MicroBooNE, ICARUS and SBND.

Short Baseline Neutrino Program at Fermilab

Anne Schukraft talk at Neutrino 2022

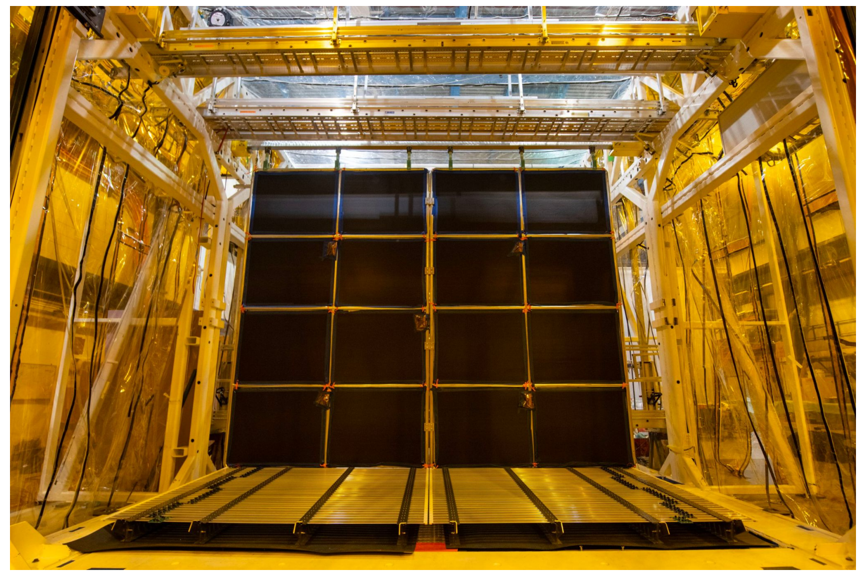


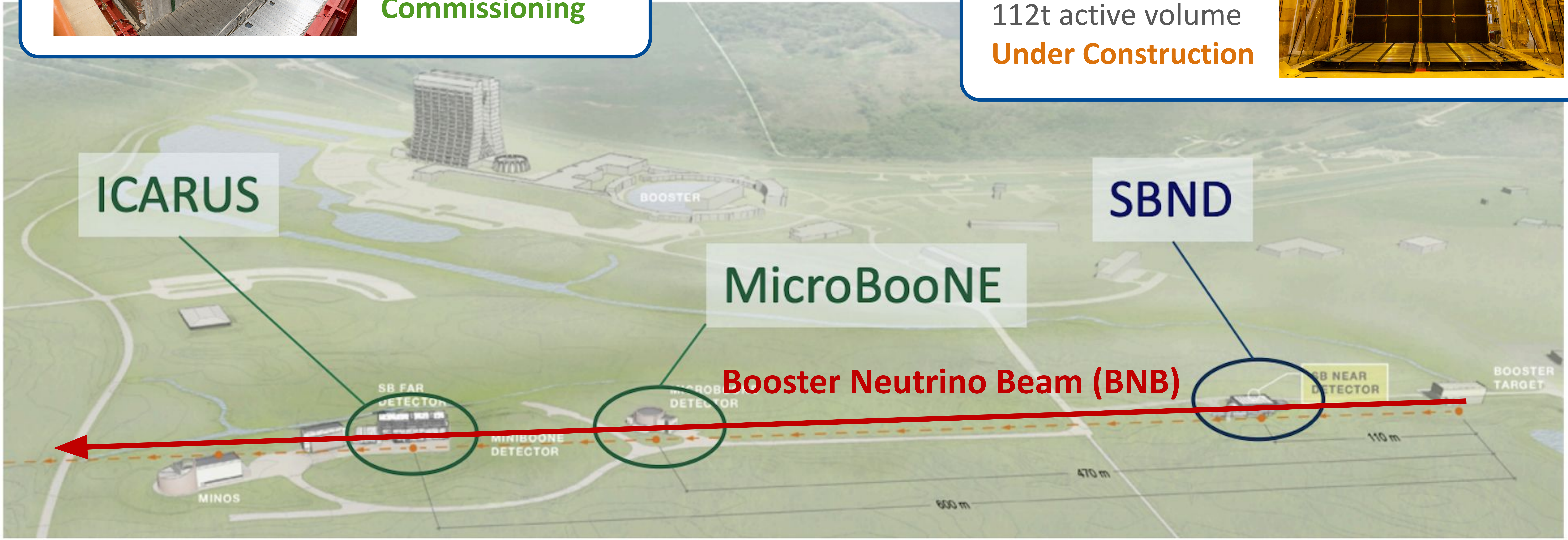
ICARUS

600m baseline
470t active volume
Commissioning

SBND

110m baseline
112t active volume
Under Construction





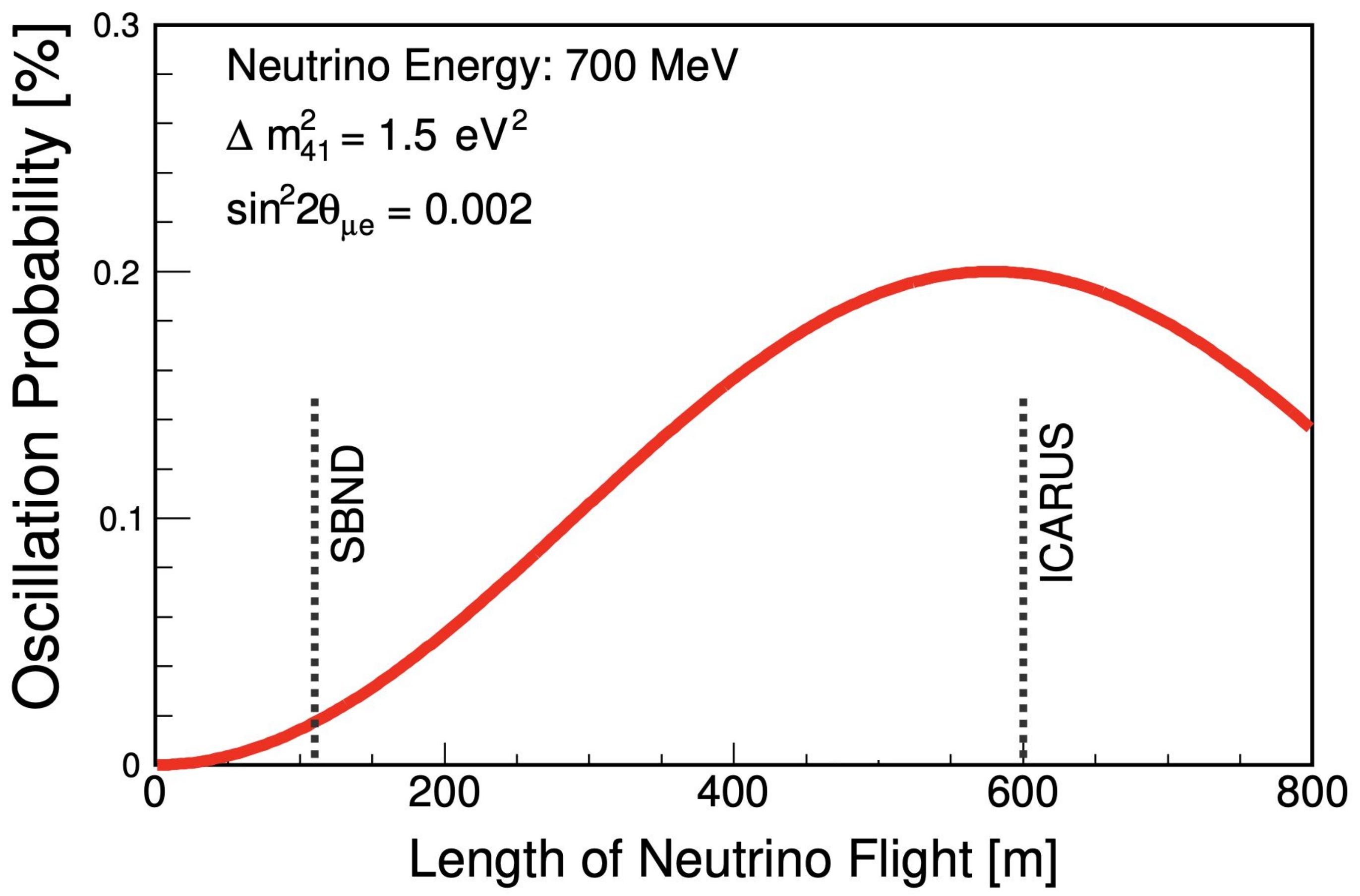
- Three detectors sampling the *same neutrino beam* at different distances

SBN Oscillation Sensitivity

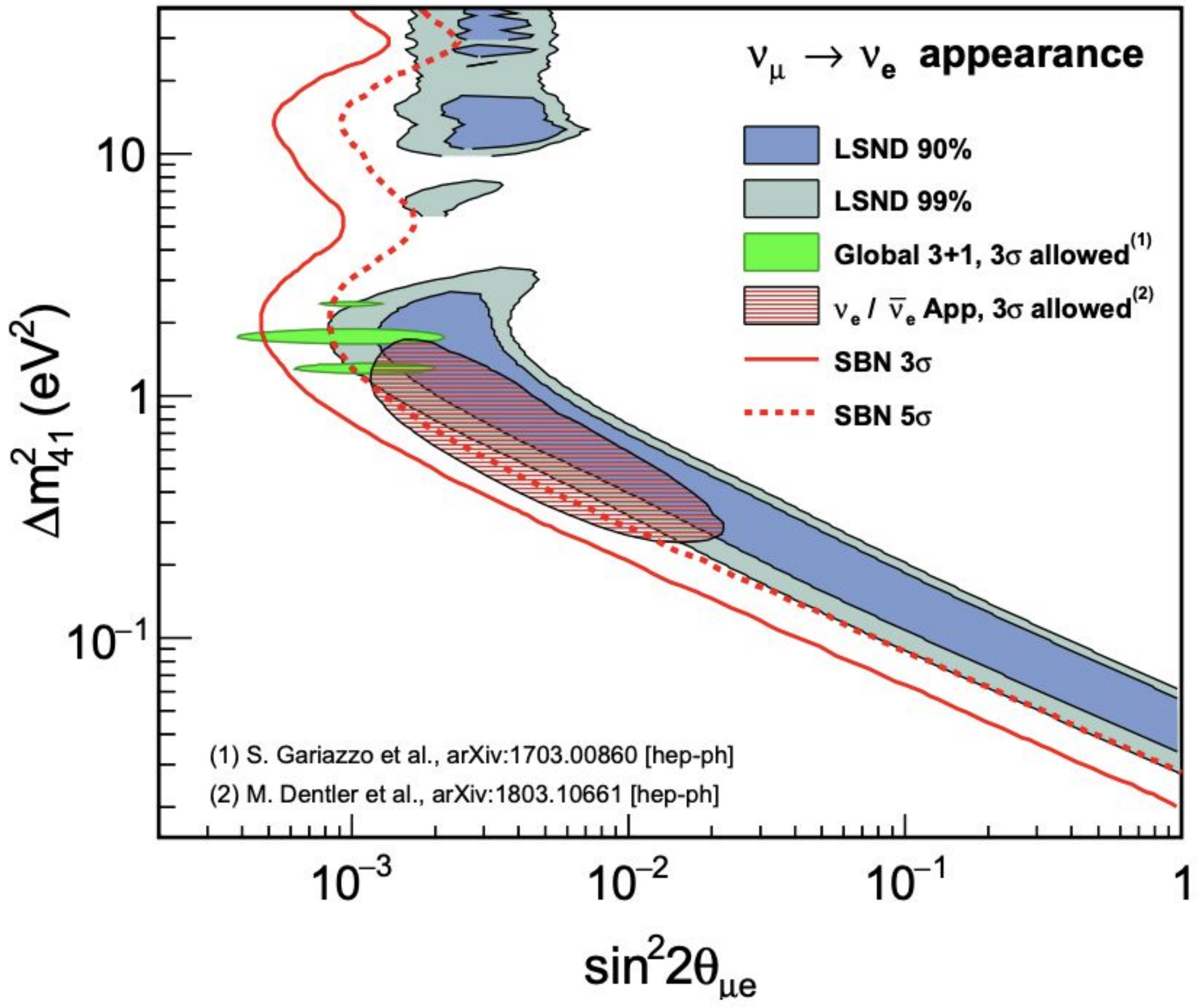
Anne Schukraft talk at Neutrino 2022

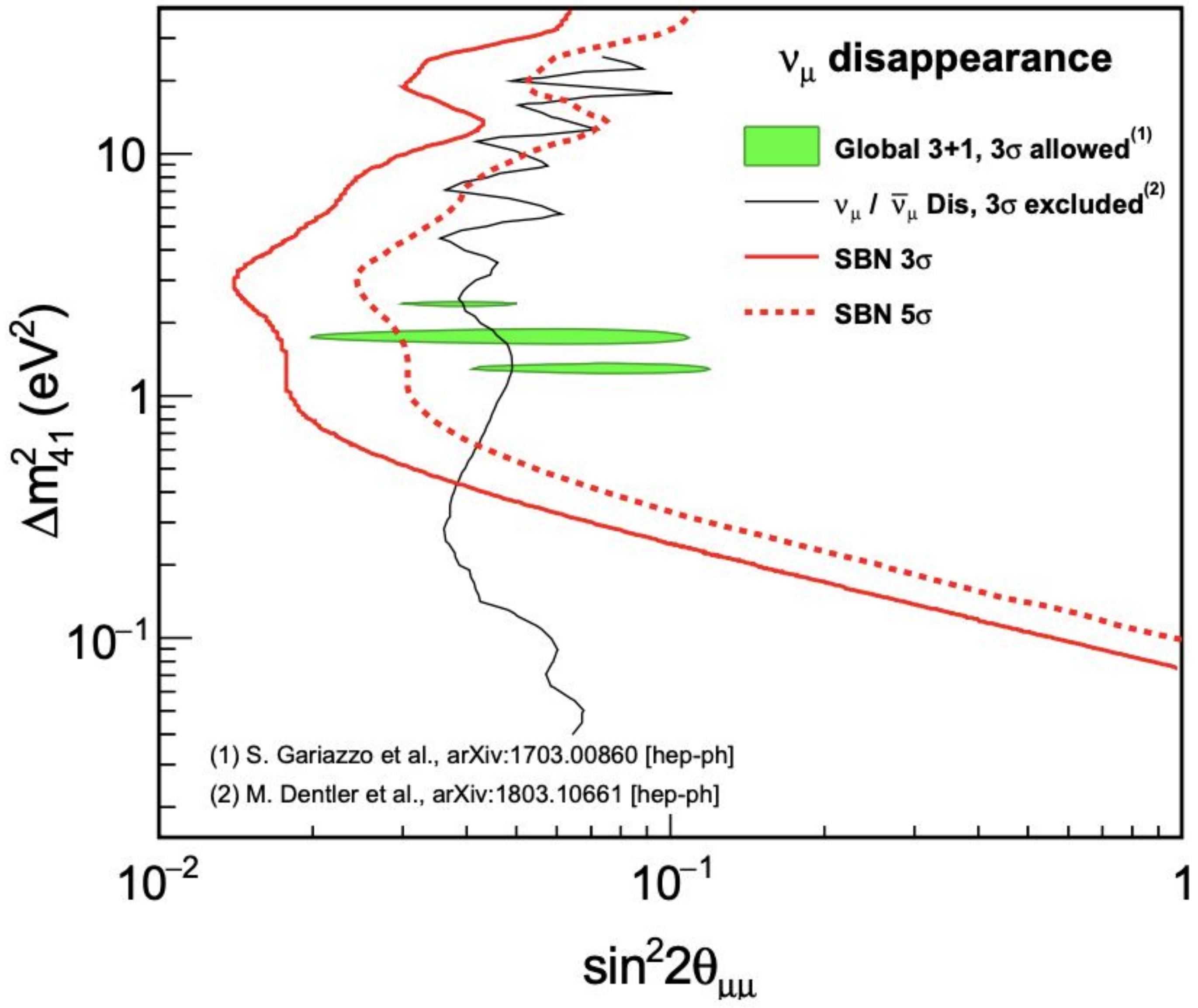
- SBND + ICARUS will test the sterile neutrino hypothesis
  - can cover the parameter space favored by past anomalies with 5σ significance
- Observing neutrino flux at different distances from the beam target
- Effective systematics constraint through near detector (SBND) and same detector technology in near and far detector
- **Search for appearance of ν_e and disappearance of ν_μ within the same experiment**
  - current results show a 4.7σ tension between ν_e appearance and ν_μ disappearance channels

(SBN sensitivities for 6.6 x 10^{20} protons on the BNB target)



P. Machado et al, arXiv:1903.04608V11





Thank you for your attention!

Back-up Slides

Coherent neutrino Scattering and NSI…………

Coherent elastic neutrino-nucleus scattering (CEvNS), which has been recently observed by the COHERENT collaboration

$$\frac{d\sigma}{dT} = \frac{G_F^2 Q_{SM}^2 M}{4\pi}\left(1 - \frac{T}{T_{\max}}\right),$$

$$Q_{SM}^2 = \left[N - (1 - 4s_W^2)Z\right]^2, \; T_{\max} = \frac{2E_\nu^2}{M + 2E_\nu},$$

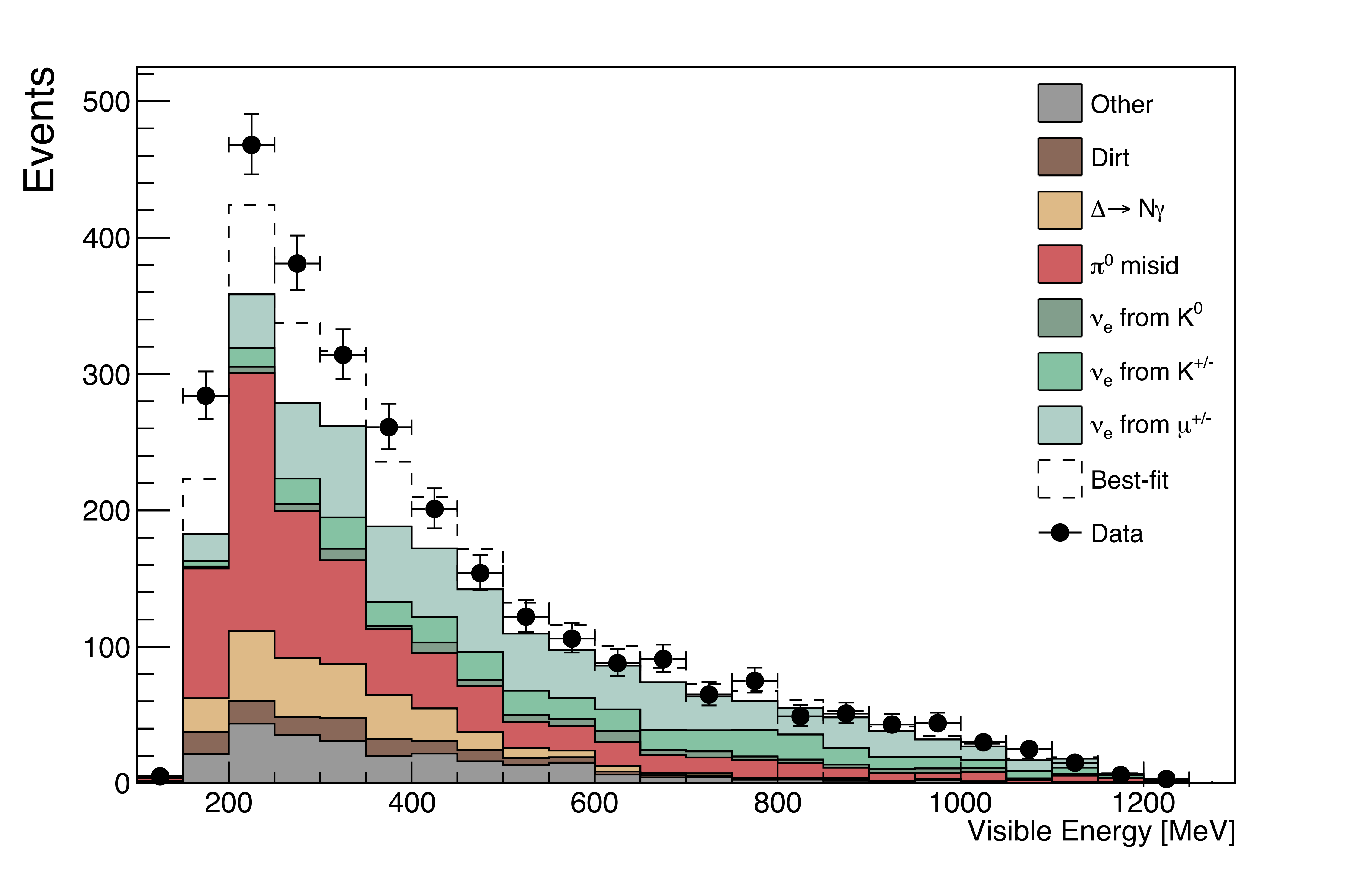
where **M** is the mass of the nucleus, **T** is the recoil energy of the nucleus, **Tmax** is the maximal recoil energy that can be generated for a certain value of neutrino energy, **N** and **Z** are the neutron and proton numbers of the nucleus.

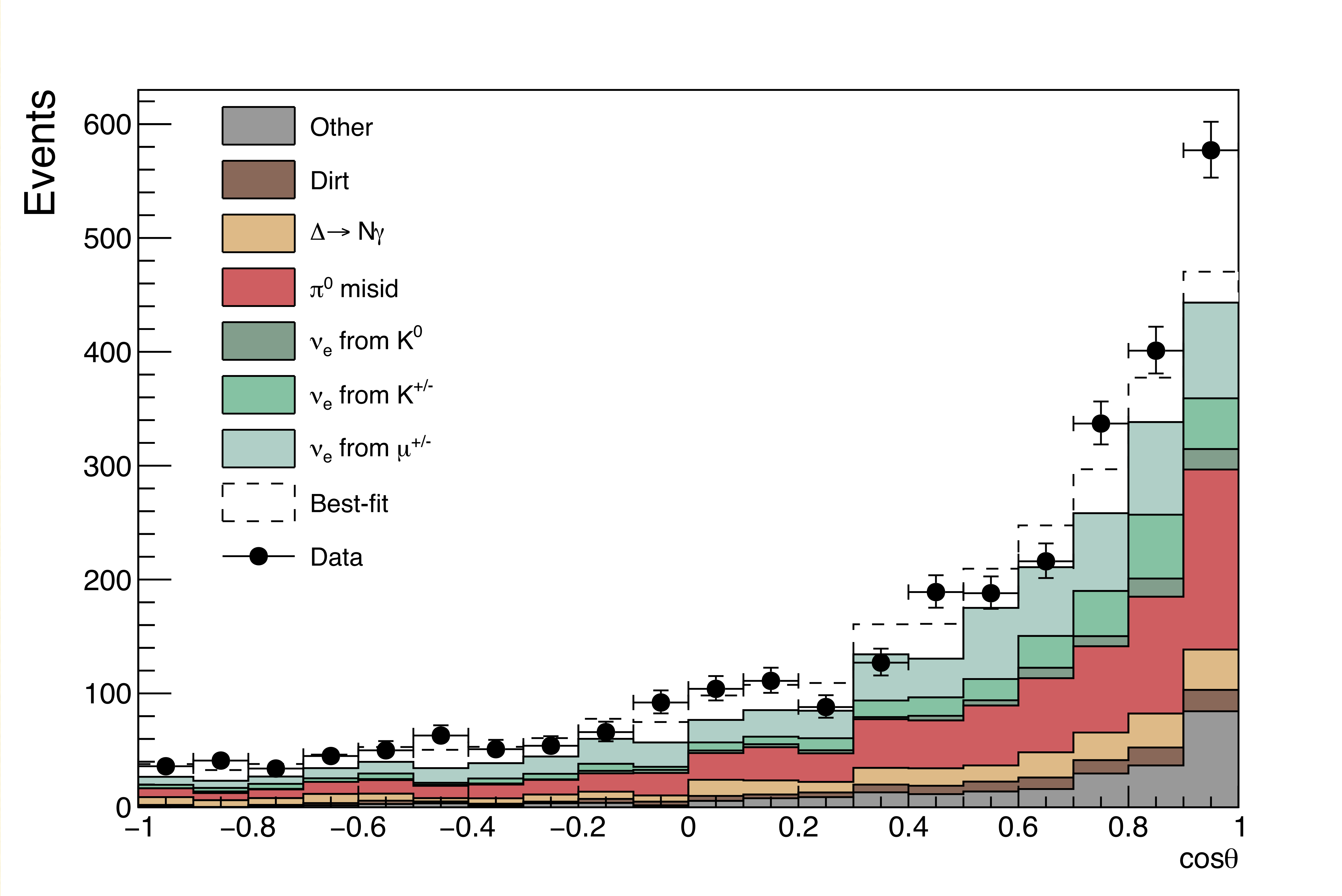
$$Q^2_{\rm NSI} \equiv 4\left[N(-\frac{1}{2}+\varepsilon^{uV}_{ee}+2\varepsilon^{dV}_{ee})+Z(\frac{1}{2}-2s^2_W+2\varepsilon^{uV}_{ee}+\varepsilon^{dV}_{ee})\right]^2$$

$$+4\sum_{\alpha=\mu,\tau}\left[N(\varepsilon^{uV}_{\alpha e}+2\varepsilon^{dV}_{\alpha e})+Z(2\varepsilon^{uV}_{\alpha e}+\varepsilon^{dV}_{\alpha e})\right]^2 .$$

For NSI, what CEvNS can measure is actually $Q^2_{\rm NSI}$, which leads to a lot of degeneracy among those NSI parameters. From studies one can summarize the current COHERENT constraints on NSIs, which are that generally around O(0.5). In the future, CEvNS experiments based on reactor sources can provide very strong constraints on NSIs, due to the potentially high statistics.

An example ……MiniBooNE anomaly





- The observation of a 4.8σ excess in electron-like events for neutrino and antineutrino modes in the MiniBooNE (MB) detector is observed

- SM: 2309 events
  Data: 2870
  Excess: 560

Excess is not small. Note it is at level of important SM backgrounds

Distinctive energy and angular distribution

Dashed line is oscillation fit. Not a good fit at low energies or forward angles where most events present

The model, ……

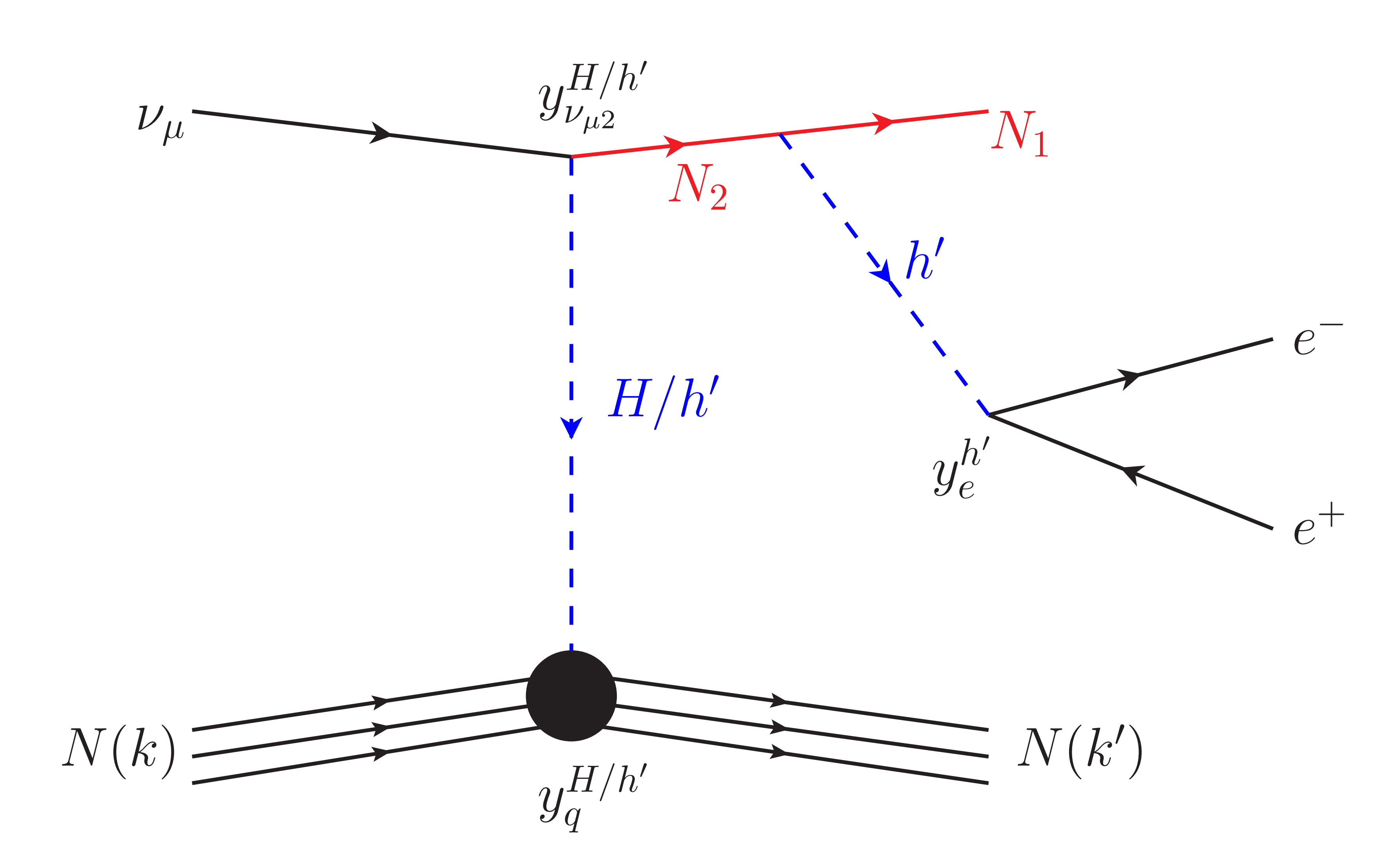
$$V= |\phi_h|^2\left(\frac{\lambda_1}{2}|\phi_h|^2+\lambda_3|\phi_H|^2+\mu_1\right)$$
$$+|\phi_H|^2\left(\frac{\lambda_2}{2}|\phi_H|^2+\mu_2\right)+\lambda_4(\phi_h^\dagger\phi_H)(\phi_H^\dagger\phi_h)$$
$$+\phi_{h'}^2\left(\lambda_2'\phi_{h'}^2+\lambda_3'|\phi_h|^2+\lambda_4'|\phi_H|^2+m'\phi_{h'}+\mu'\right)$$
$$+\Big[\phi_h^\dagger\phi_H\left(\frac{\lambda_5}{2}\phi_h^\dagger\phi_H+\lambda_6|\phi_h|^2+\lambda_7|\phi_H|^2+\lambda_5'\phi_{h'}^2-\mu_{12}\right)$$
$$+\phi_{h'}(m_1|\phi_h|^2+m_2|\phi_H|^2+m_{12}\phi_h^\dagger\phi_H)+h.c.\Big], \qquad (1)$$

$(\phi_h, \phi_H, \phi_{h'})$

Ingredients :

2nd Higgs doublet + one dark singlet , and 3 RH neutrinos

MeV energies, both for beam and particle masses



m_{N_1}	m_{N_2}	m_{N_3}	$y_u^{h'(H)}\times10^6$	$y_{e(\mu)}^{h'}\times10^4$	$y_{e(\mu)}^{H}\times10^4$
85 MeV	130 MeV	10 GeV	0.8(8)	0.73(1.6)	7.25(15.9)

$m_{h'}$	m_H	$\sin\delta$	$y_d^{h'(H)}\times10^6$	$y_{\nu_{i2}}^{h'(H)}\times10^3$	$\lambda_{N_{12}}^{h'(H)}\times10^3$
15 MeV	750 MeV	0.1	0.8(8)	1.3(12.4)	7.5(74.4)

TABLE I: Benchmark parameter values used for event generation in LSND, MB and for calculating the muon $g-2$.

(Abdallah, RG and Roy 2010.06159)

Standard Neutrino oscillations…….in the vacuum

$$P(\nu_e \to \nu_\mu; L) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right),$$

$$P(\nu_e \to \nu_e) = 1 - P(\nu_e \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_e) = P(\nu_\mu \to \nu_\mu),$$

$$P(\nu_\alpha \to \nu_\beta; L) = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

$$+\, 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

$\alpha, \beta = e, \mu, \tau$.

Putting constraints on NSI…………accelerator neutrinos, (MINOS)

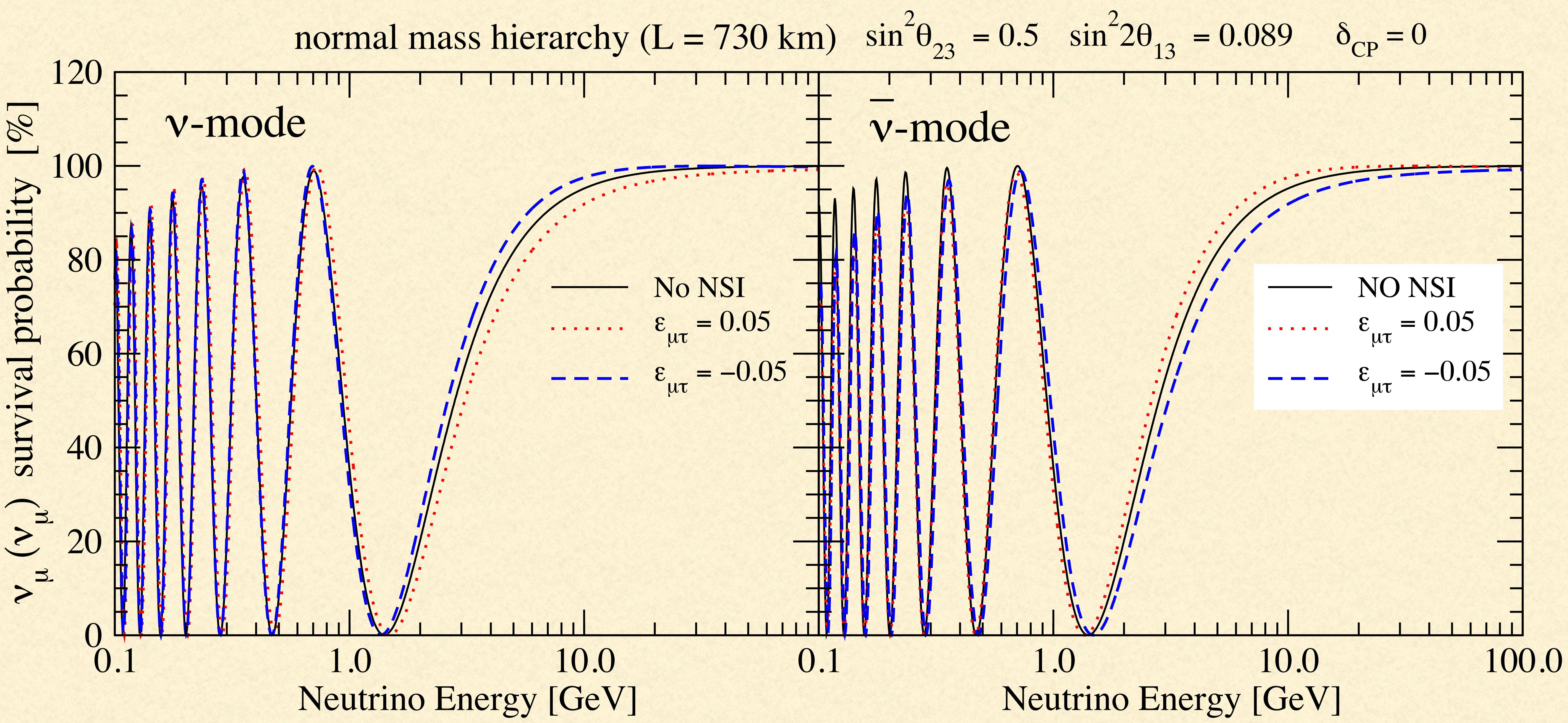


Figure 3. $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ survival probabilities as a function of neutrino energy for the MINOS baseline, $L = 730$ km without the presence of NSI with and with NSI, $\varepsilon_{\mu\tau} = \pm 0.1$. The matter density was assumed to be constant, $\rho = 3.2$ g/cm^3.

$$-0.067 < \varepsilon_{\mu\tau} < 0.023 \text{ at } 90\% \text{ CL.}$$

Miranda and Nunokawa, 1505.06254

Standard Neutrino oscillations…….in the vacuum

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix},$$

U relates the weak interaction eigenstates and the mass eigenstates through the leptonic mixing parameters θ_{12}, θ_{13}, θ_{23}, δ (the Dirac CP-violating phase), as well as ρ and σ (the Majorana CP-violating phases).

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} \equiv \cos(\theta_{ij})$ and $s_{ij} \equiv \sin(\theta_{ij})$.

Two flavour oscillations with NSI

$$i\frac{d}{dL}\begin{pmatrix}\nu_e\\ \nu_\tau\end{pmatrix} = \left[\frac{1}{2E}U\begin{pmatrix}0 & 0\\ 0 & \Delta m^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\tau}\\ \epsilon_{e\tau} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\tau\end{pmatrix}$$

$$P(\nu_e \to \nu_\tau) = \sin^2 2\theta_M \; \sin^2\left(\frac{\Delta m_M^2 L}{4E}\right)$$

$$\left(\frac{\Delta m_M^2}{2EA}\right)^2 \equiv \left(\frac{\Delta m^2}{2EA}\cos 2\theta - (1+\epsilon_{ee}-\epsilon_{\tau\tau})\right)^2 + \left(\frac{\Delta m^2}{2EA}\sin 2\theta + 2\epsilon_{e\tau}\right)$$

$$\sin 2\theta_M \equiv \frac{\Delta m^2 \sin 2\theta + 4EA\epsilon_{e\tau}}{\Delta m_M^2}$$

T Ohlsson, 1209.2710

Two flavour oscillations with NSI

Note that as $\varepsilon_{ee}, \varepsilon_{e\tau}, \varepsilon_{\tau\tau} \to 0$, i.e. as NSI effects disappear,we get

$$\left(\Delta\tilde{m}_0^2\right)^2 = \left[\Delta m^2 \cos(2\theta) - A\right]^2 + \left[\Delta m^2 \sin(2\theta)\right]^2 ,$$

$$\sin\left(2\tilde{\theta}_0\right) = \frac{\Delta m^2 \sin(2\theta)}{\Delta\tilde{m}_0^2} ,$$

Thus, we get back the SM MSW matter oscillations.

We thus see that measurements of mass-squared differences and mixing angles can be affected by the presence of NSI when we study neutrino oscillations in matter.

Putting constraints on NSI…………detection of reactor neutrinos

In general, somewhat complicated analytical expressions which mimic the form of SM probabilities are possible

$$\varepsilon^s_{e\alpha} = \varepsilon^{d*}_{\alpha e} = |\varepsilon_{e\alpha}| e^{i\phi_{e\alpha}}$$

$$\begin{aligned} \tilde{s}^2_{13} \; = \; & s^2_{13} + 2 s_{13} c_{13} \left[s_{23} \cos(\delta - \phi_{e\mu}) |\varepsilon_{e\mu}| + c_{23} \cos(\delta - \phi_{e\tau}) |\varepsilon_{e\tau}| \right. \\ & \left. - s_{23} \cos(\delta - \phi_{ee} - \phi_{e\mu}) |\varepsilon_{ee}||\varepsilon_{e\mu}| - c_{23} \cos(\delta - \phi_{ee} - \phi_{e\tau}) |\varepsilon_{ee}||\varepsilon_{e\tau}| \right] \\ & + (s^2_{23} c^2_{13} - s^2_{13}) |\varepsilon_{e\mu}|^2 + (c^2_{23} c^2_{13} - s^2_{13}) |\varepsilon_{e\tau}|^2 \\ & + 2 s_{23} c_{23} c^2_{13} \cos(\phi_{e\mu} - \phi_{e\tau}) |\varepsilon_{e\mu}||\varepsilon_{e\tau}| + \mathcal{O}(\varepsilon^3) \; , \end{aligned}$$

$$\begin{aligned} P(\bar{\nu}^s_e \to \bar{\nu}^d_e) \; = \; & 1 - \cos^4 \tilde{\theta}_{13} \sin^2 2\tilde{\theta}_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E} - \cos^2 \tilde{\theta}_{12} \sin^2 2\tilde{\theta}_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\ & - \sin^2 \tilde{\theta}_{12} \sin^2 2\tilde{\theta}_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E} \; . \end{aligned}$$