# Theoretical Overview of the MiniBooNE Neutrino Anomaly

**Carlo Giunti**

INFN, Torino, Italy

Joint INFN-UNIMI-UNIMIB Pheno Seminar

23 May 2019, Milano

# Standard Three Neutrino Mixing

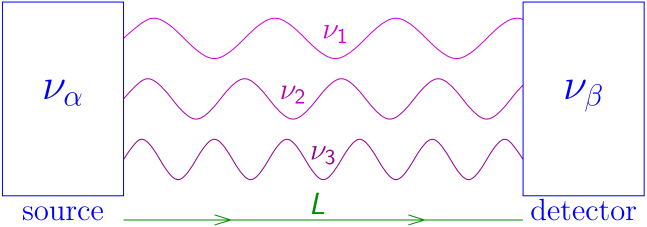
- Flavor Neutrinos: $\nu_e$, $\nu_\mu$, $\nu_\tau$ produced in Weak Interactions
- Massive Neutrinos: $\nu_1$, $\nu_2$, $\nu_3$ propagate from Source to Detector
- Neutrino Mixing: a Flavor Neutrino is a superposition of Massive Neutrinos

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

- $U$ is the $3 \times 3$ unitary Neutrino Mixing Matrix

# Neutrino Oscillations

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{\alpha 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\alpha 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\alpha 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$$E_k^2 = p^2 + m_k^2 \qquad\qquad t = L$$

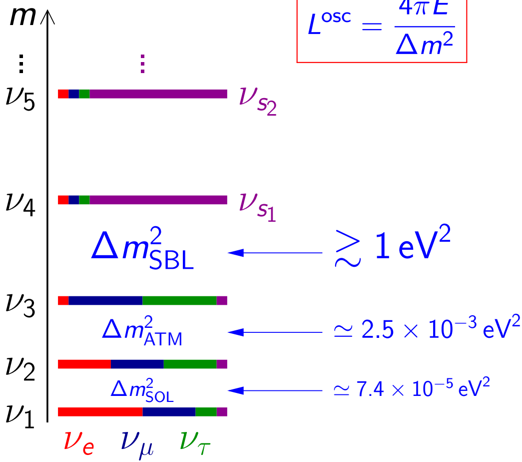
$$P_{\nu_\alpha\to\nu_\beta}(L) = |\langle\nu_\beta|\nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k} U_{\alpha k}^* U_{\beta j}^* U_{\alpha j} \exp\left(-i\frac{\Delta m_{kj}^2 L}{2E}\right)$$

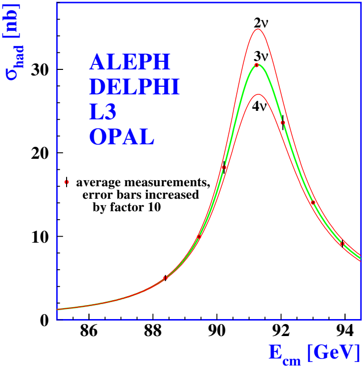
The oscillation probabilities depend on $U$ and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

- In the standard framework of three-neutrino mixing there are two independent $\Delta m^2$'s:
  - $\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\text{eV}^2$
  - $\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2$
- Atmospheric and solar neutrino oscillations are detectable at the distances
  - $L^{\text{osc}}_{\text{ATM}} \gtrsim \dfrac{E_\nu}{\Delta m^2_{\text{ATM}}} \approx 1\,\text{km}\,\dfrac{E_\nu}{\text{MeV}} = 1000\,\text{km}\,\dfrac{E_\nu}{\text{GeV}}$
  - $L^{\text{osc}}_{\text{SOL}} \gtrsim \dfrac{E_\nu}{\Delta m^2_{\text{SOL}}} \approx 50\,\text{km}\,\dfrac{E_\nu}{\text{MeV}}$
- The atmospheric and solar neutrino oscillations cannot explain flavor neutrino transitions at shorter distances.

# Beyond Three-Neutrino Mixing: Sterile Neutrinos

$$L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}$$





$$N^{\text{LEP}}_{\nu_{\text{active}}} = 2.9840 \pm 0.0082$$

Terminology: a eV-scale sterile neutrino

means: a eV-scale massive neutrino which is mainly sterile

# Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions
- Active left-handed neutrinos can mix with non-SM singlet fermions often called right-handed neutrinos
- Light left-handed anti-$\nu_R$ are light sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions

[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos $(\nu_s)$
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + $3\nu$-mixing:

$$\begin{array}{ccccccccc} \Delta m^2_{21} & \ll & |\Delta m^2_{31}| & \ll & |\Delta m^2_{41}| & \leq & \ldots \\ \nu_1 \quad \nu_2 & & \nu_3 & & \nu_4 & & \ldots \\ \nu_e \quad \nu_\mu & & \nu_\tau & & \nu_{s_1} & & \ldots \end{array}$$

- Here I consider sterile neutrinos with mass scale $\sim 1\,\mathrm{eV}$ in light of short-baseline anomalies.

- Other possibilities (not incompatible):
  - Very light sterile neutrinos with mass scale $\ll 1\,\mathrm{eV}$: important for solar neutrino phenomenology

    [de Holanda, Smirnov, PRD 69 (2004) 113002; PRD 83 (2011) 113011]

    [Das, Pulido, Picariello, PRD 79 (2009) 073010]

    Recent Daya Bay constraints for $10^{-3} \lesssim \Delta m^2 \lesssim 10^{-1}\,\mathrm{eV}^2$ [PRL 113 (2014) 141802]

  - Heavy sterile neutrinos with mass scale $\gg 1\,\mathrm{eV}$: could be Warm Dark Matter

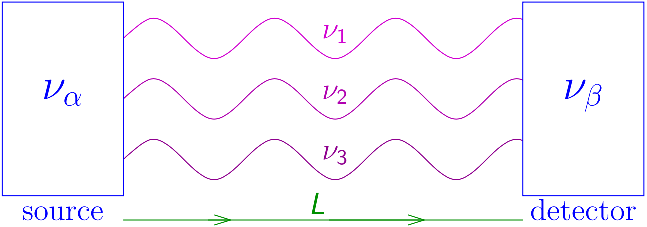
    [Asaka, Blanchet, Shaposhnikov, PLB 631 (2005) 151; Asaka, Shaposhnikov, PLB 620 (2005) 17; Asaka, Shaposhnikov, Kusenko, PLB 638 (2006) 401; Asaka, Laine, Shaposhnikov, JHEP 0606 (2006) 053, JHEP 0701 (2007) 091]

    [Reviews: Kusenko, Phys. Rept. 481 (2009) 1; Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191; Boyarsky, Iakubovskyi, Ruchayskiy, Phys. Dark Univ. 1 (2012) 136; Drewes, IJMPE, 22 (2013) 1330019]

# Short-Baseline Neutrino Oscillations

Three-Neutrino Mixing

$$|\nu_{\text{source}}\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle$$



$$|\nu_{\text{detector}}\rangle \simeq U_{\alpha 1}\,e^{-iEL}\,|\nu_1\rangle + U_{\alpha 2}\,e^{-iEL}\,|\nu_2\rangle + U_{\alpha 3}\,e^{-iEL}\,|\nu_3\rangle = e^{-iEL}|\nu_\alpha\rangle$$

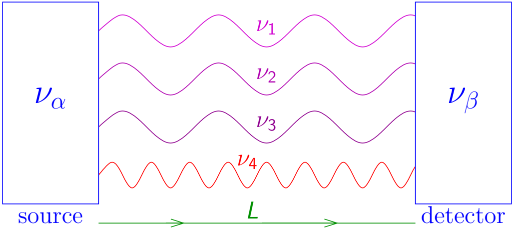
$$P_{\nu_\alpha\to\nu_\beta}(L) = \left|\langle\nu_\beta|\nu_{\text{detector}}\rangle\right|^2 \simeq \left|e^{-iEL}\langle\nu_\beta|\nu_\alpha\rangle\right|^2 = \delta_{\alpha\beta}$$

No Observable Short-Baseline Neutrino Oscillations!

# Short-Baseline Neutrino Oscillations

3+1 Neutrino Mixing

$$|\nu_{\text{source}}\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle + U_{\alpha 4}\,|\nu_4\rangle$$



$$|\nu_{\text{detector}}\rangle \simeq e^{-iEL}\left(U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle\right) + U_{\alpha 4}\,e^{-iE_4 L}\,|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$$P_{\nu_\alpha\to\nu_\beta}(L) = |\langle\nu_\beta|\nu_{\text{detector}}\rangle|^2 \neq \delta_{\alpha\beta}$$

Observable Short-Baseline Neutrino Oscillations!

The oscillation probabilities depend on $U$ and

$$\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$$

- Some authors that have poor understanding of oscillations and quantum mechanics present $\nu_\mu \to \nu_e$ short-baseline transitions due to sterile neutrinos as

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

- This is wrong!

THERE IS NO INTERMEDIATE $\nu_s$ !

# Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_{\alpha} \to \overset{(-)}{\nu}_{\beta}} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_{\alpha} \to \overset{(-)}{\nu}_{\alpha}} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

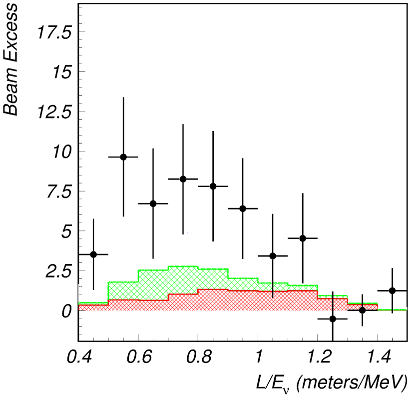
- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- $\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$
- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to $\Delta m^2_{\text{ATM}}$ [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122] and solar exp. sensitive to $\Delta m^2_{\text{SOL}}$ [Long, Li, CG, PRD 87, 113004 (2013) 113004]

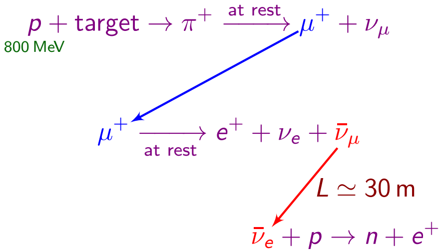
# LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e \qquad 20\,\text{MeV} \leq E \leq 52.8\,\text{MeV}$



- Well-known and pure source of $\bar{\nu}_\mu$



$\underset{800\,\text{MeV}}{p} + \text{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$

$\mu^+ \xrightarrow[\text{at rest}]{} e^+ + \nu_e + \bar{\nu}_\mu$

$L \simeq 30\,\text{m}$

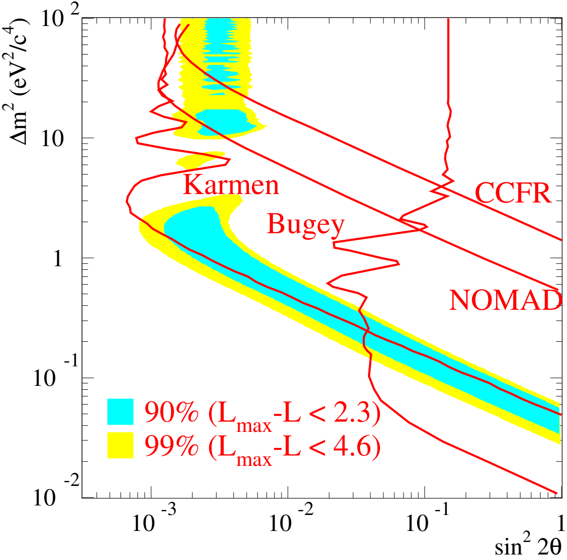
$\bar{\nu}_e + p \to n + e^+$

Well-known detection process of $\bar{\nu}_e$

- $\approx 3.8\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

[PRD 65 (2002) 112001]

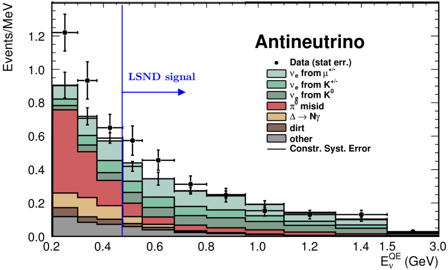
$\Delta m^2_{\text{SBL}} \gtrsim 0.1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$



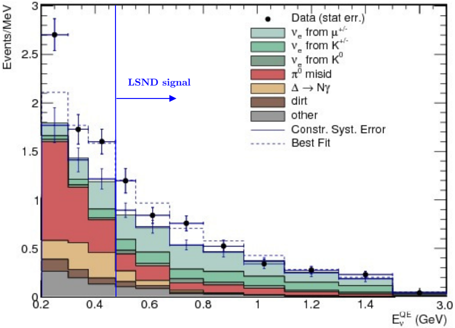
$$\Delta m^2_{\text{SBL}} \gtrsim 3 \times 10^{-2}\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \simeq 2.5 \times 10^{-3}\,\text{eV}^2 \gg \Delta m^2_{\text{SOL}}$$

# MiniBooNE

$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



$\nu_\mu \to \nu_e$ [PRL 121 (2018) 221801]



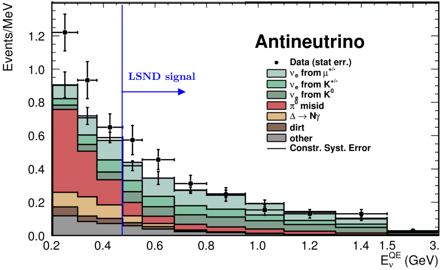
- Purpose: check the LSND signal
- Different $L \simeq 541\,\text{m}$
- Different $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$
- Similar $L/E \Longleftrightarrow$ oscillations
- No money, no Near Detector
- LSND signal expected for

  $$E \gtrsim 475\,\text{MeV}$$
- New low-energy anomaly for

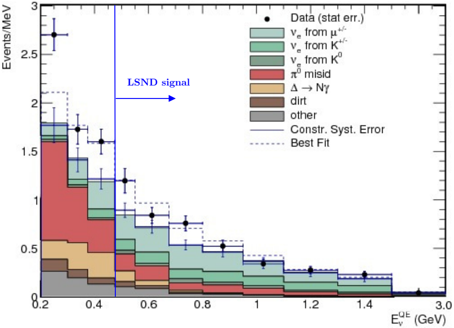
  $$E < 475\,\text{MeV}$$

# MiniBooNE

$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

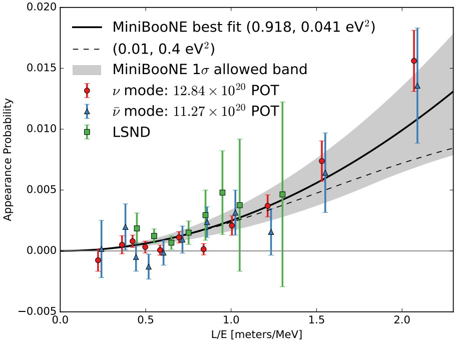


$\nu_\mu \to \nu_e$ [PRL 121 (2018) 221801]

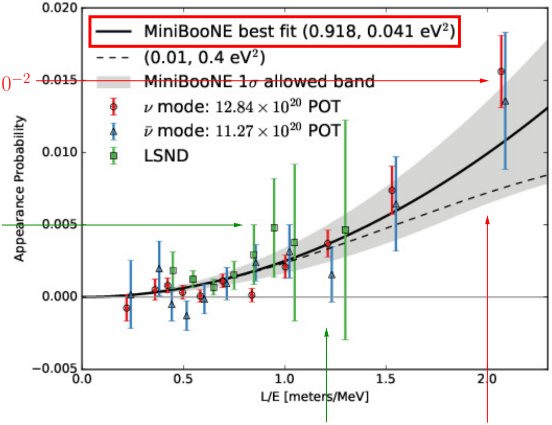


- LSND: excess for $\frac{L}{E} \lesssim 1.2 \, \frac{m}{\text{MeV}}$
- MiniBooNE: the LSND excess should be at

$$E \gtrsim \frac{541 \, \text{m}}{1.2 \, \text{m}} \, \text{MeV} \simeq 451 \, \text{MeV}$$



[MiniBooNE, PRL 121 (2018) 221801]



$\sin^2 2\vartheta_{\mu e} \simeq 1.5 \times 10^{-2}$

$\sin^2 2\vartheta_{\mu e} \simeq 5 \times 10^{-3}$

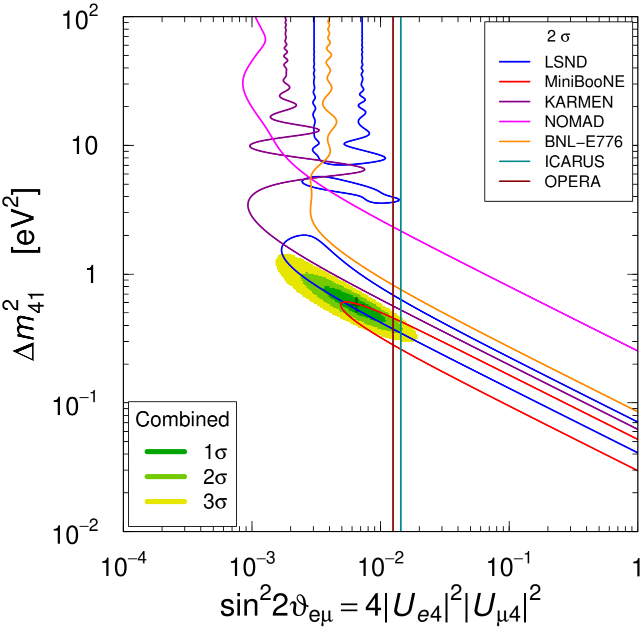
$\Delta m^2_{41} \simeq 1\,\text{eV}^2$

$\Delta m^2_{41} \simeq 0.6\,\text{eV}^2$

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\vartheta_{\mu e} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \quad \Longrightarrow \quad P^{\text{max}}_{\nu_\mu \to \nu_e} = \sin^2 2\vartheta_{\mu e}$$

for $$\frac{\Delta m^2_{41} L}{4E} = \frac{\pi}{2} \quad \Longrightarrow \quad \Delta m^2_{41} \simeq 1.2 \, \frac{E\,[\text{MeV}]}{L\,[\text{m}]}$$

# $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance



# 3+1: Appearance vs Disappearance

- SBL Oscillation parameters: $\Delta m^2_{41}$ $|U_{e4}|^2$ $|U_{\mu4}|^2$ $(|U_{\tau4}|^2)$
- Amplitude of $\nu_e$ disappearance:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- Amplitude of $\nu_\mu$ disappearance:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

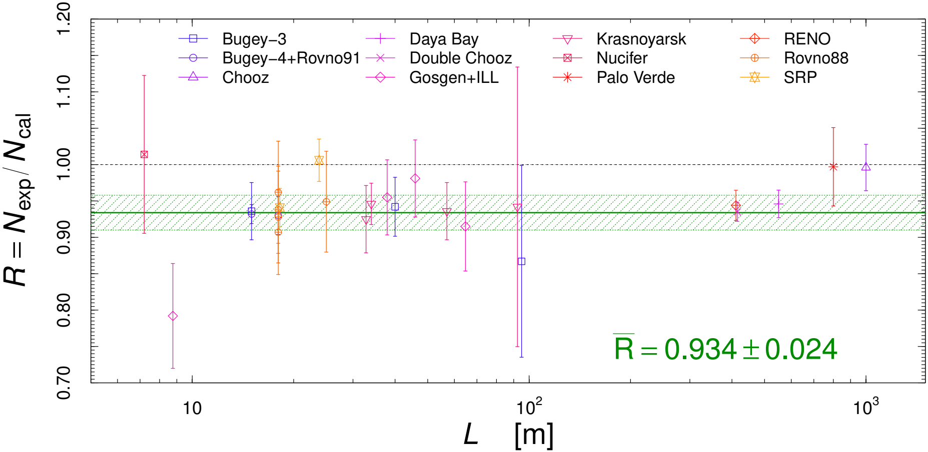
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

# Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

## New reactor $\bar{\nu}_e$ fluxes: Huber-Mueller (HM)

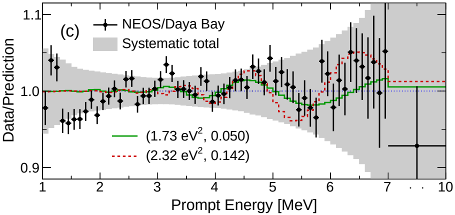
[Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]

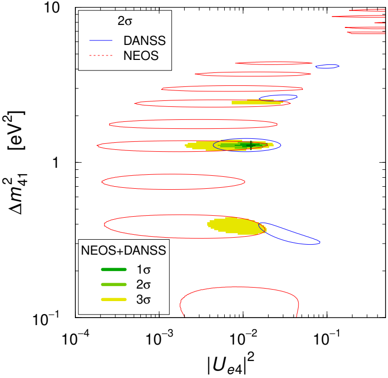


$\approx 2.8\sigma$ deficit

# Reactor Spectral Ratios

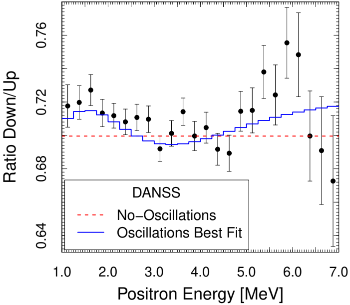
## NEOS [PRL 118 (2017) 121802, arXiv:1610.05134]





## DANSS

[PLB 787 (2018) 56, arXiv:1804.04046]



MODEL INDEPENDENT!

$\sim 3.5\sigma$

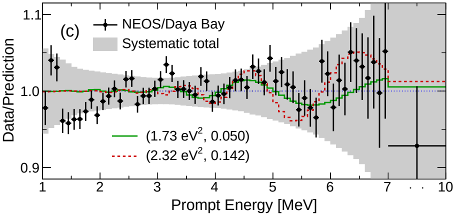
[Gariazzo, CG, Laveder, Li, PLB 782 (2018) 13, arXiv:1801.06467]

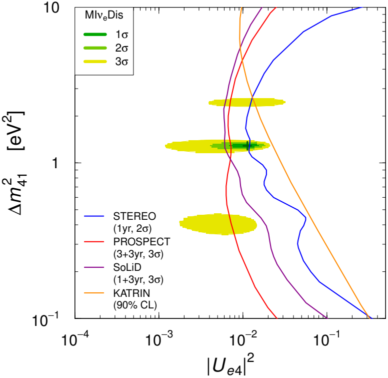
[See also: Dentler et al, JHEP 1808 (2018) 010, arXiv:1803.10661]

# Reactor Spectral Ratios

## NEOS

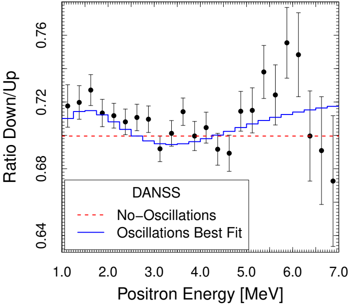
[PRL 118 (2017) 121802, arXiv:1610.05134]





## DANSS

[PLB 787 (2018) 56, arXiv:1804.04046]



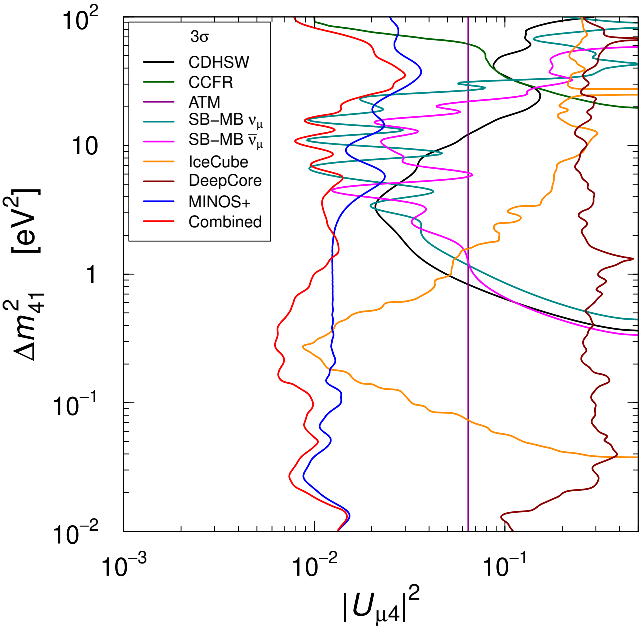
MODEL INDEPENDENT!

$\sim 3.5\sigma$

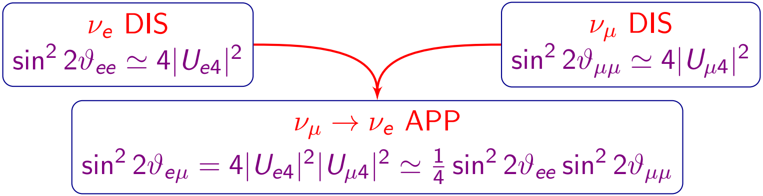
[Gariazzo, CG, Laveder, Li, PLB 782 (2018) 13, arXiv:1801.06467]

[See also: Dentler et al, JHEP 1808 (2018) 010, arXiv:1803.10661]

# $\nu_\mu$ and $\bar{\nu}_\mu$ Disappearance



# Global Appearance-Disappearance Tension



$\nu_e$ DIS

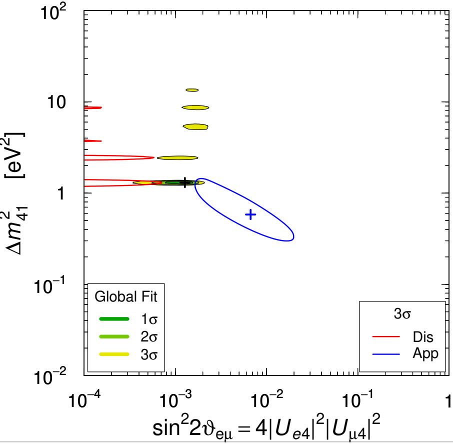
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

$\nu_\mu$ DIS

$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- Global Fit:

  $\chi^2/\mathrm{NDF} = 827.4/760$

  $\mathrm{GoF} = 4.5\%$

  $\chi^2_{\mathrm{PG}}/\mathrm{NDF}_{\mathrm{PG}} = 39.0/2$

  $\mathrm{GoF}_{\mathrm{PG}} = 3 \times 10^{-9}$ ← ☹
- Similar tension in

  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

[CG, Zavanin, MPLA 31 (2015) 1650003]

# Global Appearance-Disappearance Tension

$\nu_e$ DIS

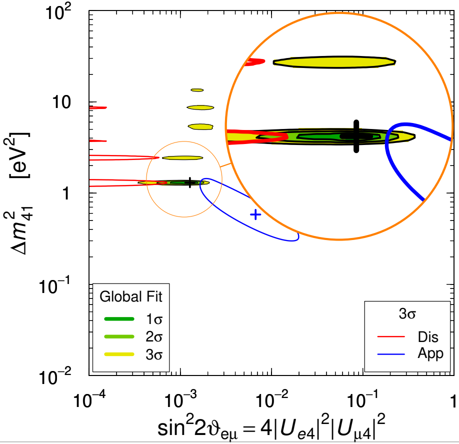
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

$\nu_\mu$ DIS

$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$



- $\nu_\mu \to \nu_e$ is quadratically suppressed!

- Global Fit:

  $\chi^2/\text{NDF} = 827.4/760$

  $\text{GoF} = 4.5\%$

  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 39.0/2$

  $\text{GoF}_{\text{PG}} = 3 \times 10^{-9}$ ← ☹

- Similar tension in

  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

[CG, Zavanin, MPLA 31 (2015) 1650003]

# Goodness of Fit

- Assumption or approximation: Gaussian uncertainties and linear model
- $\chi^2_{\text{min}}$ has $\chi^2$ distribution with Number of Degrees of Freedom

$$\text{NDF} = N_{\text{D}} - N_{\text{P}}$$

$$N_{\text{D}} = \text{Number of Data} \qquad N_{\text{P}} = \text{Number of Fitted Parameters}$$

- $\langle \chi^2_{\text{min}} \rangle = \text{NDF} \qquad \text{Var}(\chi^2_{\text{min}}) = 2\text{NDF}$
- $\text{GoF} = \int_{\chi^2_{\text{min}}}^{\infty} p_{\chi^2}(z, \text{NDF})\, dz \qquad p_{\chi^2}(z,n) = \dfrac{z^{n/2-1} e^{-z/2}}{2^{n/2}\Gamma(n/2)}$

# Parameter Goodness of Fit

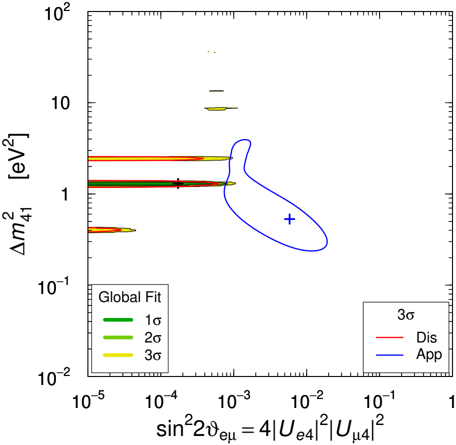
Maltoni, Schwetz, PRD 68 (2003) 033020 (arXiv:hep-ph/0304176)

- Measure compatibility of two (or more) sets of data points $A$ and $B$ under fitting model
- $\chi^2_{\text{PGoF}} = (\chi^2_{\text{min}})_{\text{A+B}} - [(\chi^2_{\text{min}})_{\text{A}} + (\chi^2_{\text{min}})_{\text{B}}]$
- $\chi^2_{\text{PGoF}}$ has $\chi^2$ distribution with Number of Degrees of Freedom

$$\text{NDF}_{\text{PGoF}} = N_{\text{P}}^{\text{A}} + N_{\text{P}}^{\text{B}} - N_{\text{P}}^{\text{A+B}}$$

- $\text{PGoF} = \int_{\chi^2_{\text{PGoF}}}^{\infty} p_{\chi^2}(z, \text{NDF}_{\text{PGoF}})\, dz$

# Global Fit Without LSND



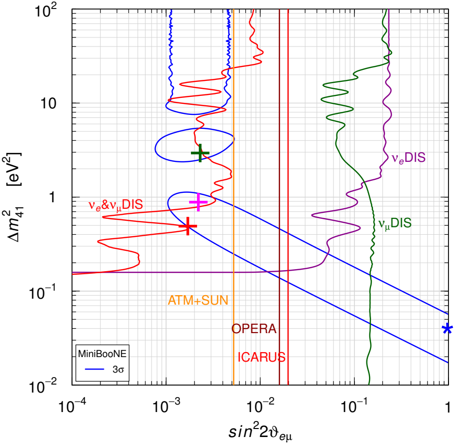
$\chi^2/\text{NDF} = 802.2/756$

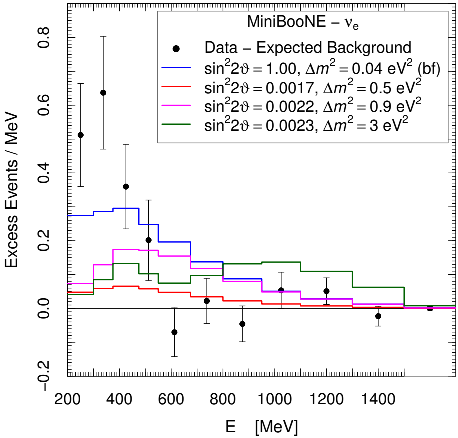
$\text{GoF} = 12\%$

$\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 22.4/2$

$\text{GoF}_{\text{PG}} = 1 \times 10^{-5}$ ← ☹

# MiniBooNE Low-Energy Anomaly





- Fit of MB low-energy excess requires small $\Delta m^2_{41}$ and large $\sin^2 2\vartheta_{e\mu}$, in contradiction with disappearance data.
- Multinucleon effects in neutrino energy reconstruction are not enough to solve the problem [Martini, Ericson, Chanfray, PRD 85 (2012) 093012; PRD 87 (2013) 013009; Ericson, Garzelli, CG, Martini, PRD 93 (2016) 073008]

# Neutrino energy reconstruction problem?

[Martini, Ericson, Chanfray, PRD 85 (2012) 093012; PRD 87 (2013) 013009]

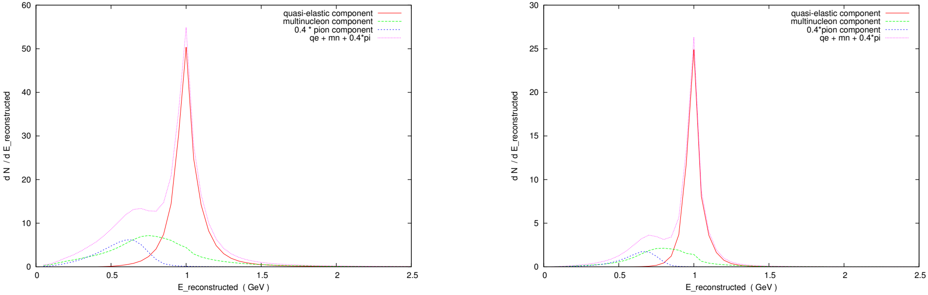
- Effect due to multinucleon interactions whose signal is indistinguishable from that due to quasielastic charged-current scattering

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

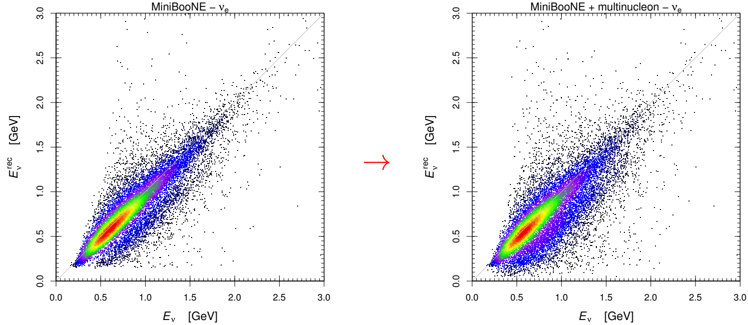
- In the MiniBooNE analysis the reconstructed neutrino energy is ($E_{\rm B} \simeq 25\,{\rm MeV}$)

$$E_\nu^{\rm QE} = \frac{2\,(M_{\rm i} - E_{\rm B})\,E_e - \left(m_e^2 - 2M_{\rm i}E_{\rm B} + E_{\rm B}^2 + \Delta M_{\rm if}^2\right)}{2\,(M_{\rm i} - E_{\rm B} - E_e + p_e \cos\theta_e)}$$

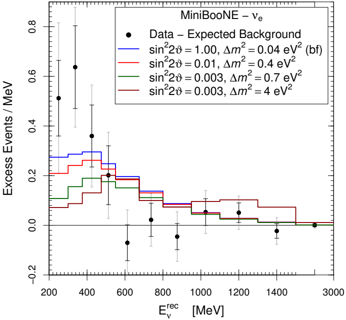
- The MiniBooNE collaboration took into account:
  - Fermi motion of the initial nucleon
  - Charged-current single charged pion production events in which the pion is not observed
    (e.g. $\nu_e + n \to \Delta^+ + e^- \to n + \pi^+ + e^-$ with $\pi^+$ absorbed by a nucleus)



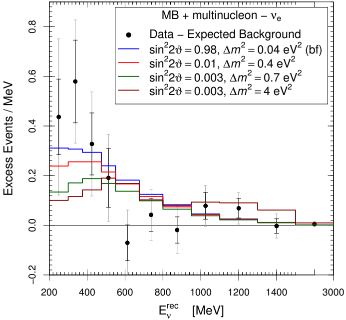
## MiniBooNE $\nu_\mu \to \nu_e$ full transmutation Monte Carlo events

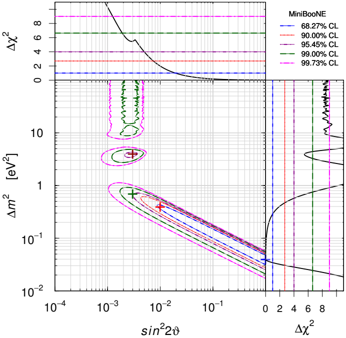


[Ericson, Garzelli, CG, Martini, PRD 93 (2016) 073008]

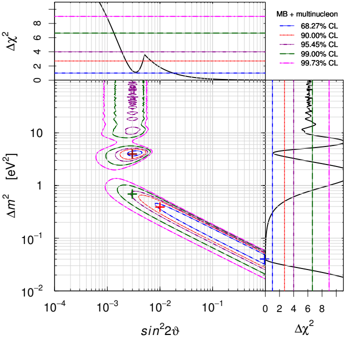

MiniBooNE – $\nu_e$
Data – Expected Background
$\sin^2 2\vartheta = 1.00$, $\Delta m^2 = 0.04$ eV$^2$ (bf)
$\sin^2 2\vartheta = 0.01$, $\Delta m^2 = 0.4$ eV$^2$
$\sin^2 2\vartheta = 0.003$, $\Delta m^2 = 0.7$ eV$^2$
$\sin^2 2\vartheta = 0.003$, $\Delta m^2 = 4$ eV$^2$
Excess Events / MeV
$E_\nu^{rec}$ [MeV]
200 400 600 800 1000 1200 1400 3000
−0.2 0.0 0.2 0.4 0.6 0.8

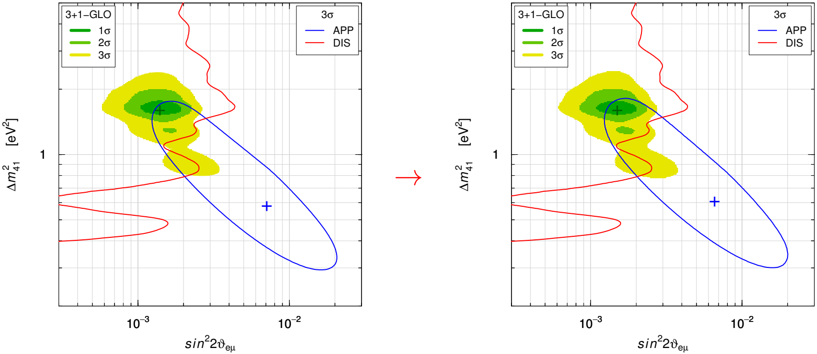
→


MB + multinucleon – $\nu_e$
Data – Expected Background
$\sin^2 2\vartheta = 0.98$, $\Delta m^2 = 0.04$ eV$^2$ (bf)
$\sin^2 2\vartheta = 0.01$, $\Delta m^2 = 0.4$ eV$^2$
$\sin^2 2\vartheta = 0.003$, $\Delta m^2 = 0.7$ eV$^2$
$\sin^2 2\vartheta = 0.003$, $\Delta m^2 = 4$ eV$^2$
Excess Events / MeV
$E_\nu^{rec}$ [MeV]
200 400 600 800 1000 1200 1400 3000
−0.2 0.0 0.2 0.4 0.6 0.8


MiniBooNE
68.27% CL
90.00% CL
95.45% CL
99.00% CL
99.73% CL
$\Delta\chi^2$
0 2 4 6 8
$\Delta m^2$ [eV$^2$]
$10^{-2}$ $10^{-1}$ 1 10
$10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$
$\sin^2 2\vartheta$
0 2 4 6 8
$\Delta\chi^2$

→


MB + multinucleon
68.27% CL
90.00% CL
95.45% CL
99.00% CL
99.73% CL
$\Delta\chi^2$
0 2 4 6 8
$\Delta m^2$ [eV$^2$]
$10^{-2}$ $10^{-1}$ 1 10
$10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$
$\sin^2 2\vartheta$
0 2 4 6 8
$\Delta\chi^2$



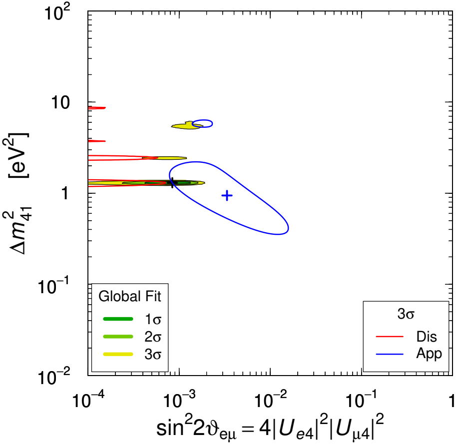
GoF = 7% PGoF = 0.2% GoF = 7% PGoF = 0.2%

[Ericson, Garzelli, CG, Martini, PRD 93 (2016) 073008]

- Multinucleon interactions can decrease slightly the MiniBooNE low-energy anomaly.
- Multinucleon interactions cannot solve the APP-DIS tension.

# Global Fit

## Without MiniBooNE



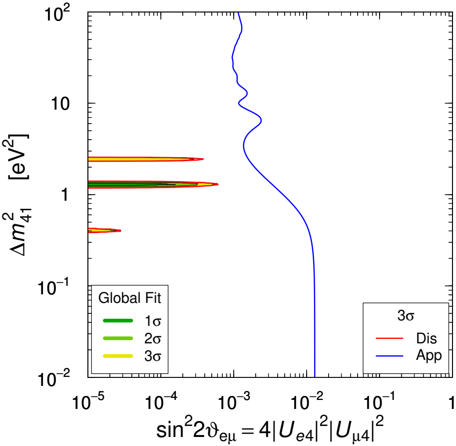
$\chi^2/\text{NDF} = 765.8/726$

$\text{GoF} = 15\%$

$\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 26.0/2$

$\text{GoF}_{\text{PG}} = 2 \times 10^{-6}$ ← ☹

## Without LSND and MB



$\chi^2/\text{NDF} = 726.9/722$

$\text{GoF} = 44\%$

$\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 0/2$

$\text{GoF}_{\text{PG}} = 1$ ← ☺

# Exotic Explanations of the MB Low-Energy Anomaly

- Generation by a particle $X$ produced in the MiniBooNE target is excluded by the angular distribution of the $\nu_e$-like events, that is not strongly forward peaked.

[Jordan, Kahn, Krnjaic, Moschella, Spitz, PRL 122 (2019) 081801]

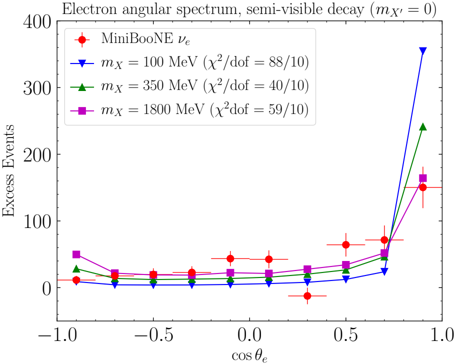
- Visible decays:

$$X \to e^+e^- \text{ or } X \to \gamma\gamma$$

$$\cos\theta_e > 0.9999$$

- Semivisible decay:

$$X \to X' + p_{\text{EM}} \longrightarrow$$



# Heavy Neutrino Generation in the Detector

- Neutrino Neutral-Current Weak Interaction Lagrangian:

$$\mathscr{L}_{\mathrm{I}}^{(\mathrm{NC})} = -\frac{g}{2\cos\vartheta_{\mathrm{W}}} Z_\rho \sum_{\alpha=e,\mu,\tau} \overline{\nu_{\alpha L}}\,\gamma^\rho\,\nu_{\alpha L}$$

- Sterile neutrinos: $\nu_{\alpha L} = \sum_{k=1}^{3+N_s} U_{\alpha k}\nu_{kL} \qquad (\alpha = e, \mu, \tau, s_1, \ldots, s_{N_s})$

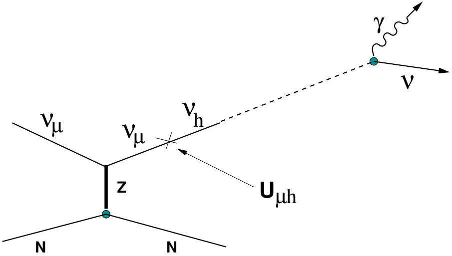
- No GIM: $\mathscr{L}_{\mathrm{I}}^{(\mathrm{NC})} = -\frac{g}{2\cos\vartheta_{\mathrm{W}}} Z_\rho \sum_{j=1}^{3+N_s} \sum_{k=1}^{3+N_s} \overline{\nu_{jL}}\,\gamma^\rho\,\nu_{kL} \sum_{\alpha=e,\mu,\tau} U_{\alpha j}^{*}\,U_{\alpha k}$

- $\sum_{\alpha=e,\mu,\tau,s_1,\ldots} U_{\alpha j}^{*}\,U_{\alpha k} = \delta_{jk}$ but $\sum_{\alpha=e,\mu,\tau} U_{\alpha j}^{*}\,U_{\alpha k} \neq \delta_{jk}$

- A heavy neutrino $\nu_h$ with $h \geq 4$ can be generated in the detector by neutral-current $\nu_\mu$ scattering.

# Heavy Sterile Neutrino Radiative Decay

[Gninenko, PRL 103 (2009) 241802, PRD 83 (2011) 015015, PRD 83 (2011) 093010, PLB 710 (2012) 86]

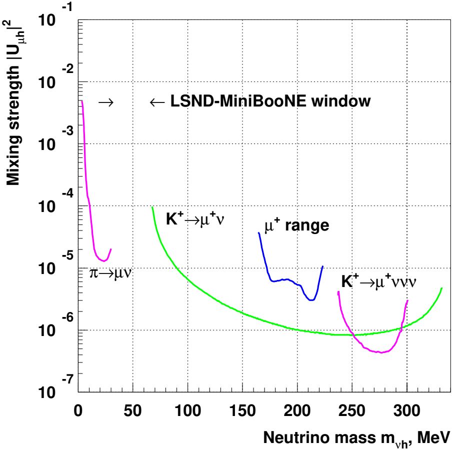


It may explain also LSND with

$$m_{\nu_h} \approx 40 - 80\,\mathrm{MeV}$$

and

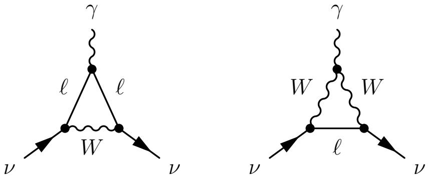
$$|U_{\mu h}|^2 \approx 10^{-3} - 10^{-2}$$



- It needs a fast radiative decay $\tau_{\nu_h} \lesssim 10^{-9}\,\text{s}$ that can be generated by a transition magnetic moment $|\mu_{hi}| \gtrsim 10^{-8}\,\mu_{\text{B}}$:

$$\Gamma_{\nu_h \to \nu_i + \gamma} = \frac{|\mu_{hi}|^2}{8\pi} m_{\nu_h}^3 \left(1 - \frac{m_{\nu_i}^2}{m_{\nu_h}^2}\right)^3$$

- Simplest extensions of the Standard Model:



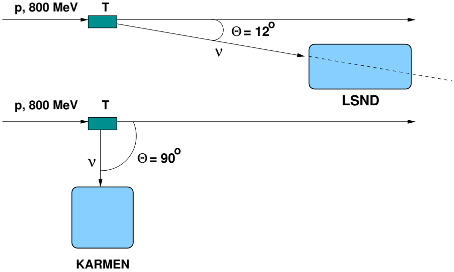
$$|\mu_{hi}| \sim 10^{-11}\,\mu_{\text{B}} \frac{m_{\nu_h}}{100\,\text{MeV}} |U_{\ell h}| \sim 10^{-12}\,\mu_{\text{B}}$$ not enough

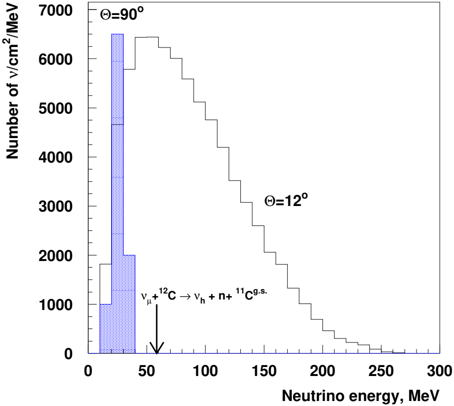
- More exotic extensions of the Standard Model may give the needed

$$|\mu_{hi}| \gtrsim 10^{-8}\,\mu_{\text{B}}$$

- It is interesting that this mechanism can explain why the LSND signal was not observed in KARMEN:

$$\nu_\mu + {}^{12}\mathrm{C} \to \nu_h + {}^{11}\mathrm{C} + n$$



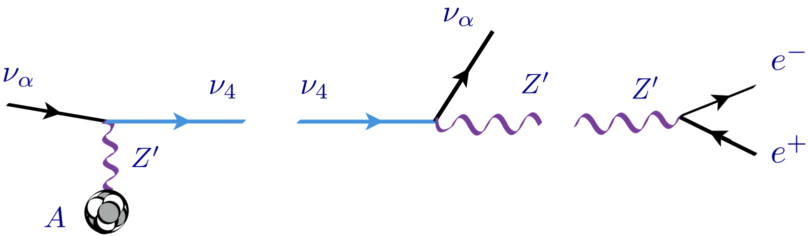


[Gninenko, PRD 83 (2011) 015015]

- This mechanism can be ruled out by Liquid Argon Time Projection Chamber (LArTPC) detectors that distinguish between electrons and photons: MicroBooNE, ICARUS, SBND (Fermilab Short-Baseline Neutrino Oscillation Program).

# Interacting Heavy Sterile Neutrino

[Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121 (2018) 241801]

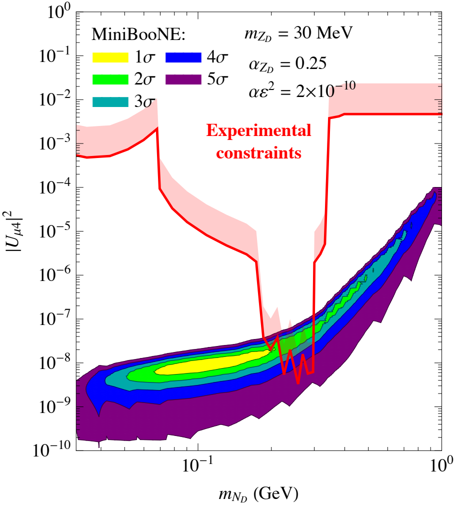


[Arguelles, Hostert, Tsai, arXiv:1812.08768]

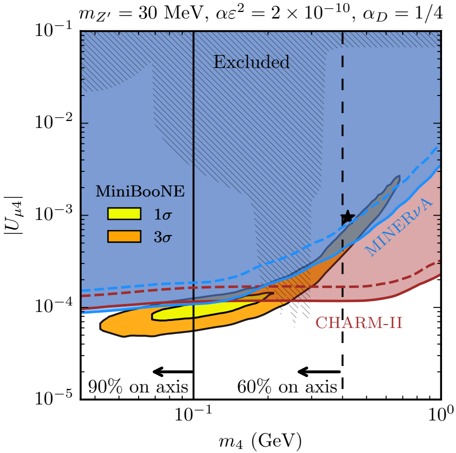
$$\mathcal{L} \supset \frac{m_{Z'}^2}{2} Z'_\mu Z'^\mu + g_{\mathcal{D}} Z'_\mu \overline{\nu}_s \gamma^\mu \nu_s + e\epsilon\, Z'^\mu J_\mu^{\mathrm{em}} + \frac{g}{c_W} \epsilon'\, Z'^\mu J_\mu^{Z}$$

$$\Gamma_{\nu_4 \to Z' + \nu_\mu} = \frac{\alpha_{\mathcal{D}}}{2} |U_{\mu 4}|^2 \frac{m_{\nu_4}^3}{m_{Z'}^2} \left(1 - \frac{m_{Z'}^2}{m_{\nu_4}^2}\right) \left(1 + \frac{m_{Z'}^2}{m_{\nu_4}^2} - 2\frac{m_{Z'}^4}{m_{\nu_4}^4}\right)$$

$$\Gamma_{Z' \to e^+ e^-} \approx \frac{\alpha\, \epsilon^2}{3} m_{Z'}$$



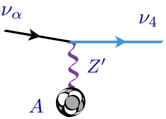
[Bertuzzo et al, PRL 121 (2018) 241801]

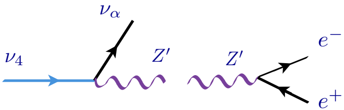


[Arguelles, Hostert, Tsai, arXiv:1812.08768]

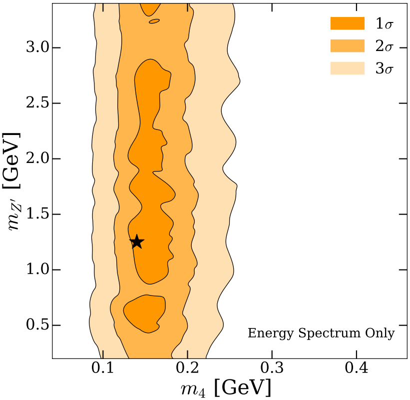
# Heavy New Gauge Boson

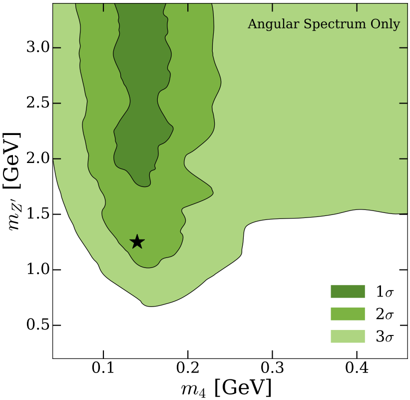
[Ballett, Pascoli, Ross-Lonergan, PRD 99 (2019) 071701]





Virtual $Z'$ (off-shell)





# Conclusions

- In principle, the simplest explanation of the MiniBooNE $\nu_e$-like excess is neutrino oscillations, that however requires a new $\Delta m^2$ associated with a sterile neutrino.

- Unfortunately, the $\nu_e$-like excess is too large to be compatible with the existing bounds on $\nu_e$ and $\nu_\mu$ disappearance in the framework of $3 + N_s$ active-sterile neutrino mixing.

- Also the LSND $\nu_e$-like excess is disfavored.

- More viable exotic explanations exist with a heavy sterile neutrino produced and decayed in the detector.

- The solution of the puzzle is expected to come from Liquid Argon Time Projection Chamber (LArTPC) detectors that can distinguish a single $\nu_e$-induced electron from a $\gamma$ or a collimated $e^+e^-$ pair.