Towards 3+1 Neutrino Mixing

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LSND

$$\bar{\nu}_\mu \to \bar{\nu}_e \qquad L \simeq 30\,\text{m} \qquad 20\,\text{MeV} \le E \le 200\,\text{MeV}$$

$$\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}})$$
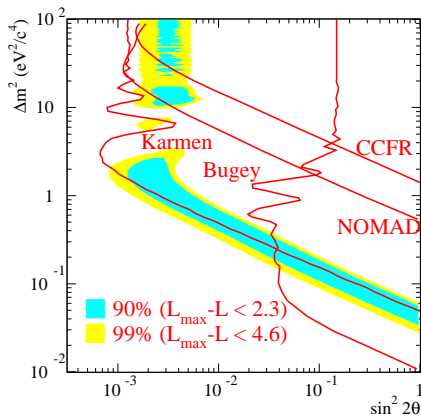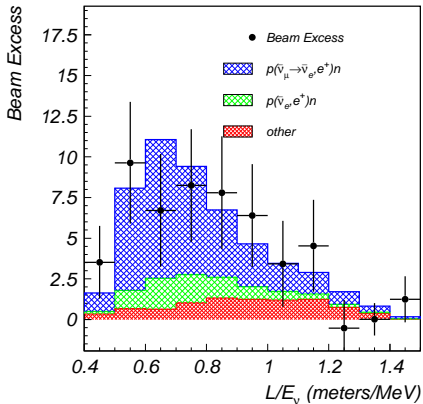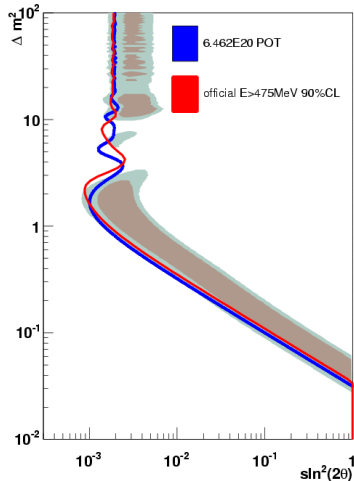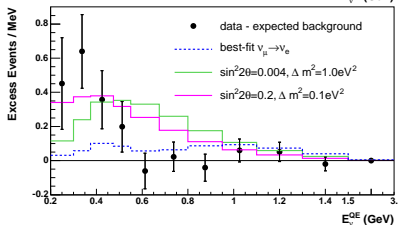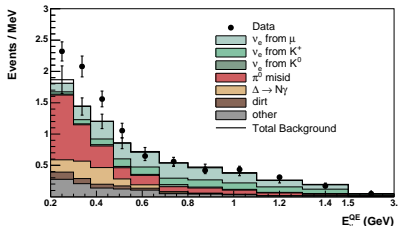
MiniBooNE Neutrinos

$\nu_\mu \to \nu_e$ $L \simeq 541\,\text{m}$ $475\,\text{MeV} \lesssim E \lesssim 3\,\text{GeV}$

[MiniBooNE, PRL 102 (2009) 101802, arXiv:0812.2243]

[Djurcic, arXiv:0901.1648]

Low-Energy Anomaly!

MiniBooNE Antineutrinos

$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 541$ m $475\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$

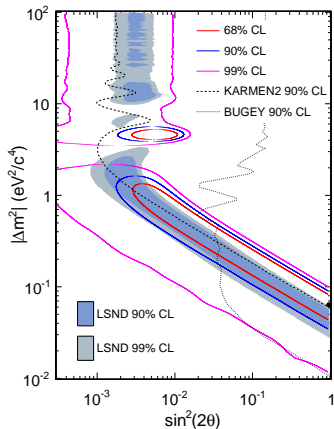[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]

Agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal!

Similar L/E but different L and $E \implies$ Oscillations!

Updated MiniBooNE $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Result

- Updated result from previous publication
  - $5.66E20 \Rightarrow 8.58E20$ protons-on-target (x1.5)
  - Reduced systematic uncertainties especially backgrounds from beam K^+ decays

- For E > 475 MeV (>200 MeV), oscillations favored over background only (null) hypothesis at the 91.1% CL (97.6% CL)
  - Consistent with LSND but less strong than previous result (99.4%)
  - Best fit: χ^2 prob. = 35.5% (51%)
    Null: χ^2 prob. = 14.9% (10%)

- Low energy excess now more prominent for antineutrino running than previous result
  - For E< 475 MeV, excess = 38.6 ± 18.5 (For all energies, excess = 57.7 ± 28.5)
  - Neutrino and antineutrino results are now more similar.

- MiniBooNE will continue running through spring 2012 (at least) towards the request of 15E20 pot (~x2 from this update)
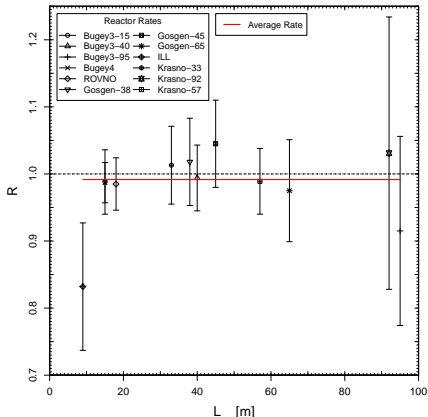 - Full data set will probe LSND signal at the 2-3 sigma level
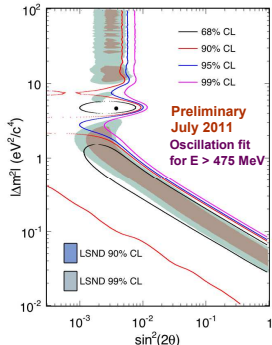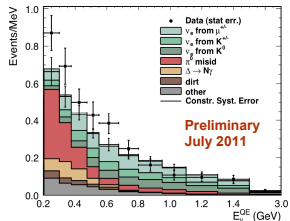
from M. Shaevitz, PANIC11, 26 July 2011

Reactor Antineutrino Anomaly

[Mention et al, arXiv:1101.2755]

Old Reactor $\bar{\nu}_e$ Fluxes

$$\overline{R} = 0.992 \pm 0.024$$

New Reactor $\bar{\nu}_e$ Fluxes

[Mueller et al, arXiv:1101.2663]
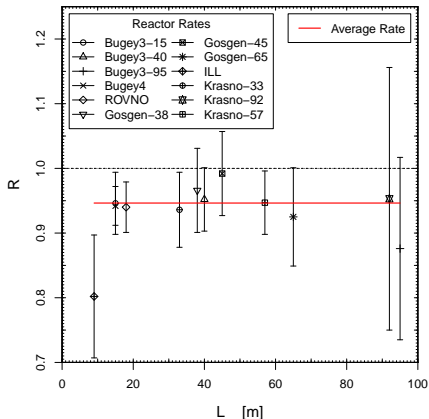
$$\overline{R} = 0.946 \pm 0.024$$

Gallium Anomaly

Gallium Radioactive Source Experiments

Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

Detection Process: $\quad \nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

ν_e Sources: $\quad e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e \qquad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

	${}^{51}\text{Cr}$				${}^{37}\text{Ar}$	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098

${}^{51}\text{Cr}$ (27.7 days)

427 keV ν (9.0%)
432 keV ν (0.9%)

747 keV ν (81.6%)
752 keV ν (8.5%)

320 keV γ

${}^{51}\text{V}$

[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]

${}^{37}\text{Ar}$ (35.04 days)

813 keV ν (9.8%)
811 keV ν (90.2%)

${}^{37}\text{Cl}$ (stable)
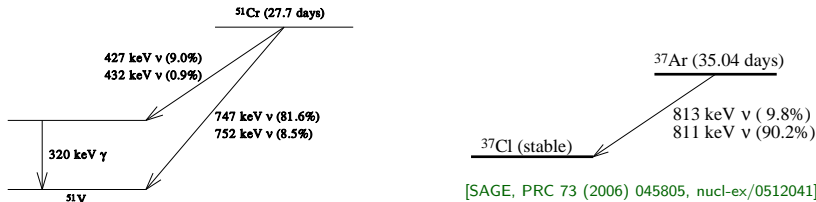
[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]
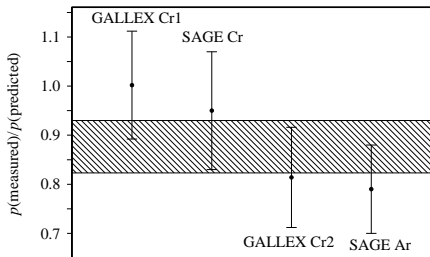
[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

$$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$$

$$\langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$$

$$R_B^{\text{Gallex-Cr1}} = 0.953 \pm 0.11$$
$$R_B^{\text{Gallex-Cr2}} = 0.812^{+0.10}_{-0.11}$$
$$R_B^{\text{SAGE-Cr}} = 0.95 \pm 0.12$$
$$R_B^{\text{SAGE-Ar}} = 0.791^{+0.084}_{-0.078}$$

$$\boxed{R_B^{\text{Ga}} = 0.86 \pm 0.05}$$

Bahcall cross section without uncertainty

[Bahcall, PRC 56 (1997) 3391, hep-ph/9710491]

$$R^{\text{Gallex-Cr1}} = 0.84^{+0.13}_{-0.12}$$
$$R^{\text{Gallex-Cr2}} = 0.71^{+0.12}_{-0.11}$$
$$R^{\text{SAGE-Cr}} = 0.84^{+0.14}_{-0.13}$$
$$R^{\text{SAGE-Ar}} = 0.70^{+0.10}_{-0.09}$$

$$\boxed{R^{\text{Ga}} = 0.76^{+0.09}_{-0.08}}$$

[Giunti, Laveder, PRC 83 (2011) 065504, arXiv:1006.3244]

Haxton cross section and uncertainty

[Haxton, PLB 431 (1998) 110, arXiv:nucl-th/9804011]

Beyond Three-Neutrino Mixing
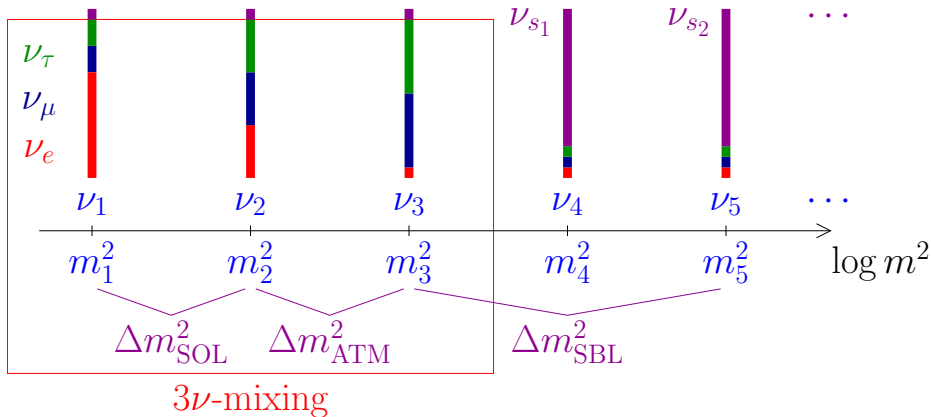
Standard Model

- Neutrinos are the only massless fermions

- Neutrinos are the only fermions with only left-handed component ν_L

Extension of the SM: Massive Neutrinos

- Simplest extension: introduce right-handed component ν_R

- Dirac mass $m_D \overline{\nu_R} \nu_L$ + Majorana mass $m_M \overline{\nu_R^c} \nu_R$

- ν_{eL}, $\nu_{\mu L}$, $\nu_{\tau L}$ + ν_{eR}, $\nu_{\mu R}$, $\nu_{\tau R}$ $\implies$ 6 massive Majorana neutrinos

Sterile Neutrinos

▶ Light anti-ν_R are called sterile neutrinos

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

▶ Sterile means no standard model interactions

▶ Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into sterile neutrinos (ν_s)

▶ Observables:

  ▶ Disappearance of active neutrinos (neutral current deficit)

  ▶ Indirect evidence through combined fit of data (current indication)

▶ Powerful window on new physics beyond the Standard Model

- In this talk I consider sterile neutrinos with mass scale $\sim 1\,\text{eV}$ in light of LSND, MiniBooNE, Reactor Anomaly, Gallium Anomaly.

- Other possibilities (not exclusive):

  - Very light sterile neutrinos with mass scale $\ll 1\,\text{eV}$: important for solar neutrino phenomenology

    [de Holanda, Smirnov, PRD 83 (2011) 113011, arXiv:1012.5627]

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

    [Kusenko, Phys. Rept. 481 (2009) 1, arXiv:0906.2968]

    [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191, arXiv:0901.0011]

Cosmology

- N_s = number of thermalized sterile neutrinos (not necessarily integer)

- CMB and LSS in ΛCDM: $N_s = 1.3 \pm 0.9$ $m_s < 0.66\,\text{eV}$ (95% C.L.)

  [Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301, arXiv:1006.5276]

  $$N_s = 1.61 \pm 0.92 \qquad m_s < 0.70\,\text{eV} \quad (95\%\ \text{C.L.})$$

  [Giusarma, Corsi, Archidiacono, de Putter, Melchiorri, Mena, Pandolfi, PRD 83 (2011) 115023, arXiv:1102.4774]

  $$N_s = 1.12^{+0.86}_{-0.74} \quad (95\%\ \text{C.L.})$$ [Archidiacono, Calabrese, Melchiorri, arXiv:1109.2767]

- BBN: $\begin{cases} N_s = 0.22 \pm 0.59 & \text{[Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313, astro-ph/0408033]} \\ N_s = 0.64^{+0.40}_{-0.35} & \text{[Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]} \\ N_s \leq 1 \text{ at } 95\%\ \text{C.L.} & \text{[Mangano, Serpico, PLB 701 (2011) 296, arXiv:1103.1261]} \end{cases}$
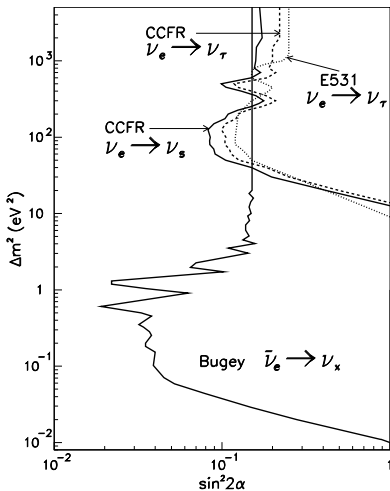
- CMB+LSS+BBN: $N_s = 0.85^{+0.39}_{-0.56}$ (95% C.L.)

  [Hamann, Hannestad, Raffelt, Wong, arXiv:1108.4136]

Direct Searches of Active-Sterile Transitions

CCFR

NC interactions $E \sim 100\,\text{GeV}$ $L \simeq 1.4\,\text{km}$

MINOS

NC sample: 89% efficiency and 61% purity

97% of ν_e-induced CC events misidentified as NC
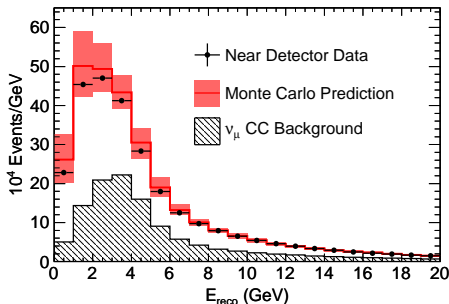
$L_{ND} = 1.04$ km
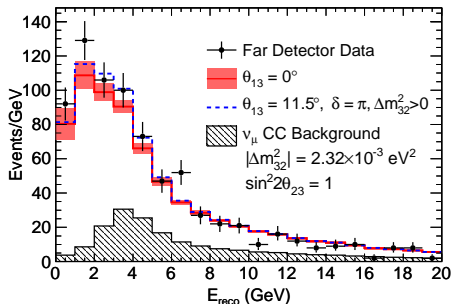
$L_{FD} = 735$ km

ϑ_{13}	χ^2/NDF	ϑ_{23}	ϑ_{24}	ϑ_{34}
0	130.4/122	45.0^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+17}_{-0.0}$
11.5	128.5/122	45.6^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+25}_{-0.0}$

$$\vartheta_{24} \lesssim 8° \text{ at } 90\% \text{ C.L.} \implies |U_{\mu 4}|^2 \simeq \sin^2 \vartheta_{24} \lesssim 0.019$$

$$\boxed{|U_{\mu 4}|^2 \lesssim 0.035 \text{ at } 99\% \text{ C.L.}}$$

Hernandez, Smirnov, arXiv:1105.5946

▶ Limit valid for $\Delta m_{41}^2 \lesssim 0.5 \text{ eV}^2$.

▶ For $\Delta m_{41}^2 \gtrsim 0.5 \text{ eV}^2$ SBL oscillations at Near Detector.

▶ MINOS insensitive to oscillations for $\Delta m_{41}^2 \gtrsim 15 \text{ eV}^2$ because oscillations already averaged at Near Detector.
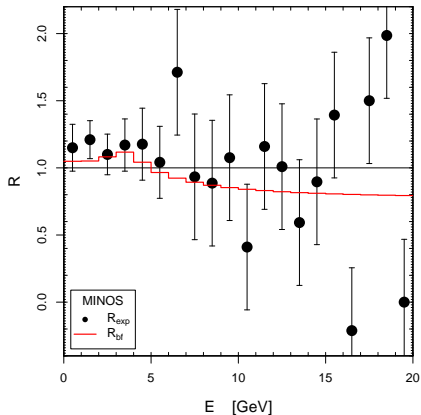
$$R = \frac{\langle 1 - P_{\nu_\mu \to \nu_s} \rangle_{\text{FD}}}{\langle 1 - P_{\nu_\mu \to \nu_s} \rangle_{\text{ND}}}$$
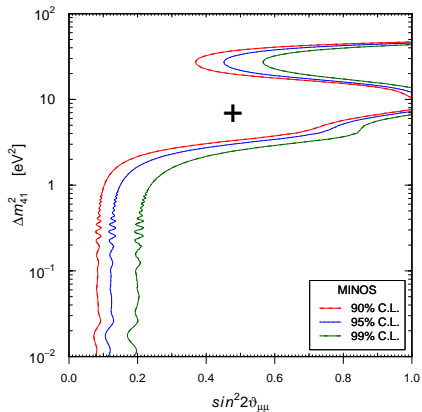
[Giunti, Laveder, arXiv:1109.4033]

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m^2 L}{4E} \right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

No CP Violation!

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m^2 L}{4E} \right) \quad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2 \right)$$

Perturbation of 3ν Mixing

$$|U_{e4}|^2 \ll 1, \quad |U_{\mu 4}|^2 \ll 1, \quad |U_{\tau 4}|^2 \ll 1, \quad |U_{s4}|^2 \simeq 1$$
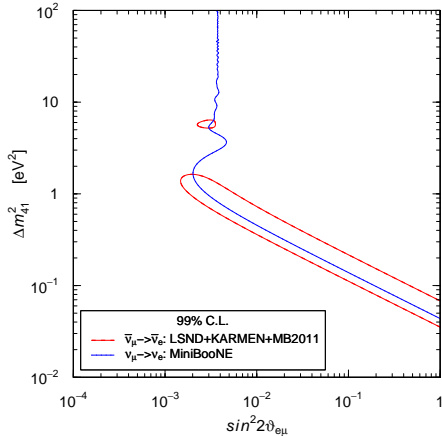
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

$$\sin^2 2\vartheta_{\alpha\alpha} \ll 1$$

$$\Downarrow$$

$$|U_{\alpha 4}|^2 \simeq \frac{\sin^2 2\vartheta_{\alpha\alpha}}{4}$$
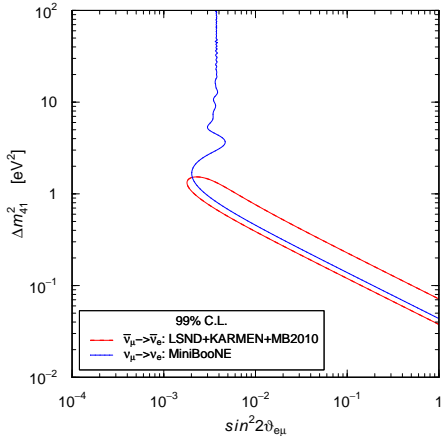
GoF = 17%,   PGoF = 0.15%   GoF = 36%,   PGoF = 3.3%

▶ Tension between $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ data is reduced with MiniBooNE 2011 antineutrino data.

▶ 3+2 $\implies$ CP Violation [Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004, hep-ph/0305255], [Maltoni, Schwetz, PRD 76, 093005 (2007), arXiv:0705.0107], [Karagiorgi et al, PRD 80 (2009) 073001, arXiv:0906.1997], [Kopp, Maltoni, Schwetz, arXiv:1103.4570], [Giunti, Laveder, arXiv:1107.1452]

▶ 3+1+NSI $\implies$ CP Violation [Akhmedov, Schwetz, JHEP 10 (2010) 115, arXiv:1007.4171]

Goodness of Fit

- Assumption or approximation: Gaussian uncertainties and linear model
- $\chi^2_{\min}$ has χ^2 distribution with Number of Degrees of Freedom
$$\text{NDF} = N_\text{D} - N_\text{P}$$
  $N_\text{D} = $ Number of Data $N_\text{P} = $ Number of Fitted Parameters
- $\langle \chi^2_{\min} \rangle = \text{NDF}$ $\text{Var}(\chi^2_{\min}) = 2\text{NDF}$
- $\text{GoF} = \displaystyle\int_{\chi^2_{\min}}^{\infty} p_{\chi^2}(z, \text{NDF}) \, dz$ $p_{\chi^2}(z, n) = \dfrac{z^{n/2-1} e^{-z/2}}{2^{n/2} \Gamma(n/2)}$

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
- $\chi^2_{\text{PGoF}} = (\chi^2_{\min})_{\text{A+B}} - [(\chi^2_{\min})_\text{A} + (\chi^2_{\min})_\text{B}]$
- χ^2_{PGoF} has χ^2 distribution with Number of Degrees of Freedom
$$\text{NDF}_{\text{PGoF}} = N_\text{P}^\text{A} + N_\text{P}^\text{B} - N_\text{P}^{\text{A+B}}$$
- $\text{PGoF} = \displaystyle\int_{\chi^2_{\text{PGoF}}}^{\infty} p_{\chi^2}(z, \text{NDF}_{\text{PGoF}}) \, dz$

Effective SBL Oscillation Probabilities in 3+2 Schemes
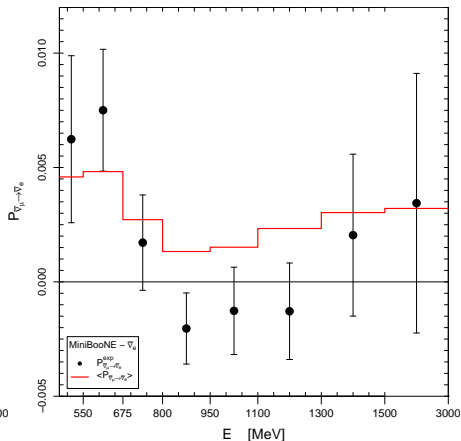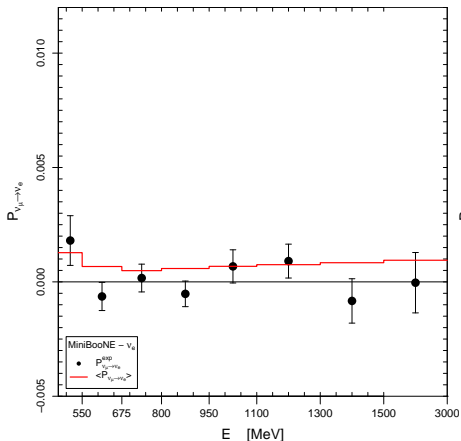
$$\phi_{kj} = \Delta m_{kj}^2 L / 4E$$

$$\eta = \arg[U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*]$$

$$P_{\overset{(-)}{\nu_\mu} \to \overset{(-)}{\nu_e}} = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2 \phi_{51}$$

$$+ 8|U_{\mu4} U_{e4} U_{\mu5} U_{e5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\overset{(-)}{\nu_\alpha} \to \overset{(-)}{\nu_\alpha}} = 1 - 4(1 - |U_{\alpha4}|^2 - |U_{\alpha5}|^2)(|U_{\alpha4}|^2 \sin^2 \phi_{41} + |U_{\alpha5}|^2 \sin^2 \phi_{51})$$

$$- 4|U_{\alpha4}|^2|U_{\alpha5}|^2 \sin^2 \phi_{54}$$

- Good: CP violation can solve the $\nu_\mu \to \nu_e$ vs $\bar\nu_\mu \to \bar\nu_e$ tension.

- Bad:
    - More parameters: 7 (vs 3 in 3+1)
    - 2 sterile neutrinos are disfavored by BBN.
    - A large sum of masses is disfavored by CMB+LSS.

3+2: MiniBooNE $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

$$P_{\overset{(-)}{\nu_\mu} \to \overset{(-)}{\nu_e}} = 4|U_{e4}|^2|U_{\mu4}|^2\sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu5}|^2\sin^2\phi_{51}$$

$$+ 4|U_{e4}U_{\mu4}U_{e5}U_{\mu5}|\cos\eta\left[\sin^2\phi_{41} + \sin^2\phi_{51} - \sin^2\phi_{54}\right]$$

$$\overset{(+)}{-} 2|U_{e4}U_{\mu4}U_{e5}U_{\mu5}|\sin\eta\left[\sin(2\phi_{41}) - \sin(2\phi_{51}) + \sin(2\phi_{54})\right]$$

Disappearance Constraints

$\bar{\nu}_e$ Disappearance
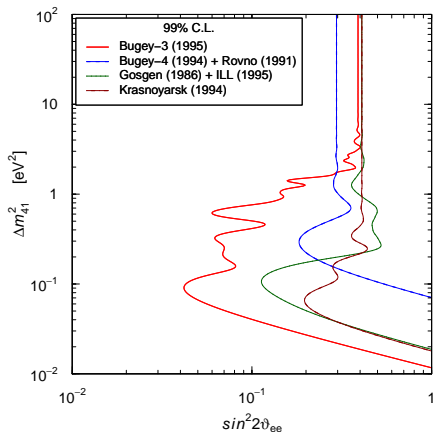
ν_μ and $\bar{\nu}_\mu$ Disappearance
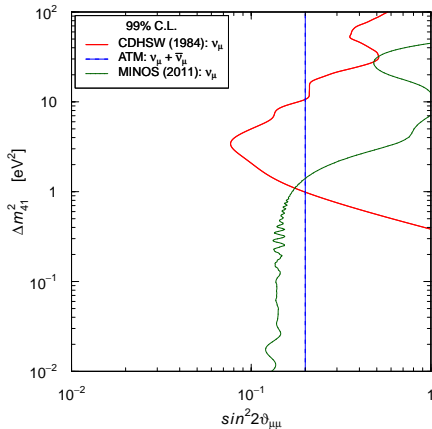
New Reactor $\bar{\nu}_e$ Fluxes

[Mueller et al., arXiv:1101.2663]

[Mention et al., arXiv:1101.2755]

ATM constraint on $|U_{\mu 4}|^2$

[Maltoni, Schwetz, PRD 76 (2007) 093005, arXiv:0705.0107]

3+1

▶ ν_e disappearance experiments:

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

▶ ν_μ disappearance experiments:

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

▶ $\nu_\mu \to \nu_e$ experiments:

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

▶ Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694, arXiv:hep-ph/9606411]

[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247, arXiv:hep-ph/9607372]

The figure shows a plot with axes $sin^2 2\vartheta_{e\mu}$ (horizontal, from 10^{-4} to 1) and Δm^2_{41} [eV^2] (vertical, from 10^{-2} to 10^2). Legend at 99% C.L.: $\overline{\nu}_e$ Disappearance, ν_μ Disappearance, Disappearance, Appearance.
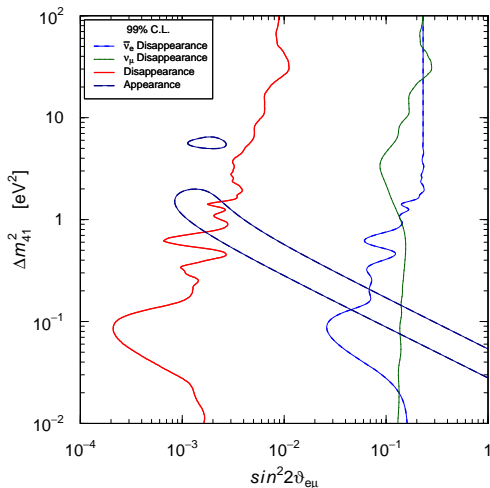
3+1

GoF = 57%

PGoF = 1%

- 3+1: Appearance-Disappearance tension
- 3+2: same tension [Kopp, Maltoni, Schwetz, arXiv:1103.4570], [Giunti, Laveder, arXiv:1107.1452]
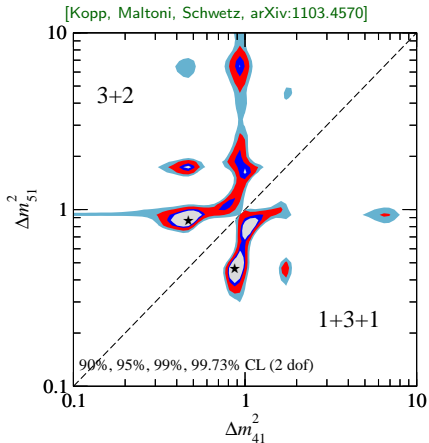- Tension reduced in 3+1+NSI [Akhmedov, Schwetz, JHEP 10 (2010) 115, arXiv:1007.4171]
- No tension in 3+1+CPTV [Barger, Marfatia, Whisnant, PLB 576 (2003) 303]
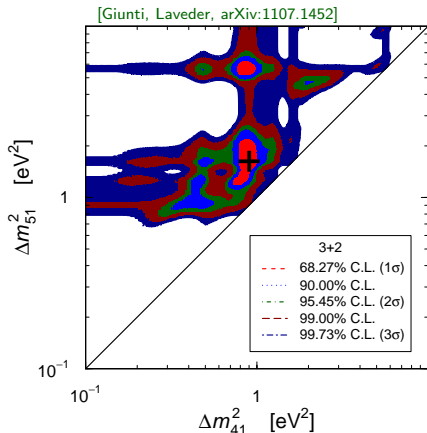 [Giunti, Laveder, PRD 82 (2010) 093016, PRD 83 (2011) 053006]

Global 3+2 Fits

[Kopp, Maltoni, Schwetz, arXiv:1103.4570]

3+2

1+3+1

90%, 95%, 99%, 99.73% CL (2 dof)

[Giunti, Laveder, arXiv:1107.1452]

3+2	
---	68.27% C.L. (1σ)
⋯⋯	90.00% C.L.
—·—·—	95.45% C.L. (2σ)
— — —	99.00% C.L.
—··—··—	99.73% C.L. (3σ)

Best Fit: $\eta = 1.64\pi$
$\Delta m_{41}^2 = 0.47\,\text{eV}^2$ $\Delta m_{51}^2 = 0.87\,\text{eV}^2$
$|U_{e4}|^2 = 0.016$ $|U_{e5}|^2 = 0.019$
$|U_{\mu4}|^2 = 0.027$ $|U_{\mu5}|^2 = 0.022$

$\chi_{\min}^2/\text{NDF} = 110.1/130$

Best Fit: $\eta = 1.52\pi$
$\Delta m_{41}^2 = 0.90\,\text{eV}^2$ $\Delta m_{51}^2 = 1.60\,\text{eV}^2$
$|U_{e4}|^2 = 0.017$ $|U_{e5}|^2 = 0.017$
$|U_{\mu4}|^2 = 0.018$ $|U_{\mu5}|^2 = 0.0064$
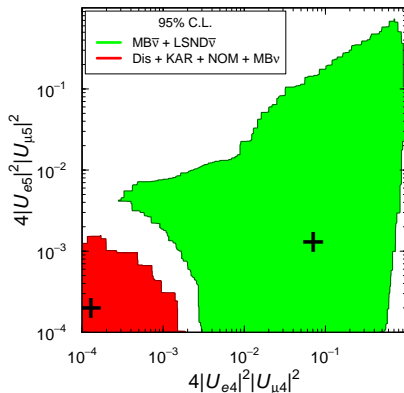
$\chi_{\min}^2/\text{NDF} = 91.6/100$

3+2: Persisting Tension

	3+1	3+2
$\Delta\chi^2_{PG}$	21.5	19.9
NDF_{PG}	2	5
$PGoF$	2×10^{-5}	1.3×10^{-3}

[Kopp, Maltoni, Schwetz, arXiv:1103.4570]

	3+1	3+2
$\Delta\chi^2_{PG}$	24.1	22.2
NDF_{PG}	2	5
$PGoF$	6×10^{-6}	5×10^{-4}

[Giunti, Laveder, arXiv:1107.1452]

- ▶ 3+2 improvement of PGoF is mainly a statistical effect!

- ▶ 3+2 is preferred to 3+1 only for CP-violating MiniBooNE neutrino antineutrino difference.
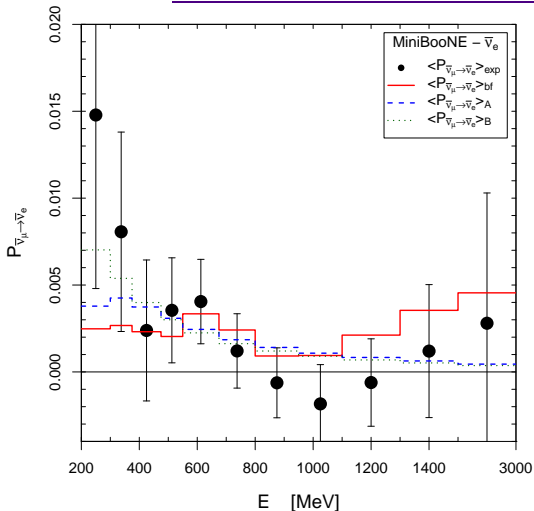
Towers 3+1 Neutrino Mixing

- ▶ Simplest scheme beyond standard three-neutrino mixing which can partially explain the data.

- ▶ It corresponds to the natural addition of one new entity (a sterile neutrino) to explain a new effect (short-baseline oscillations).

- ▶ Global χ^2 is good: $\chi^2_{\text{min}}/\text{NDF} = 120.7/124$.

- ▶ Marginal APP-DIS compatibility: $\Delta\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 9.3/2$.

- ▶ Marginal compatibility with cosmology for $\Delta m^2_{41} \lesssim 1\,\text{eV}^2$.
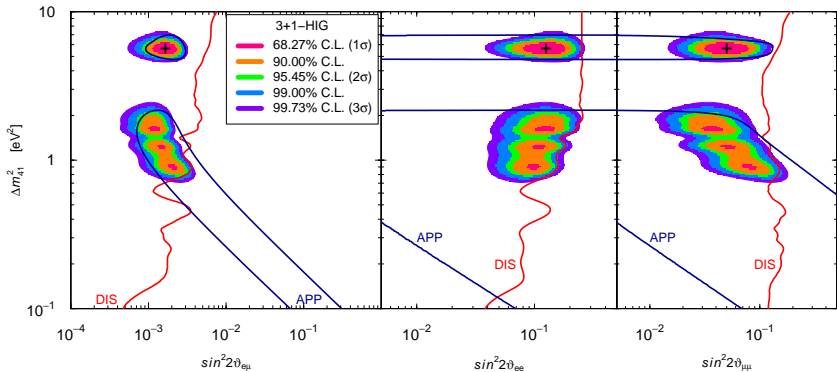
- Best fit at $\Delta m_{41}^2 \approx 5.6\,\mathrm{eV}^2 \implies m_4 \approx 2.4\,\mathrm{eV} \implies$ tension with standard cosmology.

- Large Δm_{41}^2 preferred by MiniBooNE 2011 antineutrino data.

- Small Δm_{41}^2 disfavored by MINOS constraint.

- Allowed regions at $\Delta m_{41}^2 \approx 1-2\,\mathrm{eV}^2$ marginally compatible with cosmology.
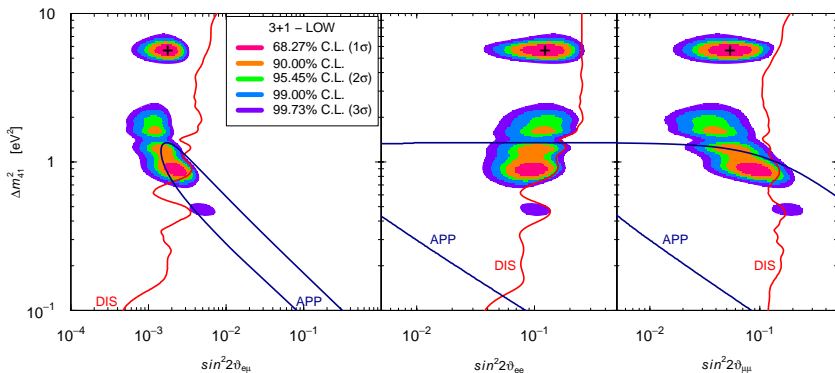
MiniBooNE Low-Energy Anomaly

bf: $\sin^2 2\vartheta_{e\mu} = 0.005$
$\Delta m^2_{41} = 4.68\,\mathrm{eV}^2$

A: $\sin^2 2\vartheta_{e\mu} = 0.005$
$\Delta m^2_{41} = 0.8\,\mathrm{eV}^2$

B: $\sin^2 2\vartheta_{e\mu} = 0.01$
$\Delta m^2_{41} = 0.5\,\mathrm{eV}^2$

[Giunti, Laveder, arXiv:1109.4033]

$$\text{GoF} = 37\% \qquad \text{PGoF} = 0.04\%$$
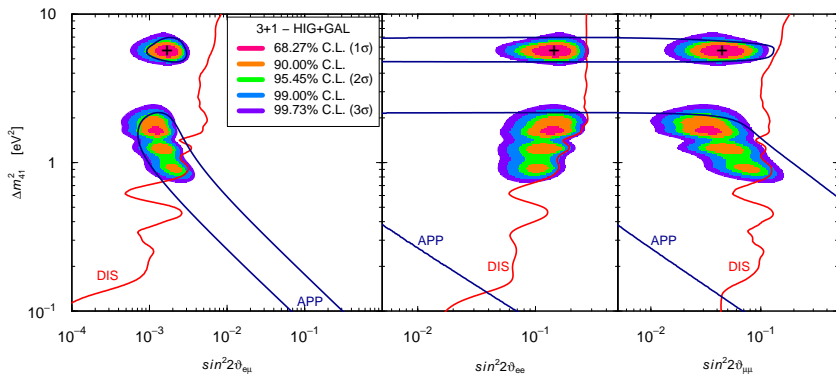
- Best fit point lies out of the region of overlap of the 3σ APP and DIS allowed regions.

- Tension indicates that MiniBooNE low-energy anomaly may have an explanation different from $\overset{\scriptscriptstyle(-)}{\nu}_\mu \to \overset{\scriptscriptstyle(-)}{\nu}_e$ oscillations.
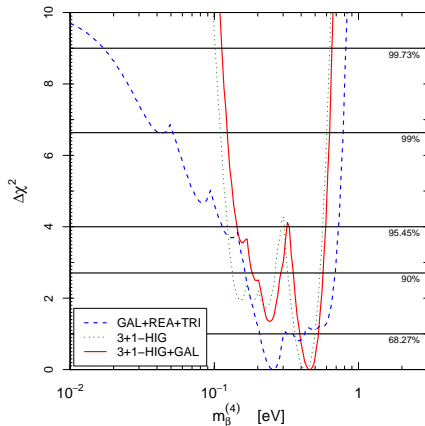
Gallium Anomaly

$$\text{GoF} = 48\% \qquad \text{PGoF} = 1\%$$

- Small impact because only four data points.

- Gallium data favor $\Delta m_{41}^2 \gtrsim 1\,\text{eV}^2$.

Testable Implications

β Decay

$(\beta\beta)_{0\nu}$ Decay
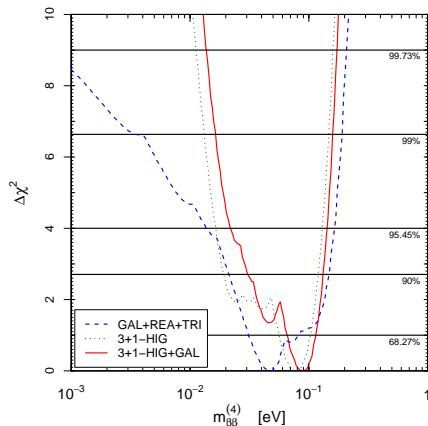
$$m_\beta^2 = \sqrt{\sum_k |U_{ek}|^2 m_k^2}$$

$$m_\beta^{(4)} = |U_{e4}| \sqrt{\Delta m_{41}^2}$$

$$m_{\beta\beta} = \left| \sum_k U_{ek}^2 m_k \right|$$

$$m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

[Giunti, Laveder, In Preparation]

Future

▶ MiniBooNE is continuing to take antineutrino data.

$$\bar{\nu}_\mu \to \bar{\nu}_e + \bar{\nu}_\mu \to \bar{\nu}_\mu$$

▶ ICARUS@CERN-PS: $L \sim 1 \text{km}$ $E \sim 1 \text{GeV}$ [C. Rubbia et al, CERN-SPSC-2011-012]

$$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$$

▶ MicroBooNE will test the MiniBooNE low-energy anomaly by measuring $\pi^0 \to 2\gamma$ background.

▶ LSND reloaded? Super-Kamiokande doped with Gadolinium
[Agarwalla, Huber, PLB 696 (2011) 359, arXiv:1007.3228.]

▶ Reactor Anomaly: Nucifer, small scintillator detector at $L = 7\text{m}$
[Lasserre, talk at EPS-HEP 2011]

▶ Possible experiment at a small-size fast neutron reactor   [Yasuda, arXiv:1107.4766]

- Gallium Anomaly: new SAGE Gallium source experiments with 2 spherical shells [Gavrin et al, arXiv:1006.2103]

- ν_e and $\bar{\nu}_e$ radioactive source experiments with low-threshold detectors.

- Borexino: $\overset{(-)}{\nu}_e + e^- \rightarrow \overset{(-)}{\nu}_e + e^-$ [Cribier et al, arXiv:1107.2335]
  [Pallavicini, talk at BEYOND3NU]
  [Ianni, Montanino, Scioscia, EPJC 8 (1999) 609, arXiv:hep-ex/9901012]

- LENS (Low Energy Neutrino Spectroscopy): [Agarwalla, Raghavan, arXiv:1011.4509]

$$\nu_e + {}^{115}\text{In} \rightarrow {}^{115}\text{Sn} + e^- + 2\gamma \qquad E_{\text{th}} = 0.1\,\text{MeV}$$

$$\bar{\nu}_e + p \rightarrow n + e^+ \qquad\qquad E_{\text{th}} = 1.8\,\text{MeV}$$

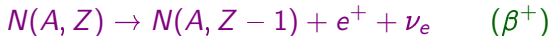- Spherical Gaseous TPC: [Vergados, Giomataris, Novikov, arXiv:1103.5307]
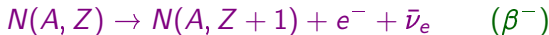 Targets: ${}^{131}\text{Xe}$, ${}^{40}\text{Ar}$, ${}^{20}\text{Ne}$, ${}^{4}\text{He}$. Sources: ${}^{37}\text{Ar}$, ${}^{51}\text{Cr}$, ${}^{65}\text{Zn}$, ${}^{32}\text{P}$.

- Coherent neutrino-nucleon scattering in low-temperature bolometers
  [Formaggio, Figueroa-Feliciano, Anderson, arXiv:1107.3512]

▶ Near-Detector Beta-Beam experiments: [Agarwalla, Huber, Link, JHEP 01 (2010) 071]

$$N(A, Z) \to N(A, Z + 1) + e^- + \bar{\nu}_e \qquad (\beta^-)$$

$$N(A, Z) \to N(A, Z - 1) + e^+ + \nu_e \qquad (\beta^+)$$

▶ ND Neutrino Factory experiments: [Giunti, Laveder, Winter, PRD 80 (2009) 073005]

$$\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$$

$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$

▶ ND+FD at Low Energy Neutrino Factory (LENF) [poster by Pascoli and Wong]

▶ CPT tests: $A_{\alpha\beta}^{\text{CPT}} = P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}$

Conclusions

- Suggestive LSND, MiniBooNE, Reactor and Gallium indications in favor of short-baseline neutrino oscillations $\implies$ sterile neutrinos

- 3+1 Neutrino Mixing:
  - No CP violation $\implies$ Neutrinos vs Antineutrinos tension
  - Appearance vs Disappearance tension
  - Marginal compatibility with cosmology.

- 3+2 Neutrino Mixing:
  - CP violation $\implies$ no Neutrinos vs Antineutrinos tension
  - Appearance vs Disappearance tension
  - Tension with cosmology.

- Neutrinos vs Antineutrinos tension has diminished with 2011 MiniBooNE data.

- Simpler 3+1 Neutrino Mixing may be enough (Occam's Razor).

- New short-baseline neutrino oscillation experiments are needed!