Neutrino physics in the precision era

Omar Miranda

Cinvestav

Dec 7, 2018

Outline

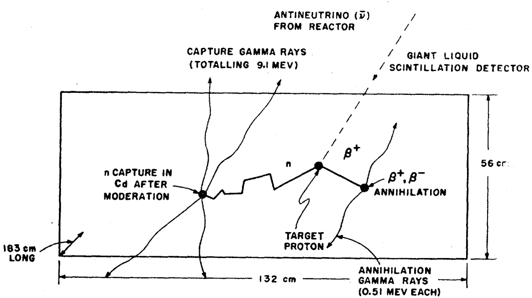
December 4th 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li nuclei and the continuous beta spectrum, I have hit upon a deseperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei **electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses.** *The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...*

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant, W. Pauli

$$\nu + p \rightarrow n + e^{+}$$



Reines, Cowan, Nature 1956, Phys. Rev. **113** p 273 (1959)

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi2}{}^+)$ and the $\tau^+(\equiv K_{\pi3}{}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are

PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

The existence of parity selection rules which work

Nuclear Physics **3** (1957) 127—131; *North-Holland Publishing Co., Amsterdam*

ON THE CONSERVATION LAWS FOR WEAK INTERACTIONS

L. LANDAU

Institute for Physical Problems, USSR Academy of Sciences, Moscow

Received 9 January 1957

Abstract: A variant of the theory is proposed in which non-conservation of parity can be introduced without assuming asymmetry of space with respect to inversion.

Various possible consequences of non-conservation of parity are considered which pertain to the properties of the neutrino and in this connection some processes involving neutrinos are examined on the assumption that the neutrino mass is exactly zero.

Introduction and motivation

Pontecorvo (1957,1967), Maki, Nakagawa, Sakata (1962)

Massive ν's:
the neutrino mass states ν_i (i=1,2,3) are different from the flavor states (weak interaction) ν_α (e, μ, τ)

$$|\nu_\alpha\rangle = \sum_i U_{ai} |\nu_i\rangle$$

$$\text{Tme: } t = 0 \quad |\nu_\alpha(x, t = 0)\rangle = \sum_i U_{\alpha i} e^{ip_i x} |\nu_i\rangle$$

$$\text{Time: } t > 0 \quad |\nu_\alpha(x, t)\rangle = \sum_i U_{\alpha i} e^{ip_i x - iE_i t} |\nu_i\rangle$$

$$\text{Ultrarelativistic } \nu\text{-s } m_i \ll p_i \qquad E_i = \sqrt{m_i^2 + p_i^2} \approx p_i + \frac{m_i^2}{2p_i}$$

$$\text{and } x \approx t \quad |\nu_\alpha(x, t)\rangle = \sum_i U_{\alpha i} e^{-i\frac{m_i^2}{2p_i} t} |\nu_i\rangle$$

Introduction and motivation

Survival probability $\nu_e \to \nu_e$

$$P_{\nu_e \to \nu_e}(x) = 1 - 1 \sin^2(2\theta) \sin^2 \left(\frac{\Delta m^2_{21}}{4E} L \right)$$

Conversion probability $\nu_e \to \nu_\mu$

$$P_{\nu_e \to \nu_\mu}(x) = \sin^2(2\theta) \sin^2 \left(\frac{\Delta m^2_{21}}{4E} L \right)$$

Introduction and motivation

Wolfenstein 1978, Mikheev & Smirnov 1985

- Neutral currents (NC): Z_0
- Charged currents (CC): $W_\pm$

$$V_e = \sqrt{2}\, G_F \left(N_e - \frac{N_n}{2} \right) , \qquad V_\mu = V_\tau = \sqrt{2}\, G_F \left(-\frac{N_n}{2} \right) .$$

Evolution ecuation

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}\, G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} .$$

Conversion probability $\nu_e \leftrightarrow \nu_\mu$:

$$P(\nu_e \to \nu_\mu;\, L) = \sin^2 2\theta_m \, \sin^2\left(\pi \frac{L}{l_m}\right) \, ,$$

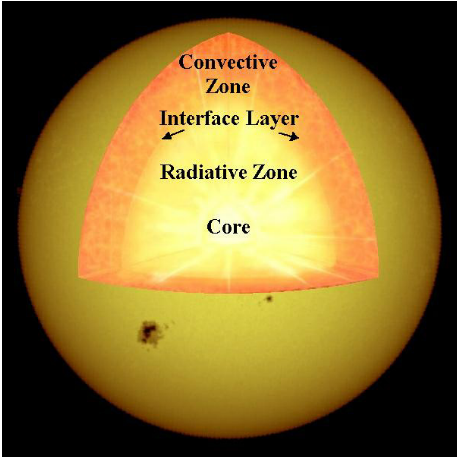
Matter mixing angle

$$\sin^2 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta}{\left(\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}\, G_F\, N_e\right)^2 + \left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta}$$

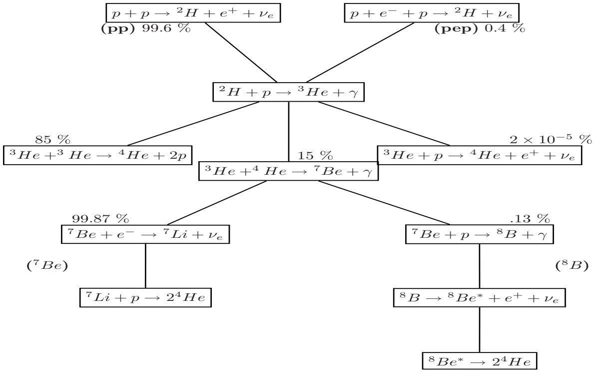
Resonance $\quad \sqrt{2}\, G_F\, N_e = \dfrac{\Delta m^2}{2E}\cos 2\theta$

Wolfenstein 1978, Mikheev & Smirnov 1985

Solar neutrinos

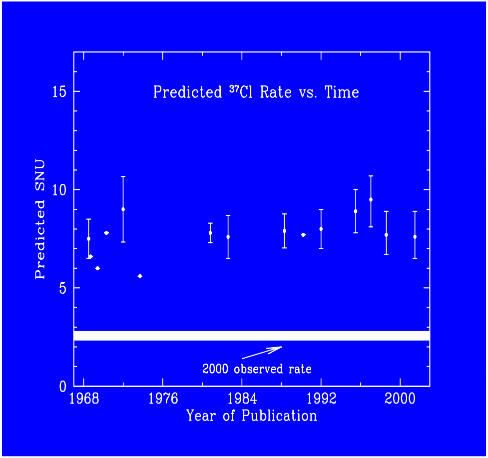


Solar neutrinos



Sola neutrinos

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar \quad Pontecorvo'46$$



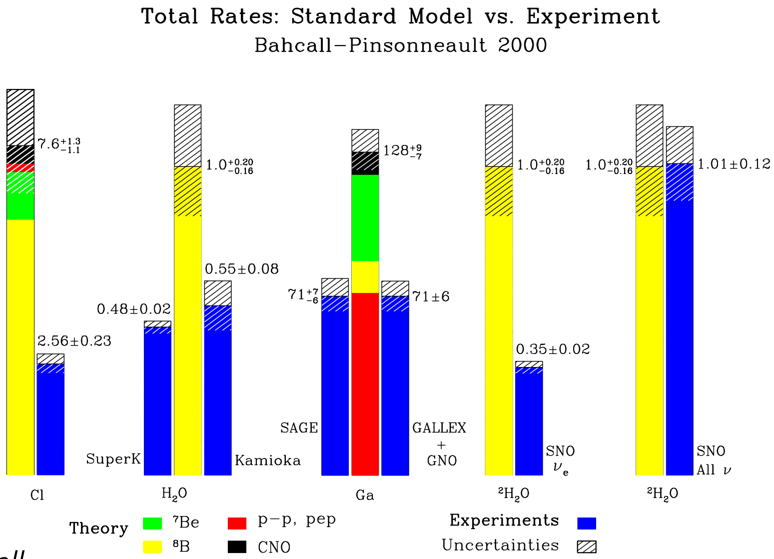
SNO Solar neutrinos

PRL **89** 011301 '02

$$\begin{array}{lcll} \nu_e + \mathrm{d} & \to & \mathrm{p} + \mathrm{p} + \mathrm{e}^- & \text{(CC)}, \\ \nu_x + \mathrm{d} & \to & \mathrm{p} + \mathrm{n} + \nu_x & \text{(NC)}, \\ \nu_x + \mathrm{e}^- & \to & \nu_x + e^- & \text{(ES)}. \end{array}$$

$$\begin{aligned} \phi_e &= 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.}) \\ \phi_{\mu\tau} &= 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.}) \end{aligned}$$

$$\phi^{\text{SNO}}_{\text{NC}} = 6.42^{+1.57}_{-1.57}(\text{stat.})^{+0.55}_{-0.58}\ (\text{syst.})$$


Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
$7.6^{+1.3}_{-1.1}$
2.56±0.23
Cl
0.48±0.02
SuperK
$1.0^{+0.20}_{-0.16}$
0.55±0.08
Kamioka
H_2O
71^{+7}_{-6}
SAGE
128^{+9}_{-7}
71±6
GALLEX
+
GNO
Ga
$1.0^{+0.20}_{-0.16}$
0.35±0.02
SNO
ν_e
^2H_2O
$1.0^{+0.20}_{-0.16}$
1.01±0.12
SNO
All ν
^2H_2O
Theory
^{7}Be
^{8}B
p−p, pep
CNO
Experiments
Uncertainties

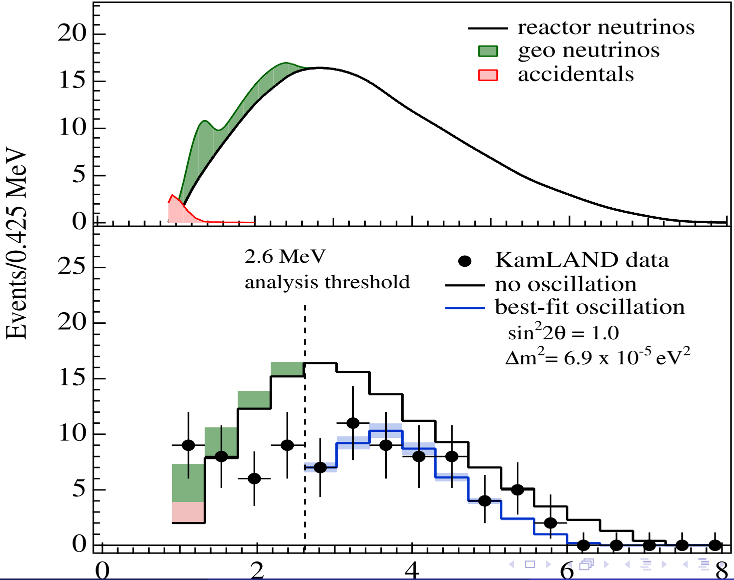
Bahcall

KamLAND

$$\bar{\nu}_e + p \to n + e^+ : \qquad P_{\bar{\nu}_e \to \bar{\nu}_\mu}(x) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}x\right)$$

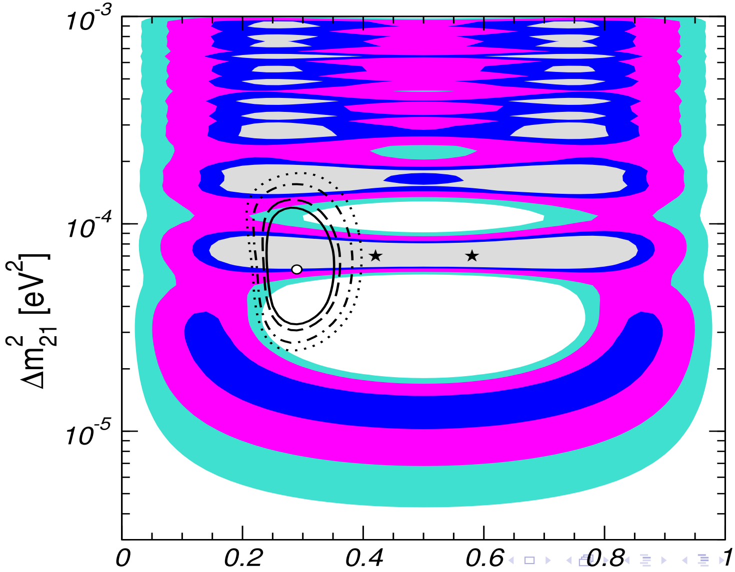
KamLAND neutrinos

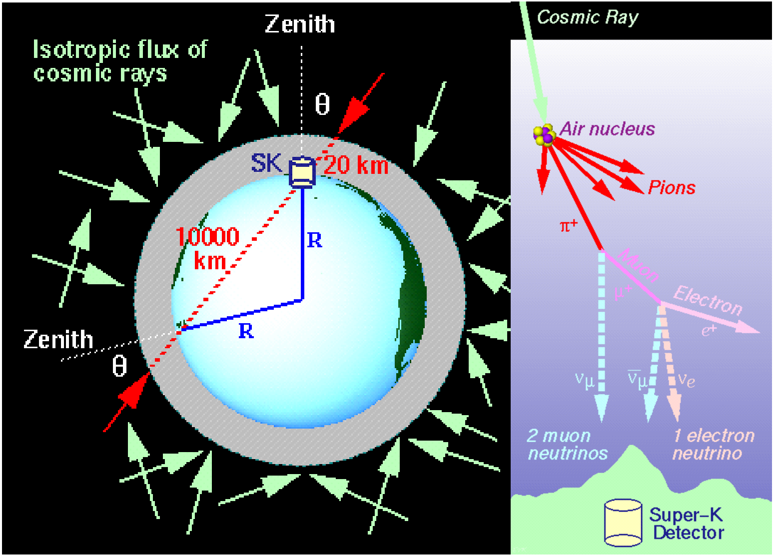
PRL **90** 021802 ’03



Solar neutrino problem solved

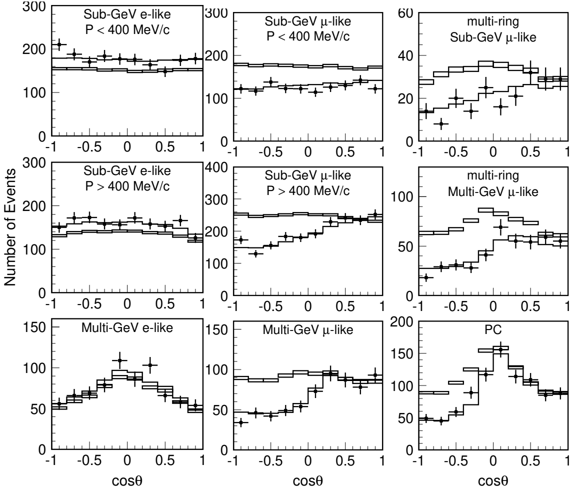
Maltoni, Schwetz, Tortola, Valle NJP **6** 122 (2004)





Super-Kamiokande atmospheric neutrino detection

Atmospheric neutrinos



Neutrino experiments

Nobel prize 2015 "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Introduction and motivation

Pontecorvo (1957,1967), Maki, Nakagawa, Sakata (1962)

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$$\text{and } x \approx t \quad |\nu_\alpha(x, t)\rangle = \sum_i U_{\alpha i} e^{-i\frac{m_i^2}{2p_i}t} |\nu_i\rangle$$

Three families

$$U = R_{23}(\theta_{23}; 0)\, R_{13}(\theta_{13}; \delta)\, R_{12}(\theta_{12}; 0)\, P\,,$$

$$R_{13}(\theta_{13}; \delta) = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}.$$

$$P = \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

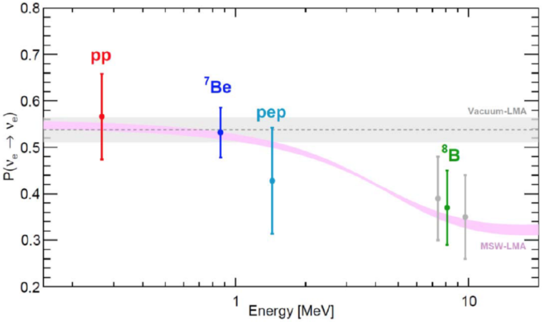
Three families

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\,e^{-i\delta} \\ -(s_{12}c_{23}+c_{12}s_{23}s_{13}\,e^{i\delta}) & (c_{12}c_{23}-s_{12}s_{23}s_{13}\,e^{i\delta}) & s_{23}c_{13} \\ (s_{12}s_{23}-c_{12}c_{23}s_{13}\,e^{i\delta}) & -(c_{12}s_{23}+s_{12}c_{23}s_{13}\,e^{i\delta}) & c_{23}c_{13} \end{pmatrix}$$

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= \left| \sum_j U^*_{\alpha j} U_{\beta j}\, e^{-i\frac{m_j^2}{2E}L} \right|^2 = \\ \delta_{\alpha\beta} &- 4\sum_{i>j} \Re\left\{U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}\right\} \sin^2\left(\frac{\Delta m_{ij}^2}{4E}L\right) \\ &+ 2\sum_{i>j} \Im\left\{U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}\right\} \sin\left(\frac{\Delta m_{ij}^2}{2E}L\right) \end{aligned}$$

Borexino

Nature **562** (2018) 505



Three families

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\,e^{-i\delta} \\ -(s_{12}c_{23}+c_{12}s_{23}s_{13}\,e^{i\delta}) & (c_{12}c_{23}-s_{12}s_{23}s_{13}\,e^{i\delta}) & s_{23}c_{13} \\ (s_{12}s_{23}-c_{12}c_{23}s_{13}\,e^{i\delta}) & -(c_{12}s_{23}+s_{12}c_{23}s_{13}\,e^{i\delta}) & c_{23}c_{13} \end{pmatrix}$$

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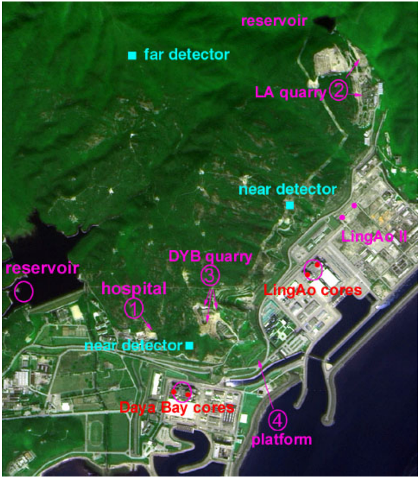
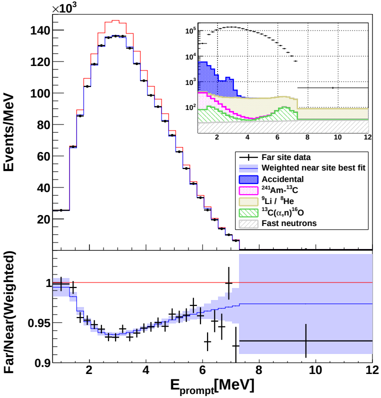
Daya Bay



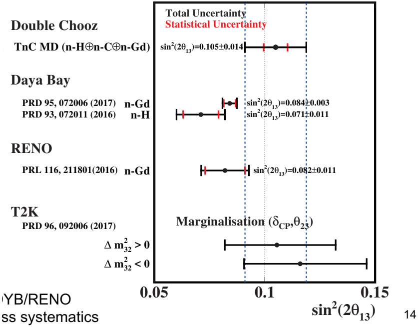
Talk by David Martinez Caicedo

Daya Bay



Daya Bay ArXiv:1809.04660

Daya Bay, Double Chooz, Reno



C. Buck Talk at the XXVIII International Conference on Neutrino Physics and Astrophysics DOI: 10.5281/zenodo.1286843

Three families

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\,e^{-i\delta} \\ -(s_{12}c_{23}+c_{12}s_{23}s_{13}\,e^{i\delta}) & (c_{12}c_{23}-s_{12}s_{23}s_{13}\,e^{i\delta}) & s_{23}c_{13} \\ (s_{12}s_{23}-c_{12}c_{23}s_{13}\,e^{i\delta}) & -(c_{12}s_{23}+s_{12}c_{23}s_{13}\,e^{i\delta}) & c_{23}c_{13} \end{pmatrix}$$

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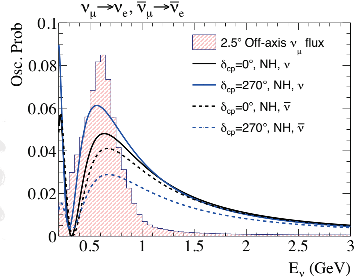
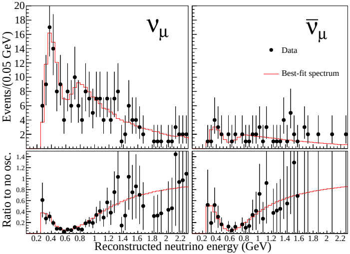
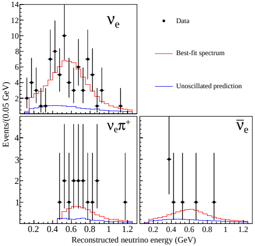
T2K



M. Waskcko Talk at the XXVIII International Conference on Neutrino Physics and Astrophysics DOI: 10.5281/zenodo.1286751

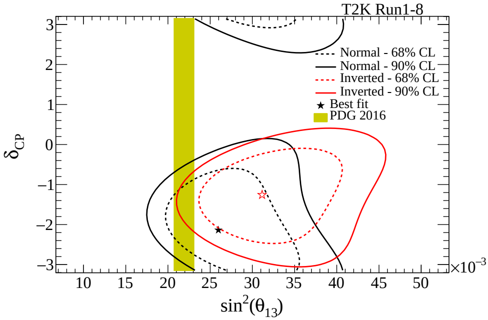




T2K Phys. Rev. Lett. **121** (2018) 171802

T2K

T2K Phys. Rev. Lett. **121** (2018) 171802



NOvA


NOvA Far Detector
MINOS Far Detector
Ontario
Wisconsin
Milwaukee
Michigan
Fermilab
Chicago
© 2007 Europa Technologies
Image © 2007 TerraMetrics
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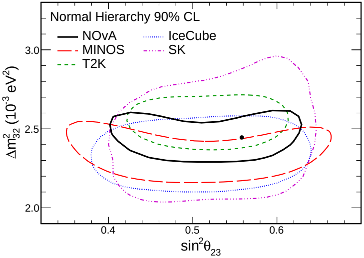
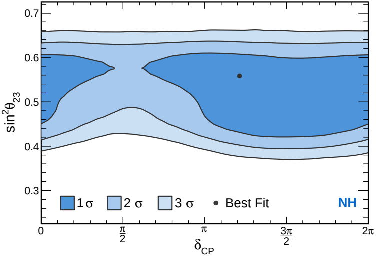
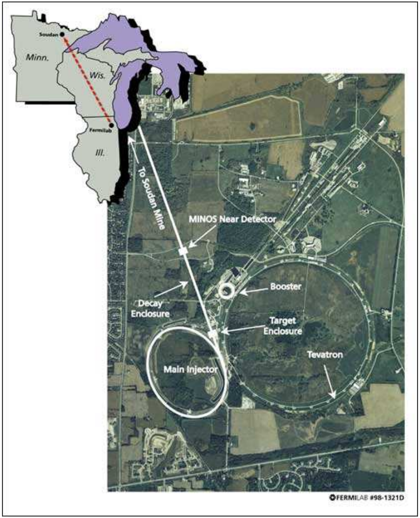
NOvA

Phys. Rev. **D98** (2018) 032012





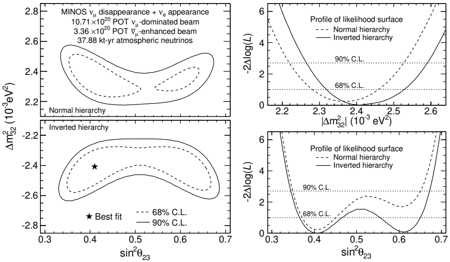
MINOS



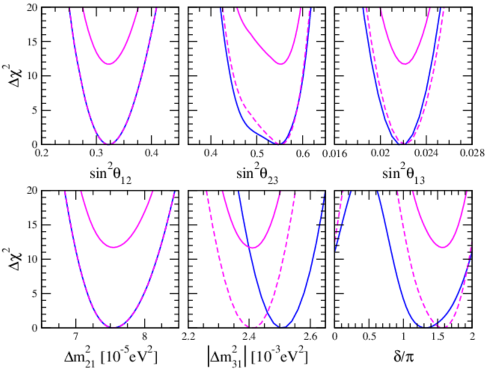
Soudan
Minn.
Wis.
Fermilab
Ill.
To Soudan Mine
MINOS Near Detector
Booster
Decay Enclosure
Target Enclosure
Tevatron
Main Injector
FERMILAB #98-1321D

MINOS

MINOS: PRL **112** 191801 (2014)



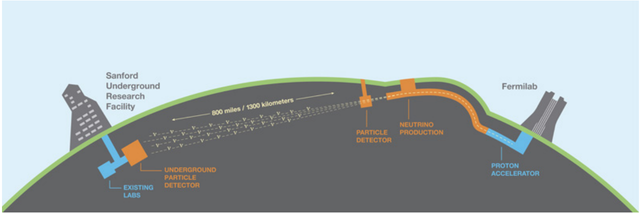
The current global picture



de Salas, **D.V. Forero**, C.A. Ternes, Tortola, Valle Phys. Lett. **B782** (2018) 633
https://globalfit.astroparticles.es/

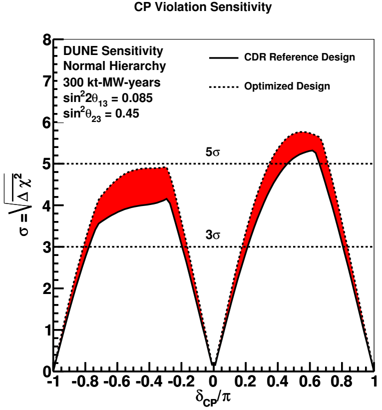
Future neutrino experiments: (Standard oscillation roads)

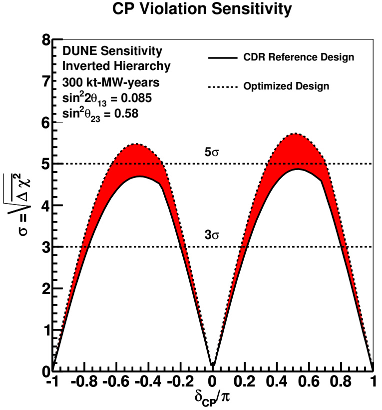
DUNE ArXiv:1807.1033



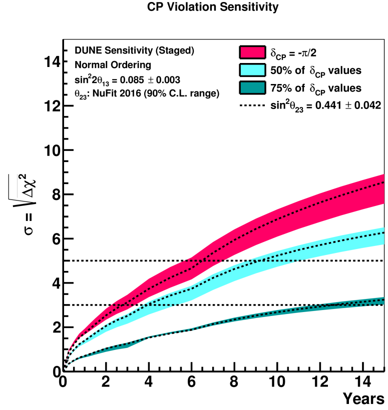
Talk by Dewys Moreno Lopez

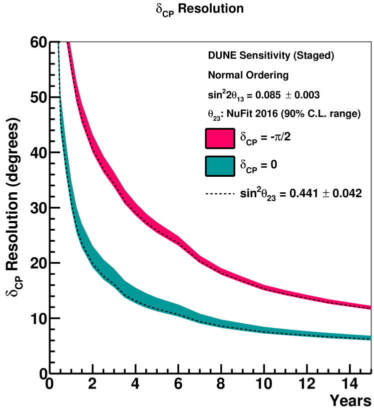
DUNE ArXiv:1512.06148





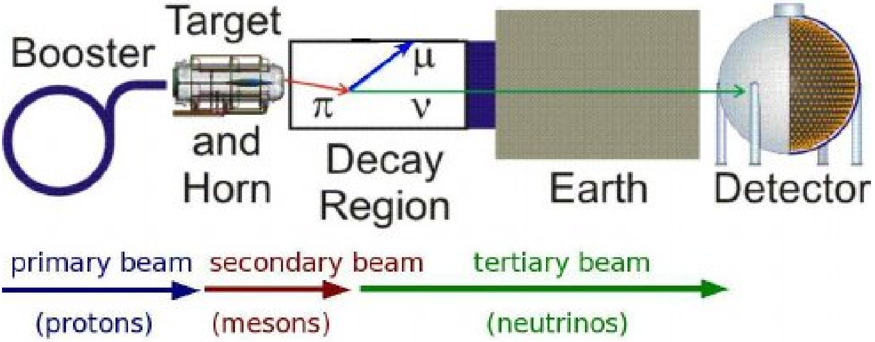
DUNE ArXiv:1807.1033





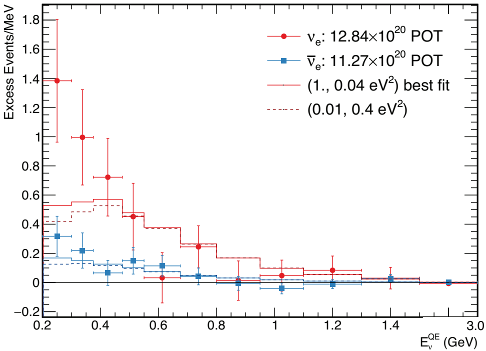
The Future: Sterile neutrinos

LSND-MiniBooNE anomaly



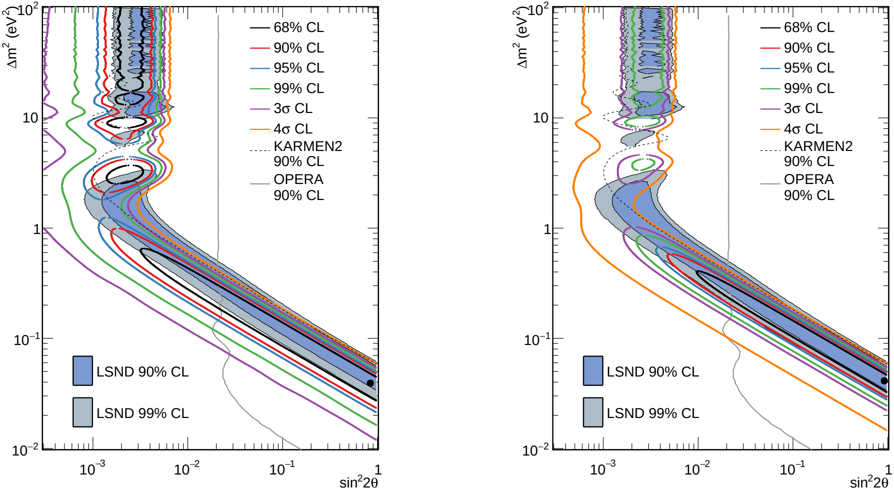
A. Aguilar-Arevalo et al. Phys.Rev. D81 (2010) 092005
Talk by David Matinez Caicedo

LSND-MiniBooNE anomaly



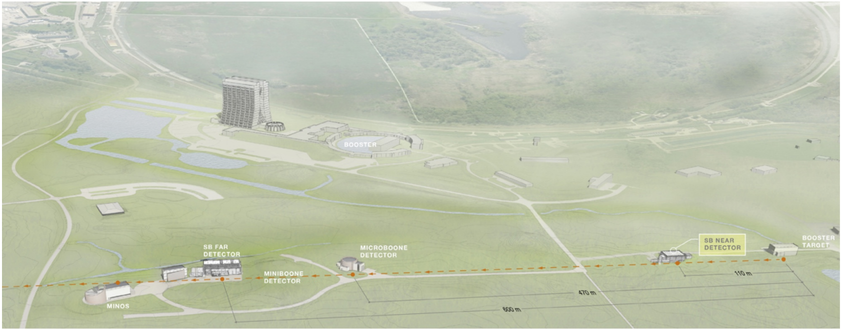
E.C. Huang Talk at the XXVIII International Conference on Neutrino Physics and Astrophysics DOI: 10.5281/zenodo.1287003

LSND-MiniBooNE anomaly



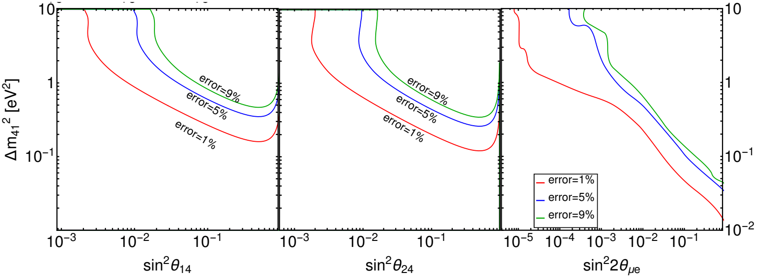
A. Aguilar-Arevalo et al. Phys. Rev. Lett. **121** (2018) 221801

Short Baseline Neutrino Experiment SBNE



ArXiv:1503.01520

DUNE near detector



OGM, Pasquini, Tortola, Valle Phys. Rev. **D97** (2018) 095026

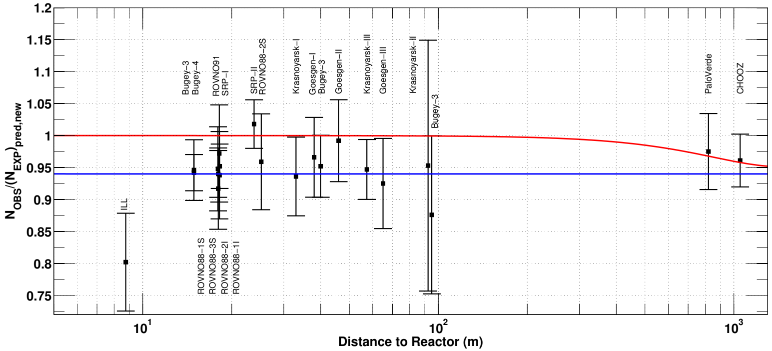
S. Choubey, D. Pramanik, Phys. Lett. **B764** (2017) 135

S. Choubey, D. Dutta, D. Pramanik, Phys. Rev. **D96** (2017) 056026

S. K. Agarwalla, S. S. Chatterjee, A. Palazzo, JHEP 1804 (2018) 091

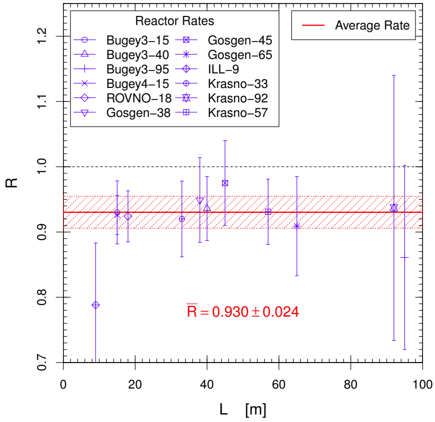
The reactor anomaly

Very short baseline IBD experiments



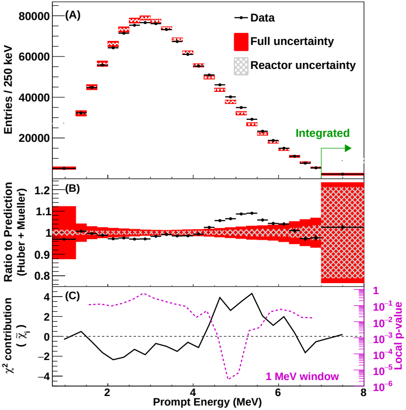
G. Mention et al. Phys.Rev. D83 (2011) 073006 arXiv:1101.2755

Very short baseline IBD experiments



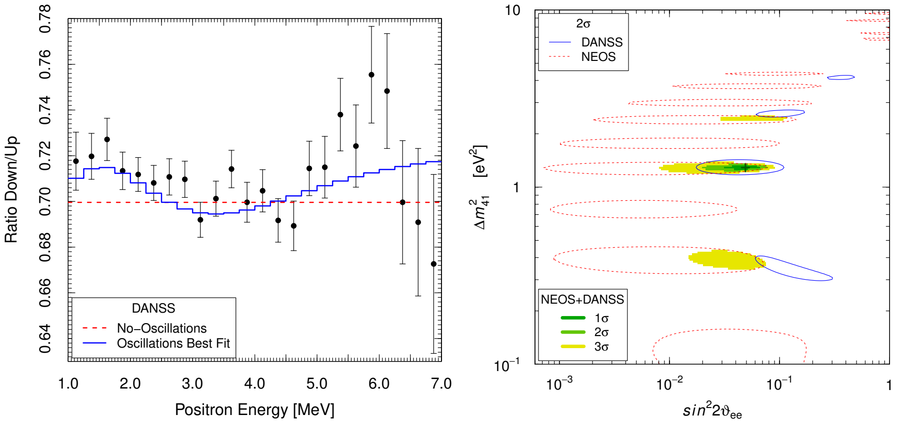
C. Giunti et al. PRD **86** 113014 (2012)

What is the reactor spectrum?



Daya Bay Chin. Phys. **C41** 013002 (2017)

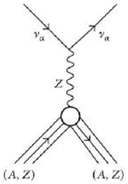
Very short baseline IBD experiments



S. Gariazzo, C. Giunti et al. Phys. Lett **B782** (2018) 13

Sterile neutrino and CENNS

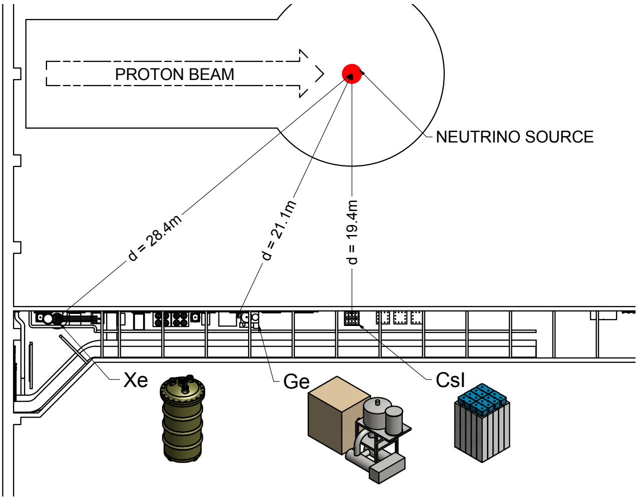
CENNS



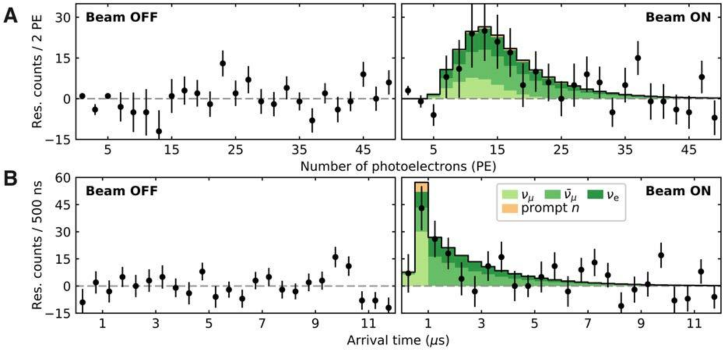
$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{[Zg_V^p + Ng_V^n]^2\right\}$$

M is the nucleus mass;
T recoil nucleus energy (from 0 to $T_{max} = 2E_\nu^2/(M + 2E_\nu)$);
E_ν neutrino energy;
$qR << 1$, $q \simeq \sqrt{2MT}$;
D. Freedman Phys. Rev. D9 1389 (1974)

COHERENT Coll. 1509.08702

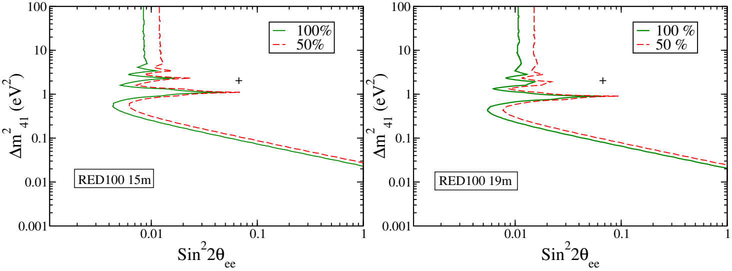


COHERENT Coll. Science 357 (2017) 1123



Future experiments to measure CENNS at reactors

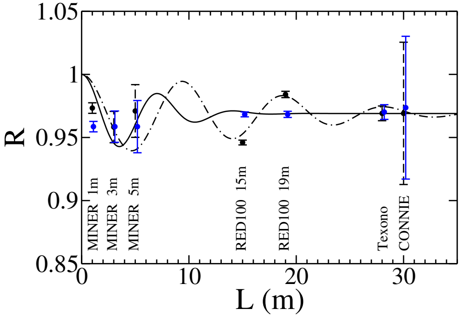
	T_{thres}	Baseline	Z/N	Det. Tec.	Fid. Mass
CONNIE	28 eV	30 m	1.0	CCD (Si)	1 kg
RED100	500 eV	19 m	0.70	Lq.Xe	100 kg
MINER	10 eV	1 m	0.81	^{72}Ge:^{28}Si (2:1)	30 kg
TEXONO	100 eV	28 m	0.79	HPGe	1 kg
CONUS	100 eV	10 m	0.79	HPGe	100 kg



Canas, Garces, OGM, **Parada**, Phys. Lett. B **776** 451 (2018)

See also B Dutta et al, Phys. Rev. D **94** 093003 (2016)

Sterile neutrino



Canas, Garces, OGM, **Parada**, Phys. Lett. B **776** 451 (2018)

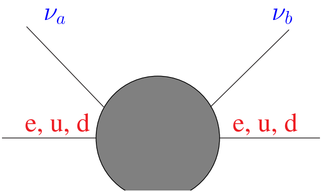
Non-standard interactions (NSI). 3 degeneracies

Non-standard interactions NSI

Most extensions of the SM predict neutral current non-standard interactions (NSI) of neutrinos which can be either flavor preserving (FD or NU) or flavor-changing (FC).

NSI effective Lagragian form:

$$\mathcal{L}_{eff}^{NSI} = -\sum_{\alpha\beta fP} \varepsilon_{\alpha\beta}^{fP} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f}\gamma^\rho P f)$$



Here $\alpha, \beta = e, \mu, \tau$; $f = e, u, d$; $P = L, R$; $L = (1 - \gamma_5)/2$; $R = (1 + \gamma_5)/2$

Oscillations in matter

- Neutral currents (NC): exchange of Z_0
- Charge currents (CC): exchange of $W_\pm$

$$V_e = \sqrt{2}\, G_F \left(N_e - \frac{N_n}{2} \right), \qquad V_\mu = V_\tau = \sqrt{2}\, G_F \left(-\frac{N_n}{2} \right).$$

Evolution equation

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}\, G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}.$$

NSI degeneracy I

$$H_{\rm NSI} = \sqrt{2} G_F N_f \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix} .$$

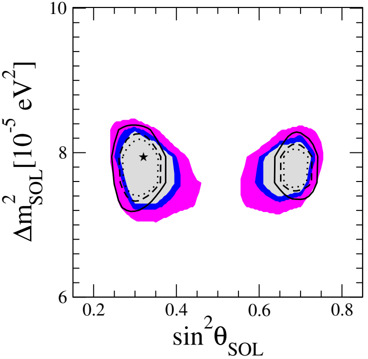
Mixing angle in matter + NSI

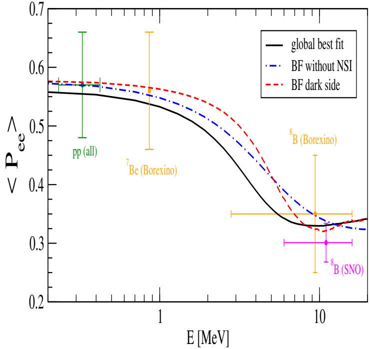
$$\tan 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right) \sin 2\theta + 2\sqrt{2} G_F \varepsilon N_d}{\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}\, G_F\, N_e + \sqrt{2}\, G_F \varepsilon'\, N_d} .$$

Resonance $\quad \frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}\, G_F\, N_e + \sqrt{2}\, G_F\, \varepsilon'\, N_d = 0 .$

$$\varepsilon' > \frac{N_e}{N_d}$$

OGM, M. Tortola, J. W. F. Valle, JHEP 0610:008 (2006) hep-ph/0406280



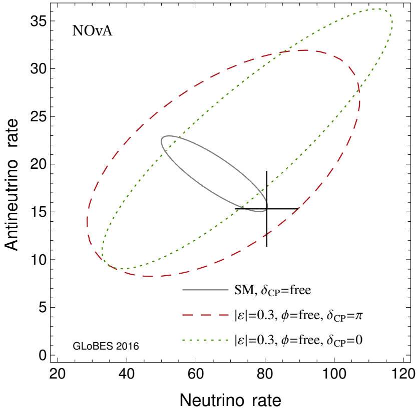


F. J. Escrihuela, OGM, M. Tortola, J. W. F. Valle, Phys. Rev. D **80** 105009 (2009)

M. C. Gonzalez-Garcia, M. Maltoni, JHEP **1309** 152 (2013)

M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz Nucl. Phys. B **908** 199 (2016)

NSI degeneracy II

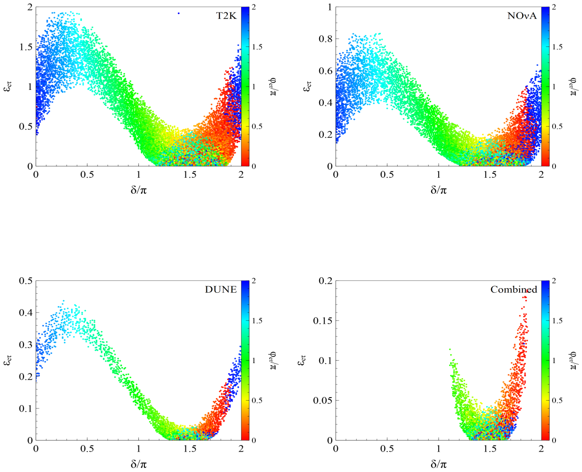


P. Huber, **D. V. Forero** Phys.Rev.Lett. 117 (2016) no.3, 031801

see OGM, Tortola, Valle PRL 117 061804 for the case of non-unitarity

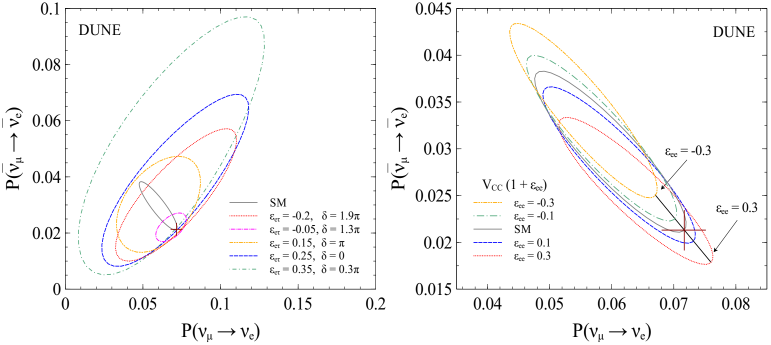
F.J. Escrihuela, **D.V. Forero**, O.G. Miranda, M. Tortola, J.W.F. Valle

NSI degeneracy II



L.J. Flores, E.A. Garces, OGM Phys. Rev. **D98** (2018) 035030

NSI degeneracy II



L.J. Flores, E.A. Garces, OGM Phys. Rev. **D98** (2018) 035030

NSI and coherent scattering

$$G_V = \left[\left(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}\right) Z + \left(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}\right) N\right] F_{nucl}^V(Q^2) \quad (1)$$

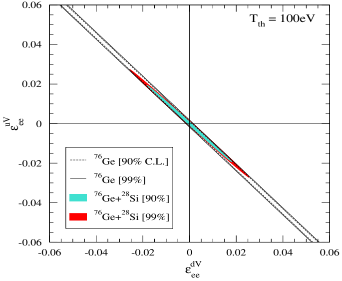
$$\begin{aligned} \frac{d\sigma}{dT}(E_\nu, T) &= \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \\ &\times \left\{\left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})\right]^2 + \right. \\ &+ \left. \sum_{\alpha=\mu,\tau}\left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV})\right]^2\right\} \end{aligned}$$

J. Barranco, OGM, T. I. Rashba JHEP 0512 (2005) 021

see also K. Scholberg PRD **73** (2007) 033005

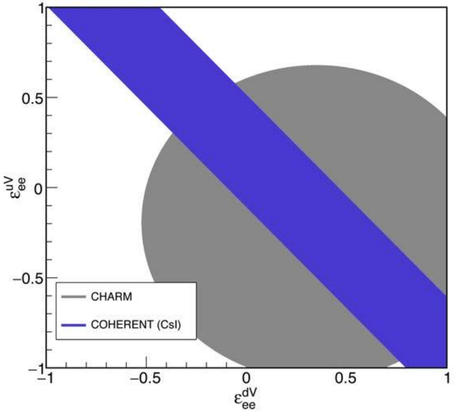
see also J. Barranco, OGM, T. I. Rashba PRD **73** (2007) 033005

Estimated bounds on NSI for TEXONO (Ge+Si)



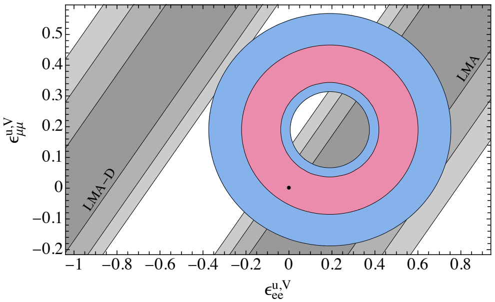
J. Barranco, OGM, T.I. Rashba JHEP 0512:021 (2005)

current bound from COHERENT



COHERENT Coll. Science 357 (2017) 1123

NSI bound from COHERENT



P. Coloma et al Phys. Rev. D 96, 115007 (2017)
see also J. Liao and D. Marfatia Phys.Lett. B775 (2017) 54-57
D. K Papoulias and T. Kosmas Phys.Rev. D97 (2018) no.3, 033003

Conclusions

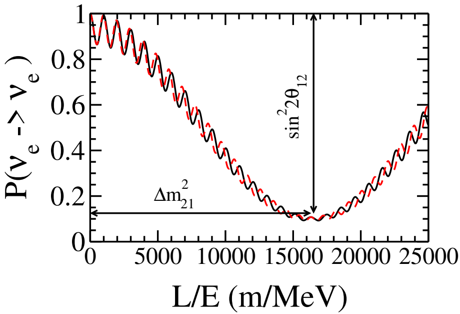
- ✓ Neutrino physics is currently in the precision era and we expect to have the complete standard picture in the next few years
- ✓ It will be possible to search for different types of physics beyond the Standard Model
- ✓ The interplay between different experiments, including non-oscillacion experiments will be crucial

Thanks

JUNO Reactor antineutrino experiment J. Phys. **G43** (2016) 030401

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)\right]$$

$$\Delta m_{32}^2 = \Delta m_{31}^2 (1 - \frac{\Delta m_{21}^2}{\Delta m_{31}^2})$$



Non-standard interactions

Non-standard neutrino-electron and neutrino quark interactions:

$$\mathcal{L} = \lambda_{ijk} \tilde{e}_R^{k*} (\bar{\nu}_L^i)^c e_L^j + \lambda'_{ijk} \tilde{d}_L^j \bar{d}_R^k \nu_L^i + \dots$$

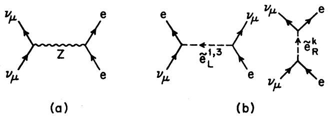
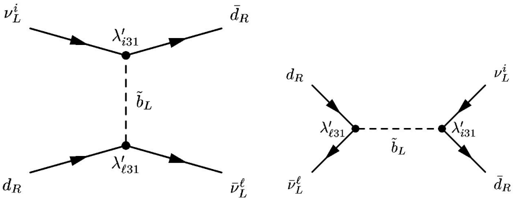


FIG. 2. Feynman diagrams for $\nu_\mu e$ scattering from (a) the standard model, and (b) the R-breaking interactions.

Barger, Giudice & Han'89

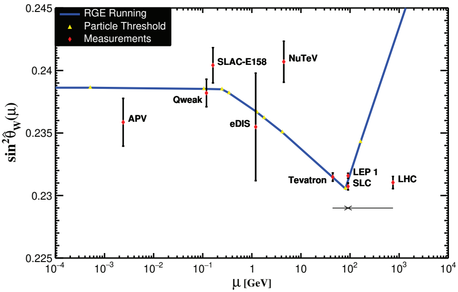


See e.g. Roulet'91, Amanik et al'05

The weak mixing angle

The weak mixing angle

- → The weak mixing angle is a fundamental parameter of the Standard Model and it has been measured with great precision at high energies.
- → At low energies its measurement has been a difficult task, especially in the neutrino sector. On one hand, the interaction of neutrinos with quarks at low energies gave measurements that appeared to be in disagreement with the SM, although a recent evaluation of the sea quark contributions reports coincidence with the standard model (R. D. Ball et al., Nucl. Phys B823 (2009) 195; W. Bentz et al., Phys. Lett B 693 (2010) 462).



PDG M. Tanabashi et al. PRD 98 (2018) 030001

Future experiments to measure CENNS at reactors

	T_{thres}	Baseline	Z/N	Det. Tec.	Fid. Mass
CONNIE	28 eV	30 m	1.0	CCD (Si)	1 kg
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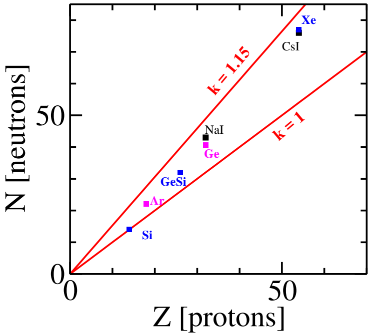
TEXONO	100 eV	28 m	0.79	HPGe	1 kg
CONUS	100 eV	10 m	0.79	HPGe	100 kg

CEvNS

$$G_V = \left[F_Z^V(q^2) g_V^p Z + F_N^V(q^2) g_V^n N \right]$$

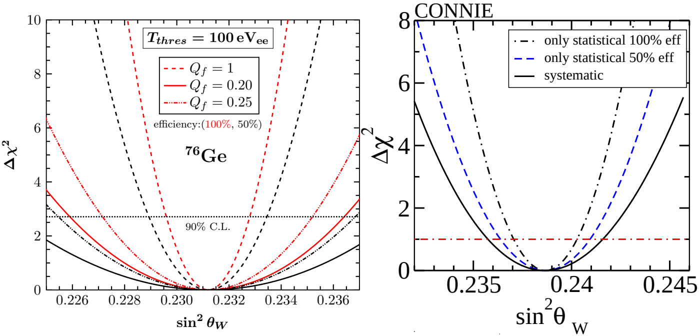
$$\begin{aligned} g_V^p &= \rho_{\nu N}^{\mathrm{NC}} \left(\frac{1}{2} - 2\hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) \\ g_V^n &= -\frac{1}{2} \rho_{\nu N}^{\mathrm{NC}} \end{aligned}$$

Target for CEνNS



updated from J. Barranco, OGM, T.I. Rashba JHEP 0512:021 (2005)

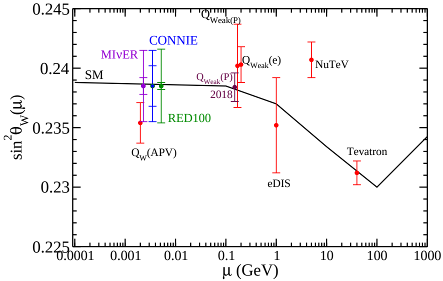
Texono and CONNIE



T.S. Kosmas, OGM, D.K. Papoulias, M. Tortola, J.W.F. Valle, PLB **750** 459 (2015)

B.C. Canas, A. Parada, et al. Phys. Lett. B **784**, 159 (2018)

expectations for $\sin^2\theta_W$



Canas, Parada et al. Phys. Lett. B **784**, 159 (2018)

D. Androic et al., Nature **557** 207 (2018)

C. Patrignani et al., Chin. Phys. C **40** 100001 (2016)

For the current constraint from COHERENT see D. K. Papoulias and T. Kosmas Phys.Rev. D97 (2018) no.3, 033003