Abstract

In neutrino oscillation physics numerous exact degeneracies exist under the name LMA-Dark. These degeneracies make it impossible to determine the sign of Δm^2_{31} known as the atmospheric mass ordering with oscillation experiments alone in the presence of new neutrino interactions. The combination of different measurements including multiple oscillation channels and neutrino scattering experiments lifts some aspects of these degeneracies. In fact, previous measurements of coherent elastic neutrino nucleus scattering (CEvNS) by COHERENT already ruled out the LMA-Dark solution for new physics with mediators heavier than $M_{Z'} \sim 50$ MeV while cosmological considerations disfavor these scenarios for mediators lighter than $M_{Z'} \sim 3$ MeV. Here I leverage new reactor data which provides the strongest bounds on CEvNS with light mediators to date. We show that this data completely removes the degeneracies in the ν_e sector for mediators down to the MeV scale at which point constraints from the early universe take over. While the LMA-Dark degeneracy is lifted in the ν_e sector, it can still be restored in the ν_μ and ν_τ sector or with very specific couplings to up and down quarks, and I speculate on a path forward.

Towards Solidifying the Discrete Mass Ordering Measurement in the Presence of New Physics

Peter B. Denton

Magnificent CEvNS

June 10, 2025

P. Coloma, PBD, M. Gonzalez-Garcia, M. Maltoni, T. Schwetz 1701.04828
PBD, Y. Farzan, I. Shoemaker 1804.03660
PBD, J. Gehrlein 2008.06062
PBD, J. Gehrlein 2204.09060

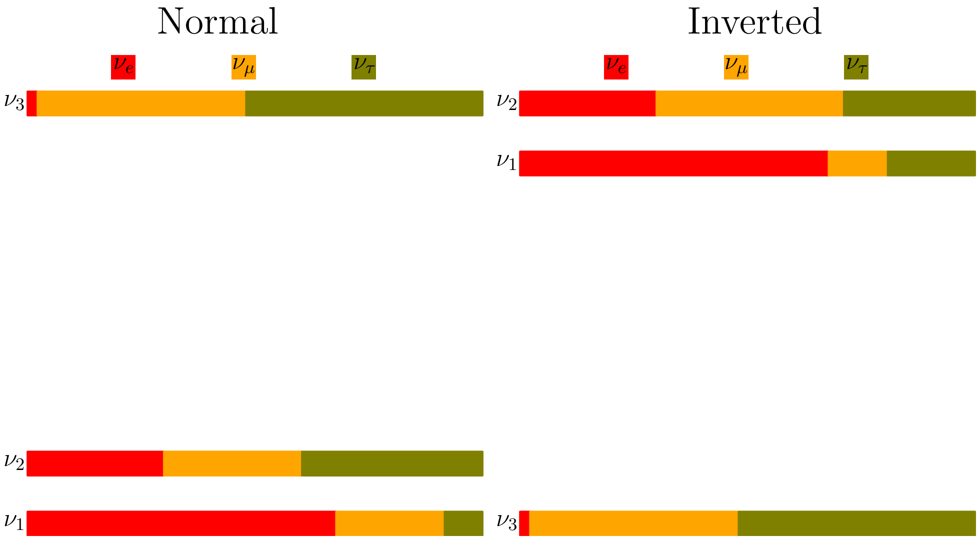
Brookhaven National Laboratory

One Motivation For CEvNS

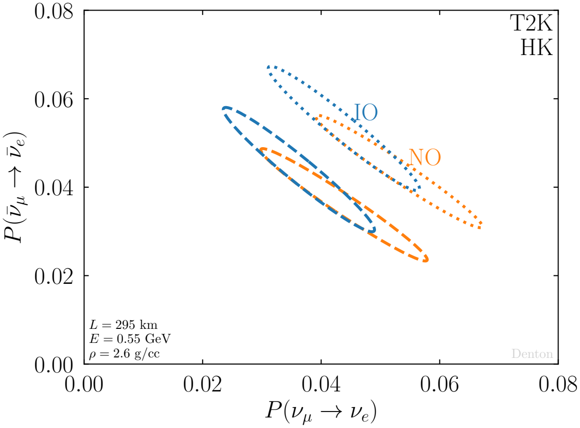
Why measure CEvNS?

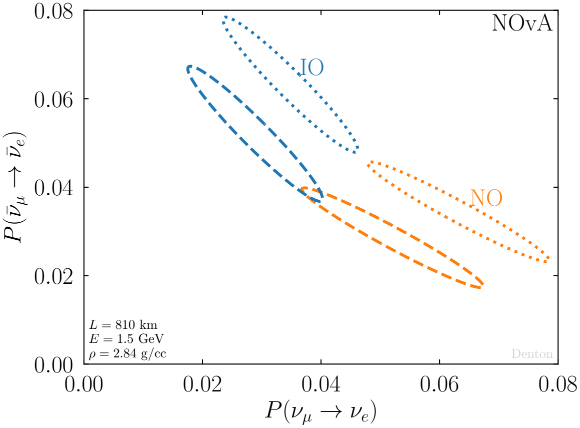
1. It's there
2. Measure SM parameters
3. Look for new physics
4. **Rule out degeneracies in oscillations**

Mass ordering: what is it?



Mass ordering: what is it really?



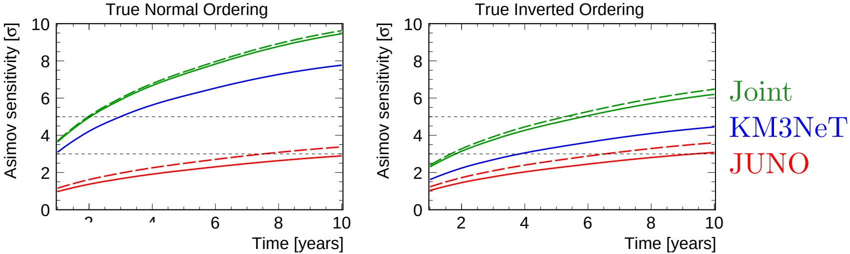


Mass ordering current status: oscillations

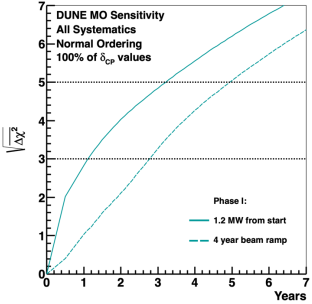
1. NOvA and T2K both prefer NO over IO
2. NOvA+T2K prefers IO over NO
3. SK still prefers NO over IO – statistics complicated
4. + Daya Bay & RENO $\Rightarrow$ slight preference NO
5. = no significant preference either way; with SK $\sim 2\sigma$

PBD, J. Gehrlein, R. Pestes 2008.01110
K. Kelly, et al. 2007.08526
I. Esteban, et al. 2007.14792
F. Capozzi, et al. 2107.00532
P. de Salas, et al. 2006.11237
I. Esteban, et al. 2410.05380

Mass ordering: future sensitivities



JUNO, KM3NeT 2108.06293
JUNO, IceCube 1911.06745
Note: if lower octant, KM3NeT is less sensitive



Matter effect ⇒ DUNE 2203.06100

$$\Delta m^2_{ee} = c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32}$$

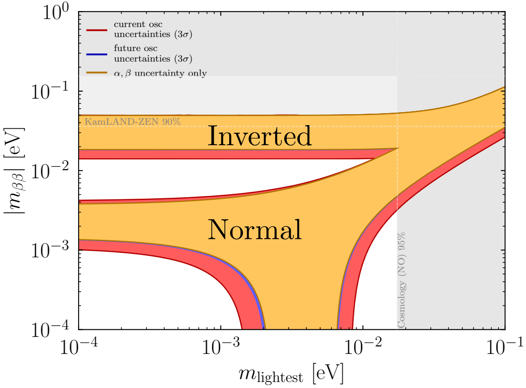
$$\Delta m^2_{\mu\mu} = s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} + \mathcal{O}(s_{13}\Delta m^2_{21})$$

Differ by $\pm\sim 1.1\%$ in each mass ordering

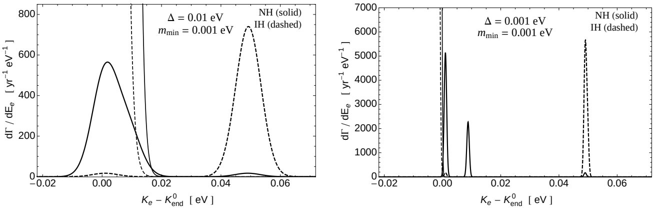
H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283

Mass ordering: broad implications

- Affects cosmology
- Affects galactic SN signal
- Affects $0\nu\beta\beta$
- Affects flavor models
- Affects end point measurements
- Affects CνB



PBD, J. Gehrlein 2308.09737



A. Long, C. Lunardini, E. Sabancilar 1405.7654

New physics:
Vector Non-standard neutrino interactions (vNSI)

vNSI at the Lagrangian Level

EFT Lagrangian:

$$\mathcal{L}_{\rm vNSI}=-2\sqrt{2}G_F\sum_{f,P,\alpha,\beta}\epsilon_{\alpha,\beta}^{f,P}(\bar\nu_\alpha\gamma^\mu P_L\nu_\beta)(\bar f\gamma_\mu P f)$$

with $\Lambda=\frac{1}{\sqrt{2\sqrt{2}\epsilon G_F}}$.

Simplified model Lagrangian:

$$\mathcal{L}_{\rm vNSI}=g_\nu Z'_\mu\bar\nu\gamma^\mu\nu+g_f Z'_\mu\bar f\gamma^\mu f$$

which gives a potential

$$V_{\rm vNSI}\propto\frac{g_\nu g_f}{q^2+m_{Z'}^2}$$

Models with large NSIs consistent with CLFV:

Y. Farzan, I. Shoemaker 1512.09147 Y. Farzan, J. Heeck 1607.07616 D. Forero and W. Huang 1608.04719
K. Babu, A. Friedland, P. Machado, I. Mocioiu 1705.01822 PBD, Y. Farzan, I. Shoemaker 1804.03660
U. Dey, N. Nath, S. Sadhukhan 1804.05808 Y. Farzan 1912.09408

Degeneracies

Vacuum Oscillation Degeneracies ☹

Vacuum oscillations described by:

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger$$

1. Diagonal degeneracy ⇒ no sensitivity to m_1.
2. By CPT can send $H \to -H^*$

$$\Delta m^2_{21} \to -\Delta m^2_{21} \quad , \qquad \Delta m^2_{31} \to -\Delta m^2_{31} \quad , \qquad \delta \to -\delta$$

Vacuum oscillations ⇒ impossible to determine either mass ordering

A. de Gouvea, A. Friedland, H. Murayama hep-ph/0002064
P. Bakhti, Y. Farzan 1403.0744
P. Coloma, T. Schwetz 1604.05772
PBD, S. Parke 2106.12436

Solar Neutrinos ☺

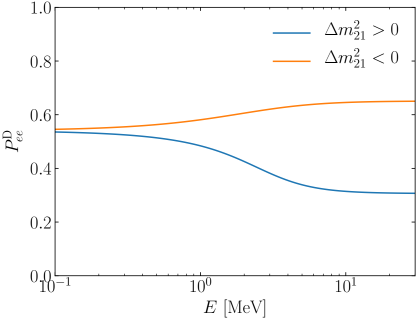
In matter

$$H=\frac{1}{2E}\left[U\begin{pmatrix}0&&\\&\Delta m^2_{21}&\\&&\Delta m^2_{31}\end{pmatrix}U^\dagger+a\begin{pmatrix}1&&\\&0&\\&&0\end{pmatrix}\right]$$

$a\equiv 2\sqrt{2}G_FN_eE$

Subtracted NC matter effect: diagonal degeneracy

Given KamLAND:



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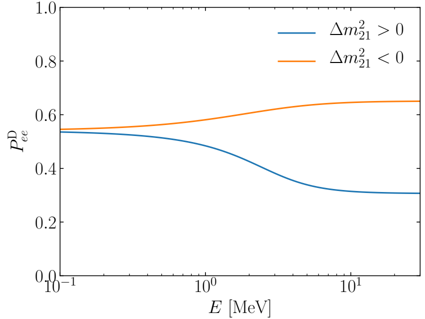
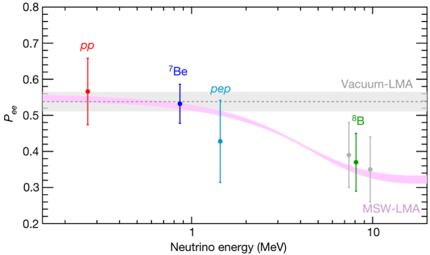


We know $\Delta m^2_{21}>0$ so degeneracy is broken by matter

Measuring the atmospheric mass ordering in DUNE also breaks the degeneracy

Unless ...



New Physics ☹

In matter

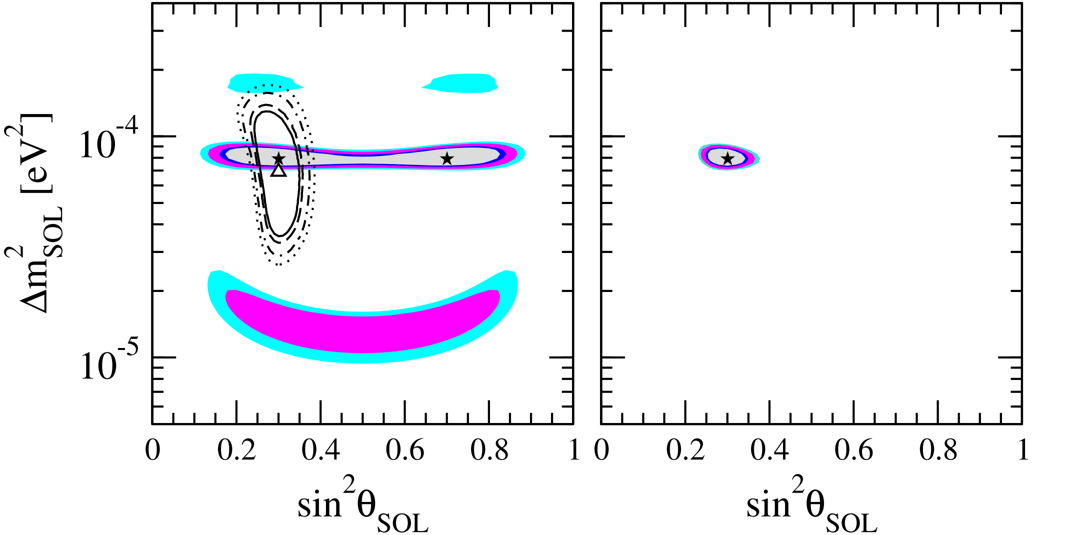
$$H = \frac{1}{2E}\left[U\begin{pmatrix}0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger + a\begin{pmatrix}1 & & \\ & 0 & \\ & & 0\end{pmatrix}\right]$$

equivalent to:

$$-H^*_{\rm vNSI} = \frac{1}{2E}\left[U^*\begin{pmatrix}0 & & \\ & -\Delta m^2_{21} & \\ & & -\Delta m^2_{31}\end{pmatrix}U^T + a\begin{pmatrix}1\mathbf{-2} & & \\ & 0 & \\ & & 0\end{pmatrix}\right]$$

This factor $\epsilon_{ee} = -2$ restores the degeneracy even in matter for all oscillation measurements

Best Fit Assuming Standard Neutrino Physics

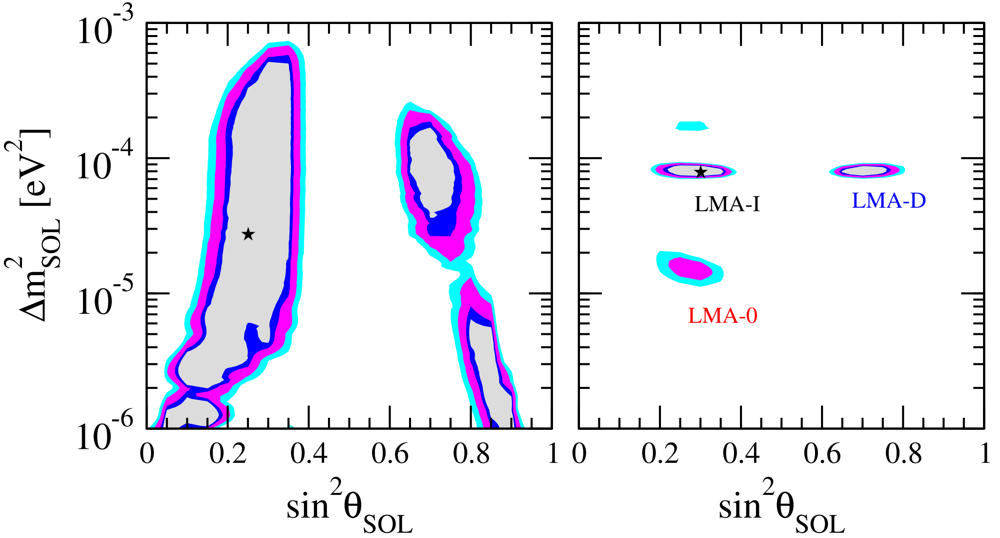


90%, 95%, 99% and 99.73% CL

O. Miranda, M. Tórtola, J. Valle hep-ph/0406280

KamLAND (color), solar (black)

Best Fit Assuming Standard Neutrino Physics



90%, 95%, 99% and 99.73% CL

O. Miranda, M. Tórtola, J. Valle hep-ph/0406280

Solar (left), solar + KamLAND (right), $\Delta\chi^2 = 80.2 - 79.7$.

Quark Contribution in NSI ☺

Need $\epsilon_{ee} = -2$,

$$\epsilon_{ee} = (2 + Y_n)\epsilon_{ee}^{u,V} + (1 + 2Y_n)\epsilon_{ee}^{d,V} = -2$$

$Y_n = N_n/N_e$ and is $\sim 1/3$ in the Sun and 1.05 in the Earth's crust

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If $\epsilon^u = \epsilon^d$, in the sun $\epsilon_{ee}^{u,V} = -1/2$.

For the same parameters in the Earth, $\epsilon_{ee} = -3.1$ which is quite different from -2

Quark Contribution in NSI ☺

Need $\epsilon_{ee}=-2$,

$$\epsilon_{ee}=(2+Y_n)\epsilon_{ee}^{u,V}+(1+2Y_n)\epsilon_{ee}^{d,V}=-2$$

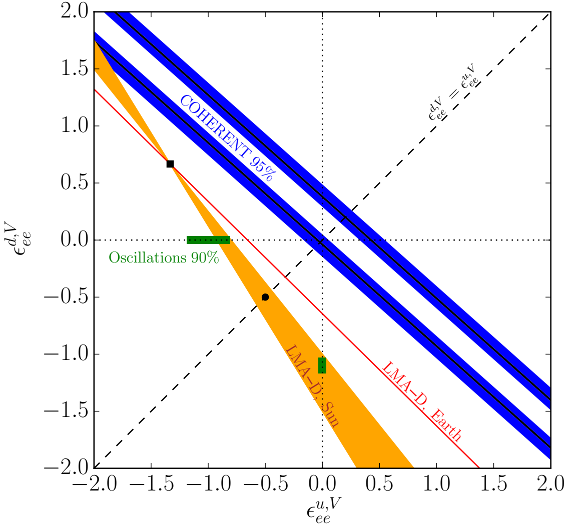
$Y_n=N_n/N_e$ and is $\sim 1/3$ in the Sun and 1.05 in the Earth's crust

If $\epsilon^u=\epsilon^d$, in the sun $\epsilon_{ee}^{u,V}=-1/2$.
For the same parameters in the Earth, $\epsilon_{ee}=-3.1$ which is quite different from -2

Matter effect $\Rightarrow$ ϵ_{ee} has only been measured in the Sun,
DUNE-LBL will make a $\sim 30\%$ measurement in the crust

K. Kelly, S. Parke 1802.06784

Quark Combinations ☹



PBD, Y. Farzan, I. Shoemaker 1804.03660

- Clear that matter effect measurement comes from solar
- Precision measurements can break this if
  - $\epsilon^u = 0$
  - $\epsilon^u = \epsilon^d$
  - $\epsilon^d = 0$
- No oscillation measurements in any materials and for any level of precision can break this if:

$$\epsilon_{ee}^{u,V} = -4/3\,, \quad \epsilon_{ee}^{d,V} = 2/3$$

Oscillations can go no further

NSI in Scattering Experiments Probe Different Scales

NSI affects:

- **Oscillation**: $q^2 = 0$, the effect is valid for any* $M_{Z'}$

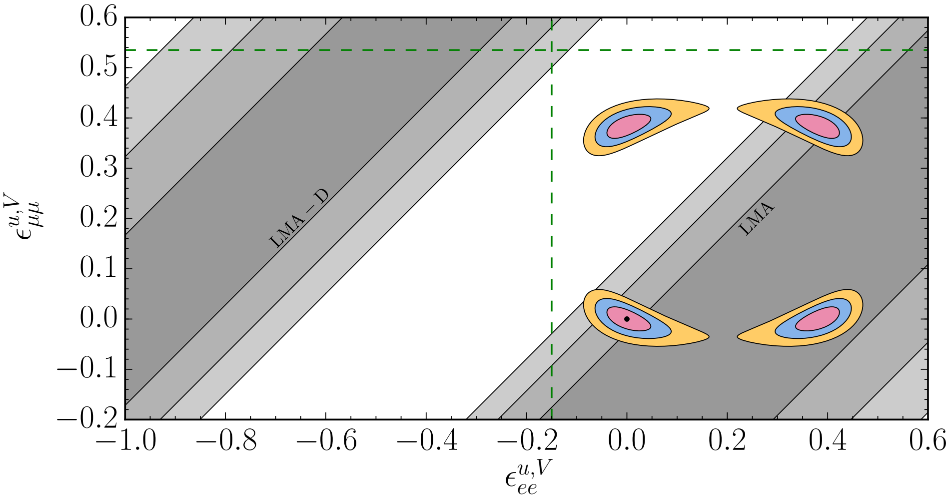
  *See e.g. M. Wise, Y. Zhang 1803.00591

- **Scattering**: the NSI potential is suppressed if $q^2 > M_{Z'}^2$

Regime	$M_{Z'}$	Status
Tevatron/LHC	$\gtrsim 10 - 100$ GeV	Exists
CHARM/NuTeV (DIS)	$\gtrsim 1$ GeV	Exists
COHERENT (CEvNS)	$\gtrsim 50$ MeV	Exists
Early universe	$\lesssim 5$ MeV	Exists
Reactor CEvNS	$\gtrsim 1$ MeV	New!
Oscillation	Any	Exists

For $M_{Z'} \gtrsim 1$ TeV, $\epsilon \sim \mathcal{O}(1)$ is no longer perturbative

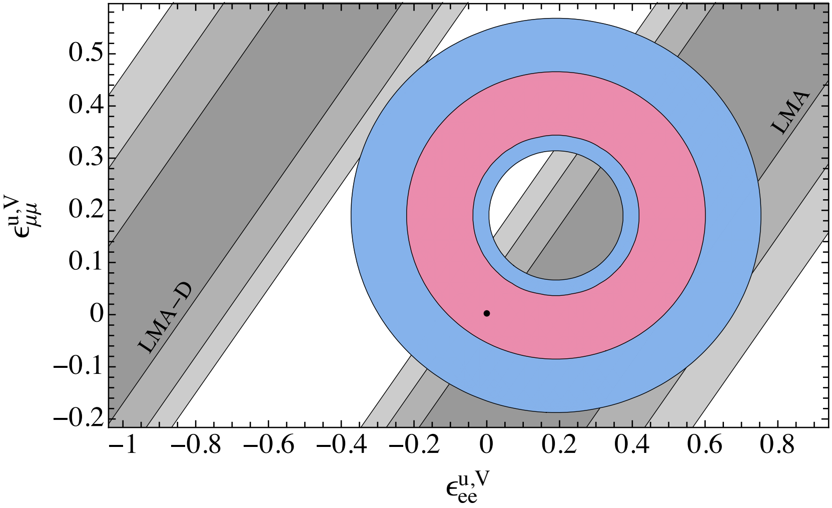
COHERENT Sensitivity to Exclude LMA-Dark



Predicted sensitivity measuring SM with 10 kg·yrs of ^{76}Ge.

PBD, et al. 1701.04828

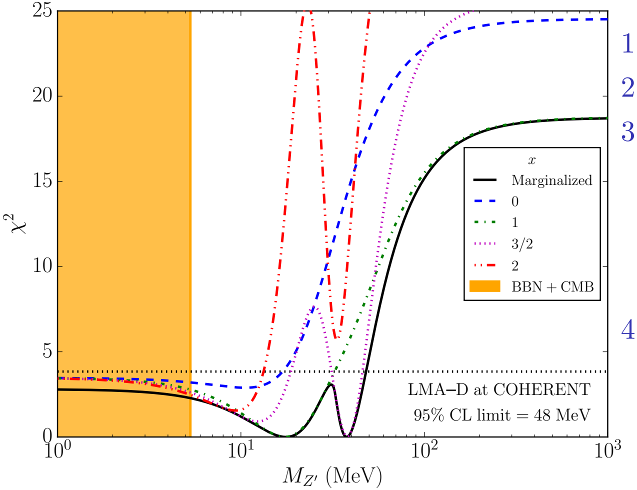
COHERENT Excludes LMA-Dark ☺



Counts only, no timing

P. Coloma, et al. 1708.02899

General LMA-Dark Constraints from COHERENT ☹



PBD, Y. Farzan, I. Shoemaker 1804.03660

1. Assume $\epsilon^u = \epsilon^d$
2. LMA-Dark ruled out for $M_{Z'} > 17$ MeV
3. Oscillations sensitive to diagonal degeneracy:
   General Oscillation Degeneracy:

$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (x - 2, x, x)$$

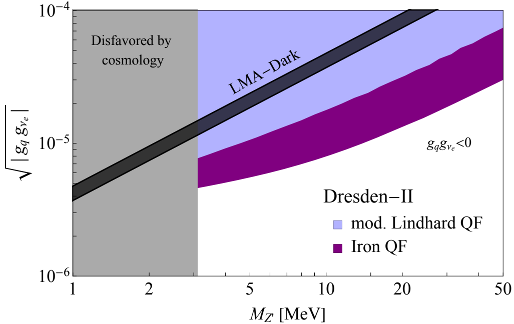
4. LMA-Dark and diagonal degeneracy ruled out for $M_{Z'} > 48$ MeV

Reactor can cover
mass range for $x = 0, \ldots$

Reactor CEvNS data ☺

$$\epsilon_{ee}^{u,V} = \epsilon_{ee}^{d,V}$$

$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (-2, 0, 0)$$



Covers region for either quenching factor!

High significance CEvNS detection not necessary

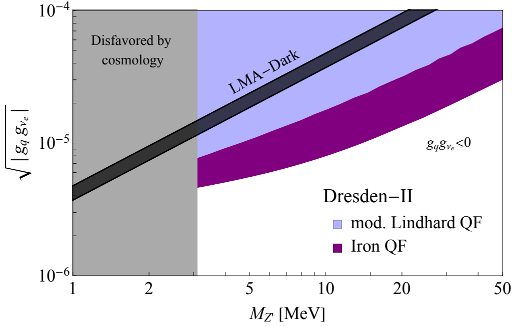
Similar result with CONUS data

PBD, J. Gehrlein 2204.09060

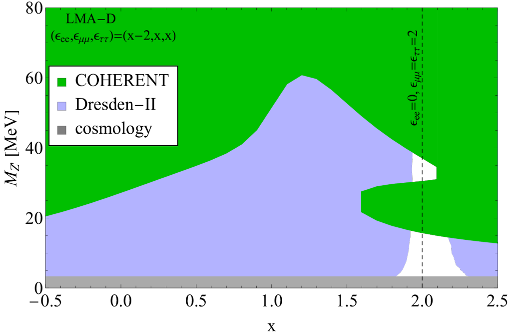
Reactor CEvNS data ☺

$$\epsilon_{ee}^{u,V} = \epsilon_{ee}^{d,V}$$

$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (-2, 0, 0)$$



$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (x-2, x, x)$$



Covers region for either quenching factor!

High significance CEvNS detection not necessary

Similar result with CONUS data

Need a low-threshold π-DAR:
Coherent Captain Mills

PBD, J. Gehrlein 2204.09060

CCM 2105.14020

Future: relax quark couplings

Future matter effect measurements at DUNE

- LBL: measure matter effect in Earth

  K. Kelly, S. Parke 1802.06784

- Solar: measure matter effect in Sun and Earth

  F. Capozzi, et al. 1808.08232

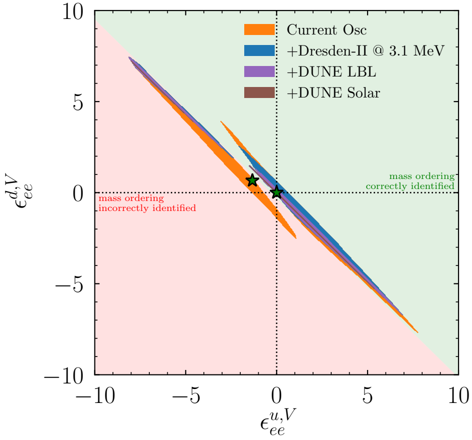
- Atmospherics: measure matter effect in Earth

  PBD, R. Pestes 2110.01148

A sliver remains for certain quark combinations even for $\epsilon_{ee} = -2$ $(x = 0)$

Need better solar and long-baseline oscillations

$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (-2, 0, 0)$



PBD, J. Gehrlein 2204.09060

Summary

- Exact degeneracies will be present in every oscillation experiment
- Measuring the sign of Δm^2_{ij} *requires* the matter effect

  JUNO relies on solar measurements to determine the mass ordering
- The sign of Δm^2_{31} shows up in many neutrino searches
- New physics makes probing the mass ordering impossible with oscillations
- Oscillation experiments in different materials (Earth, Sun) helps, somewhat
- Scattering experiments help a lot, but only for heavy enough mediators
- Early universe constrains light mediators
- MeV mediator gap ~~will be~~ has been covered by reactor CEvNS experiments
- Two regions remain:
  - Mostly in $\epsilon_{\mu\mu}$, $\epsilon_{\tau\tau}$ sector
  - Mostly couples to protons not neutrons
- Need low threshold detector in π-DAR source and DUNE!
- It is possible to eliminate this degeneracy in coming years

Backups

Oscillating Oscillation Degeneracies

There is a degeneracy that can be repeatedly broken and restored:

1. Can't determine mass orderings ☹
2. Matter effect breaks this ☺
3. NSIs restore the degeneracy ☹
4. Quark contribution breaks this ☺
5. Specific NSIs restores the degeneracy ☹
6. Scattering experiments breaks this ☺
7. The degeneracy is restored for light mediators ☹
8. LMA-Dark, light mediator, diagonal degeneracy restore the degeneracy ☹
9. BBN and CMB cover light mediators ☺

Mass ordering current status: all

From oscillations:

$$\text{Normal}: \quad m_1 + m_2 + m_3 > 60 \text{ meV} \qquad \text{Inverted}: \quad m_1 + m_2 + m_3 > 100 \text{ meV}$$

Cosmology: $m_1 + m_2 + m_3 < 90$ meV at 95% CL

E. Valentino, S. Gariazzo, O. Mena 2106.15267

$\rightarrow$ 20 meV precision with DESI, EUCLID, ...

Pushing to very low (negative?) masses!?

N. Craig, et al. 2405.00836
Many caveats: T. Bertólez-Martínez, et al. 2411.14524

See also KATRIN 2406.13516

Mass ordering current status: all

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N. Craig, et al. 2405.00836
Many caveats: T. Bertólez-Martínez, et al. 2411.14524

See also KATRIN 2406.13516

PRIORS?

Some claim "decisive" Bayesian evidence for normal

R. Jimenez, et al. 2203.14247

More general prior assumptions ⇒ no significant information from cosmology

S. Gariazzo, et al. 1801.04946
S. Gariazzo, et al. 2205.02195

Neutrino Mass Eigenstate Definition: Aside

The mass eigenstates can be numbered in a number of different ways

1. $|U_{e1}| > |U_{e2}| > |U_{e3}|$
2. $m_1 < m_2 < m_3$
3. $m_1 < m_2$ and $|U_{e3}| < |U_{e1}|$ and $|U_{e3}| < |U_{e2}|$
4. $\vdots$

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2. $m_1 < m_2 < m_3$
3. $m_1 < m_2$ and $|U_{e3}| < |U_{e1}|$ and $|U_{e3}| < |U_{e2}|$
4. $\vdots$

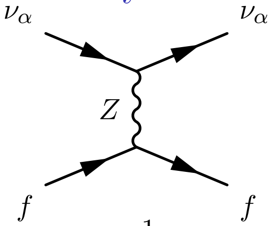
- #3 was commonly used in solar neutrinos
- We know that in the solar sector all three are equivalent
- We take #1 as our definition

Under definition #3 the LMA-Dark degeneracy is

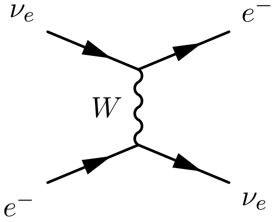
$$\sin\theta_{12} \leftrightarrow \cos\theta_{12} \quad , \qquad \Delta m^2_{31} \to -\Delta m^2_{32} \quad , \qquad \delta \to \pi - \delta$$

Less symmetric $\Rightarrow$ more errors

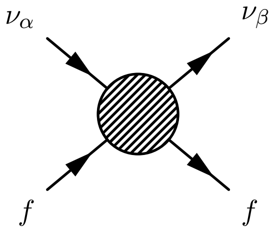
Matter Effects in Feynman Diagrams



$$V_{\rm NC}=\mp\frac{1}{2}\sqrt{2}G_Fn_n$$

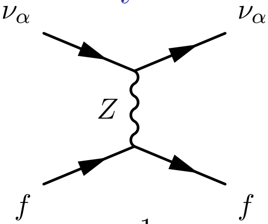


$$V_{\rm CC}=\pm\sqrt{2}G_Fn_e$$

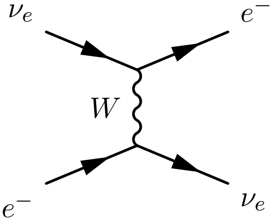


$$V_{\rm NSI}=\pm\epsilon_{\alpha\beta}^{f,X}\sqrt{2}G_Fn_f$$

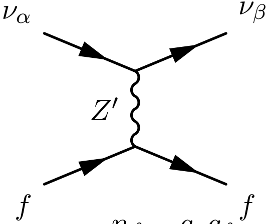
Matter Effects in Feynman Diagrams



$$V_{\rm NC} = \mp\frac{1}{2}\sqrt{2}G_F n_n$$



$$V_{\rm CC} = \pm\sqrt{2}G_F n_e$$



$$V_{\rm NSI} = \frac{n_f}{2}\frac{g_\nu g_f}{q^2+m_{Z'}^2}$$

NSI at the Hamiltonian Level

$$H^{\text{vac}} = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger$$

$$H^{\text{mat,SM}} = \frac{a}{2E} \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

$$H^{\text{mat,NSI}} = \frac{a}{2E} \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\alpha\beta} = \sum_{f \in \{e,u,d\}} \epsilon^{f,V}_{\alpha\beta} \frac{N_f}{N_e}$$

$$H = H^{\text{vac}} + H^{\text{mat,SM}} + H^{\text{mat,NSI}}$$

NSI: The Epsilons

The $\epsilon_{\alpha\beta}$ have 9 dof's, it's actually must worse

NSI: The Epsilons

The $\epsilon_{\alpha\beta}$ have 9 dof's, it's actually must worse

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d} Y_f \epsilon_{\alpha\beta}^{f,V}$$

with

$$Y_f = \frac{n_f}{n_e}$$

dof's $= 9 \times 3 \times 2 = 54$

If SPVAT then 135

In SNe/early universe $\nu\nu$ NSSI as well

NSI: The Epsilons

The $\epsilon_{\alpha\beta}$ have 9 dof's, it's actually must worse

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d} Y_f \epsilon_{\alpha\beta}^{f,V}$$

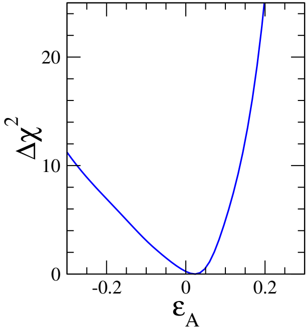
with

$$Y_f = \frac{n_f}{n_e}$$

dof's $= 9 \times 3 \times 2 = 54$

If SPVAT then 135

In SNe/early universe $\nu\nu$ NSSI as well



- Axial is not constrained by oscillations, only scattering

  Axial constraints from SNO-NC by O. Miranda, M. Tórtola, J. Valle hep-ph/0406280

- Limit to just vector, up, down, real: dof=12

Numerical Exploration

arXiv.org > hep-ph > arXiv:hep-ph/0406280

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High Energy Physics - Phenomenology

Are solar neutrino oscillations robust?

O. G. Miranda, M. A. Tortola, J. W. F. Valle

(Submitted on 24 Jun 2004 (v1), last revised 7 Sep 2006 (this version, v3))

The robustness of the large mixing angle (LMA) oscillation (OSC) interpretation of the solar neutrino data is considered in a more general framework where non-standard neutrino interactions (NSI) are present. Such interactions may be regarded as a generic feature of models of neutrino mass. The 766.3 ton-yr data sample of the KamLAND collaboration are included in the analysis, paying attention to the background from the reaction ^13C(\alpha,n) ^16O. Similarly, the latest solar neutrino fluxes from the SNO collaboration are included. In addition to the solution which holds in the absence of NSI (LMA-I) there is a 'dark-side' solution (LMA-D) with sin^2 theta_Sol = 0.70, essentially degenerate with the former, and another light-side solution (LMA-0) allowed only at 97% CL. More precise KamLAND reactor measurements will not resolve the ambiguity in the determination of the solar neutrino mixing angle theta_Sol, as they are expected to constrain mainly Delta m^2. We comment on the complementary role of atmospheric, laboratory (e.g. CHARM) and future solar neutrino experiments in lifting the degeneracy between the LMA-I and LMA-D solutions. In particular, we show how the LMA-D solution induced by the simplest NSI between neutrinos and down-type-quarks-only is in conflict with the combination of current atmospheric data and data of the CHARM experiment. We also mention that establishing the issue of robustness of the oscillation picture in the most general case will require further experiments, such as those involving low energy solar neutrinos.

Comments: 13 pages, 6 figures; Final version to appear in JHEP

"Dark Side" from: A. de Gouvêa, A. Friedland, H. Murayama hep-ph/0002064

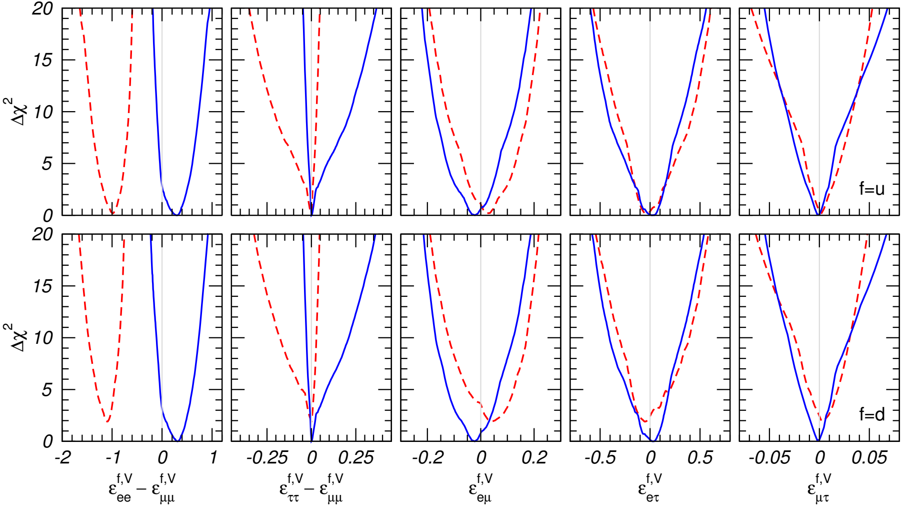
Modern Global Analysis

A modern global fit reveals:

- LMA-Dark solution is very much accommodated by oscillation data
- $\epsilon_{ee} = 0$ slightly disfavored
  - Solar upturn
- Slight information from quark composition
  - Due to different neutron fractions in the Sun and Earth

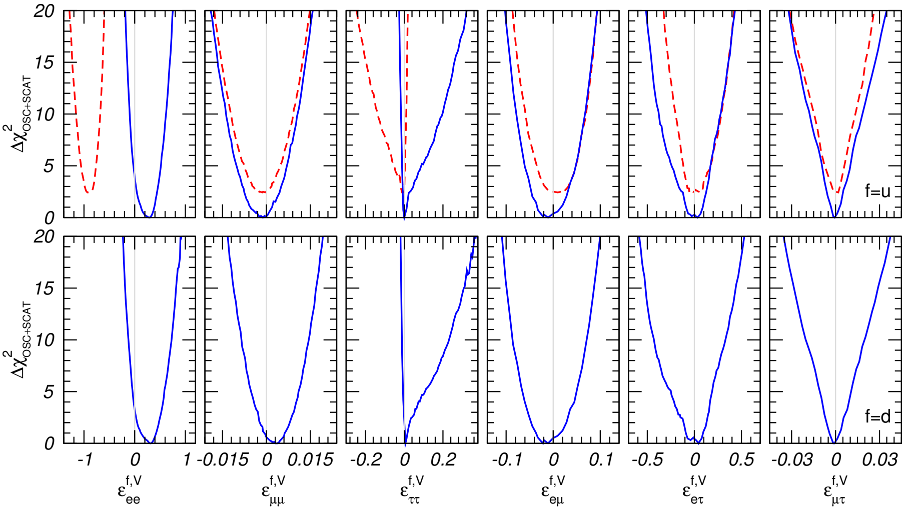
P. Coloma, PBD, M. Gonzalez-Garcia, M. Maltoni, T. Schwetz 1701.04828

NSI Global Fit Oscillation Data



Blue: $\Delta m^2_{21} > 0$, Red: $\Delta m^2_{21} < 0$ P. Coloma, PBD, M. Gonzalez-Garcia, M. Maltoni, T. Schwetz 1701.04828

Heavy NSI Constraints



Heavy $\Rightarrow m_{Z'} \gtrsim 1$ GeV. All oscillation experiments, CHARM, and NuTeV.

Mass ordering: new physics degeneracies

In the presence of new physics such as NSI we have:

$$[\mathrm{NO}] + [\epsilon = 0] \quad \equiv \quad [\mathrm{IO}] + [\epsilon_{ee} = -2]$$

$$[\mathrm{IO}] + [\epsilon = 0] \quad \equiv \quad [\mathrm{NO}] + [\epsilon_{ee} = -2]$$

Equivalences hold even if all oscillation probabilities are *perfectly* measured

P. Bakhti, Y. Farzan 1403.0744

P. Coloma, T. Schwetz 1604.05772

PBD, S. Parke 2106.12436

PBD, J. Gehrlein 2204.09060

This is known as the **LMA-Dark** solution

Is the mass ordering robust?

Need **scattering** to break

Can probe same NC $\epsilon = -2$ process in scattering, but...

CHARM and NuTeV for $M_{Z'} \gtrsim 10$ GeV

PBD, et al. 1701.04828

COHERENT for $M_{Z'} \gtrsim 50$ MeV and cosmology for $M_{Z'} \lesssim 5$ MeV

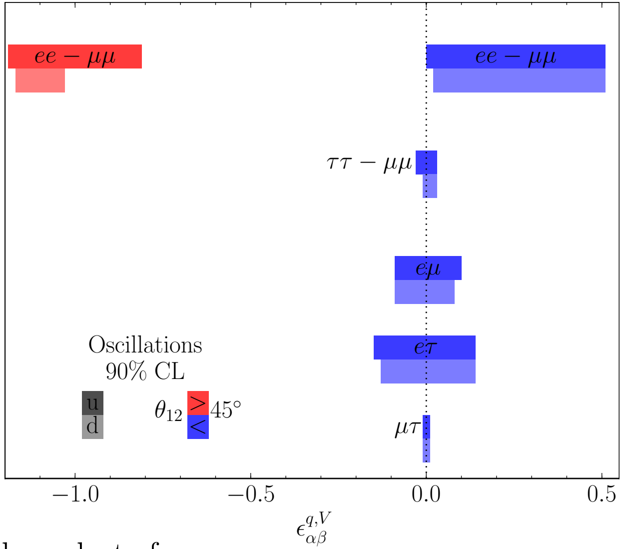
PBD, Y. Farzan, I. Shoemaker 1804.03660

Dresden-II for any mediator mass

PBD, J. Gehrlein 2204.09060

Can still evade with $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$ or certain u / d combinations

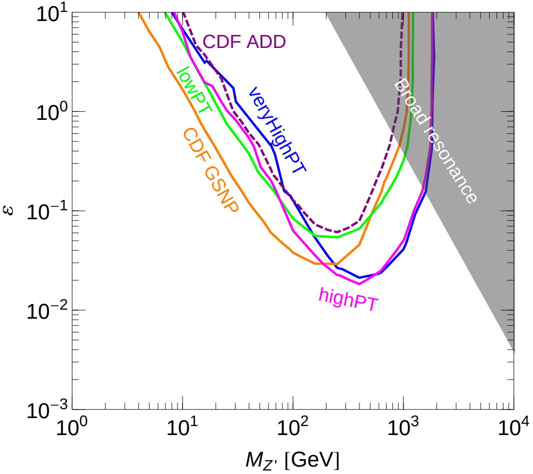
NSI Global Fit: Oscillations

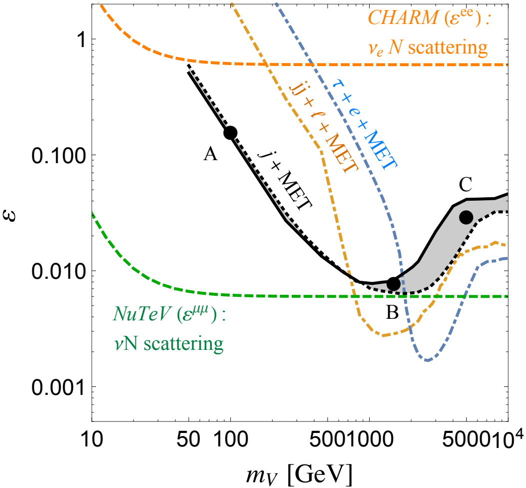


Oscillations are independent of $m_{Z'}$.

PBD, et al. 1701.04828

High Energy Collider Constraints





A. Friedland, et al. 1111.5331 D. Franzosi, M. Frandsen, and I. Shoemaker 1507.07574

CHARM

CHARM measured NC and CC $\overset{(-)}{\nu}_e$ cross sections with nuclei,

$$R_{\rm NC/CC}=(\tilde g_e^L)^2+(\tilde g_e^R)^2=0.406\pm0.140$$

at $\langle E_\nu\rangle=54$ GeV on Fe.

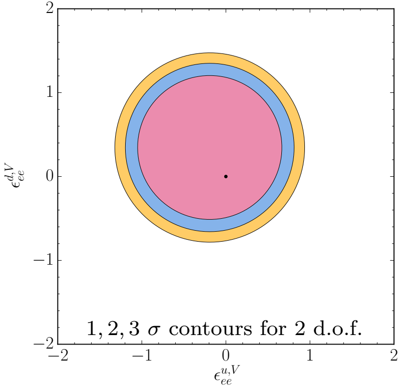
CHARM Collaboration, PLB180 (1986)

$$(\tilde g_e^P)^2=\sum_{q=u,d}\left[(g_q^P+\epsilon_{ee}^{q,P})^2+\sum_{\alpha\neq e}|\epsilon_{e\alpha}^{q,P}|^2\right]$$

2-loop radiative corrections for SM couplings

J. Erler, S. Su 1303.5522

$R_{e,\rm SM}=0.333$ for $q^2\sim20$ GeV^2.



PBD, et al. 1701.04828

NuTeV

NuTeV measured NC and CC ν_μ and $\bar\nu_\mu$ cross sections with nuclei.

$$R_\mu^\nu=\frac{\sigma(\nu_\mu X\to\nu_\mu X)}{\sigma(\nu_\mu X\to\mu X)}=(\tilde g_\mu^L)^2+r(\tilde g_\mu^R)^2=0.3919\pm0.0013$$

$$R_\mu^{\bar\nu}=\frac{\sigma(\bar\nu_\mu X\to\bar\nu_\mu X)}{\sigma(\bar\nu_\mu X\to\bar\mu X)}=(\tilde g_\mu^L)^2+\frac{1}{r}(\tilde g_\mu^R)^2=0.4050\pm0.0027$$

at $\langle E_\nu\rangle=60$ GeV on Fe.

$r=\frac{\sigma(\bar\nu_\mu X\to\bar\mu X)}{\sigma(\nu_\mu X\to\mu X)}$

NuTeV Collaboration hep-ex/0110059

G. P. Zeller PhD thesis

This leads to $\chi^2_{\rm NuTeV,SM}\sim9$ which is the NuTeV anomaly.

NuTeV Corrected

Measurements need to be corrected,

- Improved nuclear models
- Iron is not isoscalar
- Updated PDFs including the strange quark

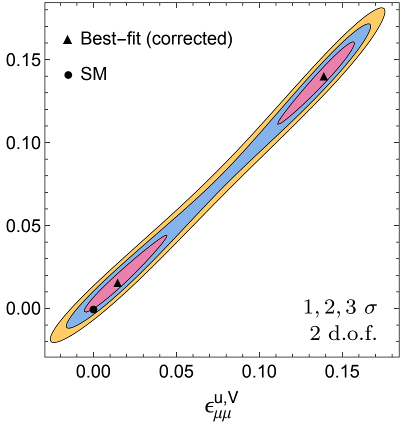
NNPDF Collaboration 0906.1958

W. Bentz, et al. 0908.3198

$$\delta R^{\nu}_{\mu,\mathrm{exp}} = 0.0017\,, \quad \delta R^{\bar{\nu}}_{\mu,\mathrm{exp}} = -0.0016\,,$$

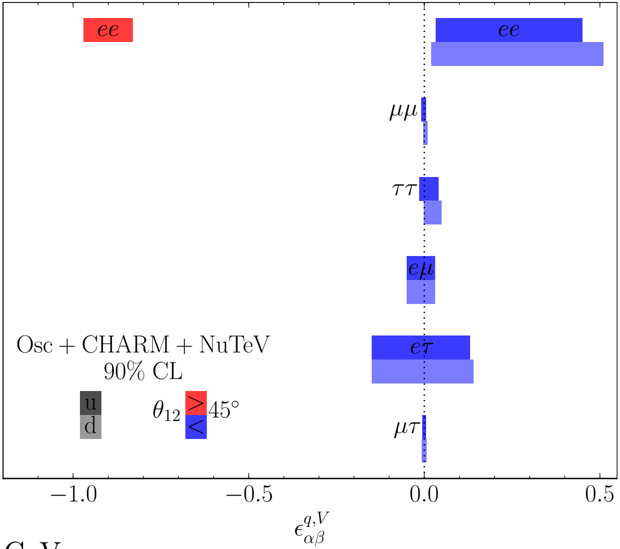
$$R_{\mathrm{exp,true}} = R_{\mathrm{exp,orig}} + \delta R$$

Corrected $\chi^2_{\mathrm{NuTeV,SM}} \sim 2.3$.



PBD, et al. 1701.04828

Heavy NSI Global Fit: CHARM & NuTeV



Heavy $\Rightarrow m_{Z'} \gtrsim 1$ GeV.

PBD, et al. 1701.04828

Coherent Elastic ν Nucleus Scattering: CEvNS ("Sevens")

CEvNS := ν scattering off the weak charge of entire nucleus

The CEvNS cross section is very high, but recoil energies are very low:

> *Our suggestion may be* **an act of hubris**, *because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.*

D. Freedman, PRD 9 (1974)

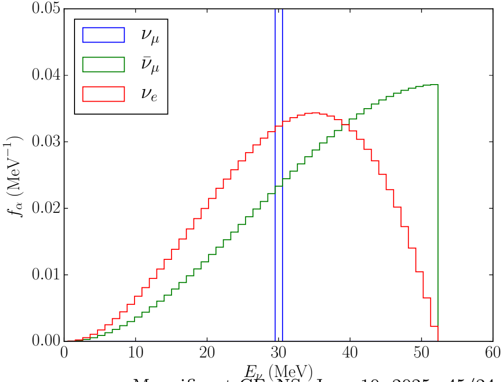
COHERENT

Spallation Neutron Source at Oak Ridge in a **π-DAR** configuration.

K. Scholberg hep-ex/0511042

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

$$f_{\nu_\mu} = \delta\left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right),$$
$$f_{\bar{\nu}_\mu} = \frac{64}{m_\mu}\left[\left(\frac{E_\nu}{m_\mu}\right)^2\left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right)\right],$$
$$f_{\nu_e} = \frac{192}{m_\mu}\left[\left(\frac{E_\nu}{m_\mu}\right)^2\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right)\right].$$



Detector 22 m from source with $E_{\rm tr} = 5$ keV.

COHERENT

Observed spectrum:

$$\frac{dN_\alpha}{dE_r} = N_t \Delta t \int dE_\nu \phi_\alpha(E_\nu) \frac{d\sigma_\alpha}{dE_r}(E_\nu)\,,$$

Neutrino nucleon cross section:

$$\frac{d\sigma_\alpha}{dE_r} = \frac{G_F^2}{2\pi}\frac{Q_{w\alpha}^2}{4} F^2(2ME_r) M \left(2 - \frac{ME_r}{E_\nu^2}\right)\,,$$

Form factors from: C. Horowitz, K. Coakley, D. McKinsey astro-ph/0302071

Electroweak charge:

$$\frac{1}{4}Q_{w\alpha}^2 = \left[Z(g_p^V + 2\epsilon_{\alpha\alpha}^{u,V} + \epsilon_{\alpha\alpha}^{d,V}) + N(g_n^V + \epsilon_{\alpha\alpha}^{u,V} + 2\epsilon_{\alpha\alpha}^{d,V})\right]^2 + \sum_{\beta\neq\alpha}\left[Z(2\epsilon_{\alpha\beta}^{u,V} + \epsilon_{\alpha\beta}^{d,V}) + N(\epsilon_{\alpha\beta}^{u,V} + 2\epsilon_{\alpha\beta}^{d,V})\right]^2\,.$$

$Z = 32,\ N = 44.$

$g_p^V = \frac{1}{2} - 2\sin^2\theta_W,\ g_n^V = -\frac{1}{2}.$

SNS Beam Details

Pulsed beam: flavor discrimination

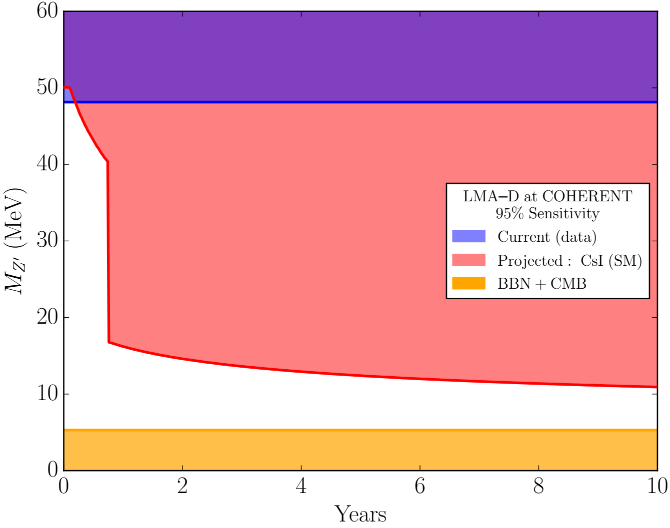
- The ν_μ from the π^+ decay forms the prompt signal.
- The ν_e and $\bar{\nu}_\mu$ form the delayed signal.
- Probability that the muon decays within the pulse width,

$$P_c = \frac{1}{t_w}\int_0^{t_w} dt \left[1 - e^{-(t_w - t)/\Gamma\tau}\right] = 0.138$$

- We expect ~ 100 prompt and ~ 200 delayed.

Systematics: beam normalization at 10% and 20% background.

Future LMA-Dark Sensitivity at COHERENT

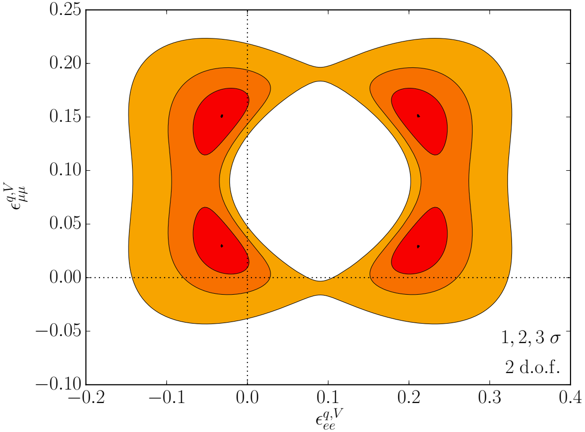


← Gap?

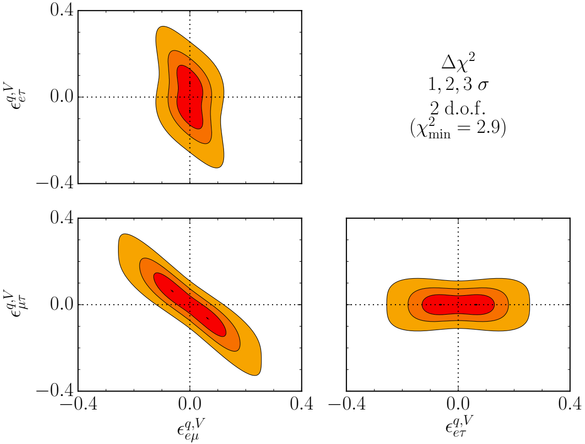
PBD, Y. Farzan, I. Shoemaker 1804.03660

NSI Projections: COHERENT

Limit ourselves to $\epsilon^u = \epsilon^d$



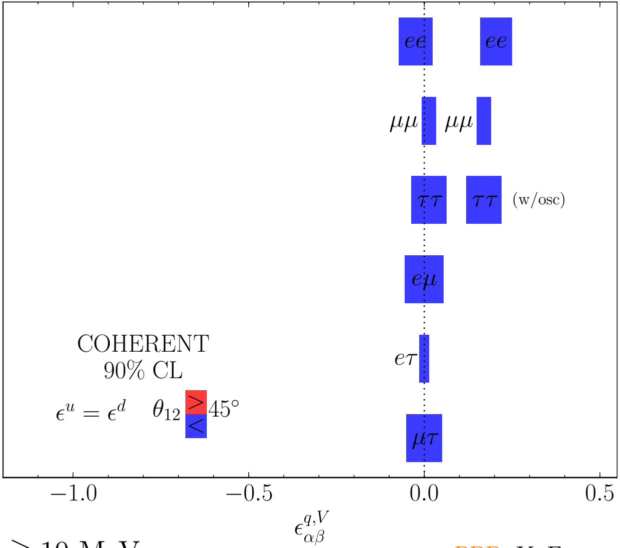
Diagonal



Off-Diagonal

PBD, Y. Farzan, I. Shoemaker 1804.03660

NSI Constraints: COHERENT

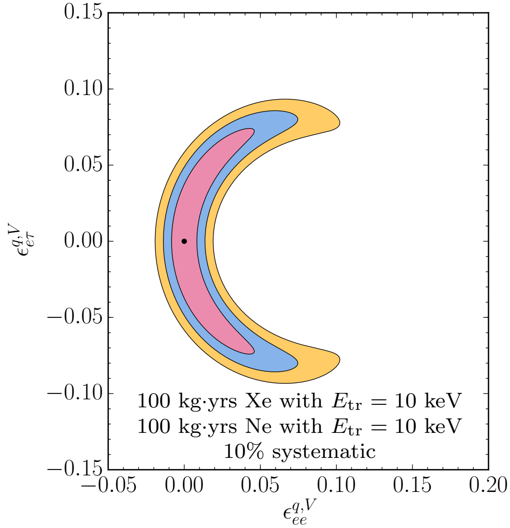


Valid down to $m_{Z'} \gtrsim 10$ MeV

PBD, Y. Farzan, I. Shoemaker 1804.03660

Looking to the COHERENT Future

Interference of different materials is powerful.



$$\epsilon_{ee,\rm deg}^{q,V} = \frac{1}{3}\frac{Y_n - (1 - 4\sin^2\theta_W)}{Y_n + 1}$$

$$Y_n \in [1, 1.43]$$

$$\epsilon_{ee,\rm deg}^{q,V} \in [0.15, 0.18]$$

Solar upturn?

Recap: Oscillations and the Diagonal Terms

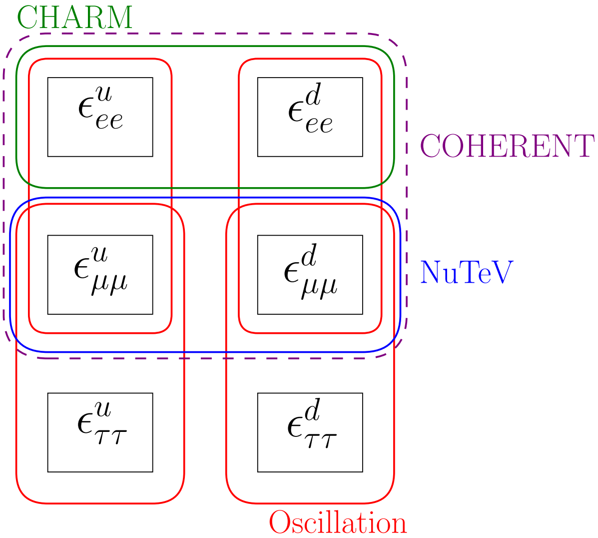
Solar
Chlorine, Gallex/GNO, SAGE, Super-K, Borexino, and SNO.

Atmospheric
Super-K, MINOS, and T2K.

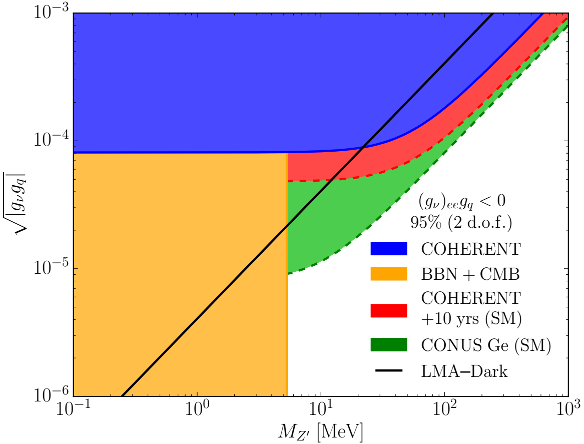
Reactor
CHOOZ, Palo Verde, Double CHOOZ, Daya Bay, and RENO.

Short baseline
Bugey, ROVNO, Krasnoyarsk, ILL, Gösgen, and SRP.

Global fit to oscillation data

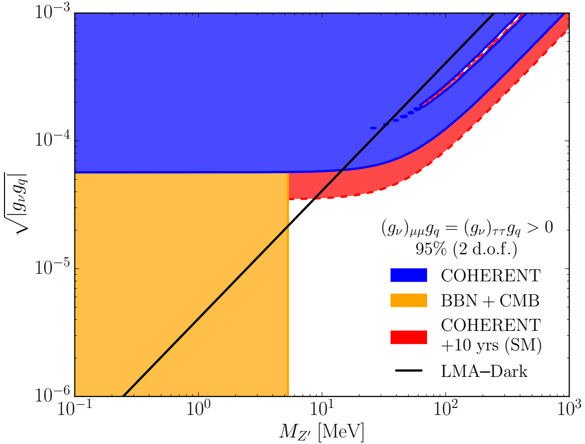


Present and Future LMA-Dark Bounds ☹



ϵ_{ee} only

$x = 0$



$\epsilon_{\mu\mu}, \epsilon_{\tau\tau}$ only

$x = 2$

PBD, Y. Farzan, I. Shoemaker 1804.03660

Light Mediator Coverage

1. **Early universe**: $m_{Z'} \lesssim 0.1 - 1$ MeV
   $\Rightarrow Z'$ is relativistic at BBN, $\Delta N_{\rm eff} = 3 \times 4/7 = 1.7$

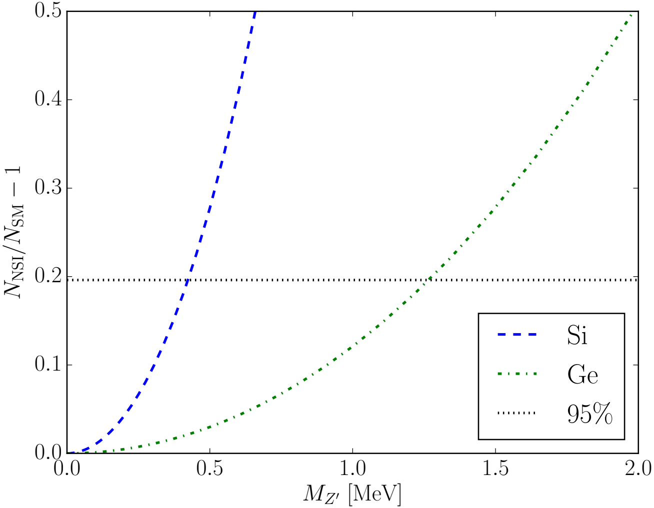
   $N_{\rm eff}$-BBN measurements require $\boldsymbol{m_{Z'} > 5.3}$ **MeV** and $g_\nu < 10^{-9}\frac{m_{Z'}}{\rm MeV}$

   A. Kamada, H. Yu 1504.00711

   Relevant $\sqrt{g_\nu g_q} \sim 10^{-5}$

2. **Reactor CEvNS**: Sensitive to $M_{Z'} \gtrsim 1$ MeV

Reactor Sensitivity for CONUS



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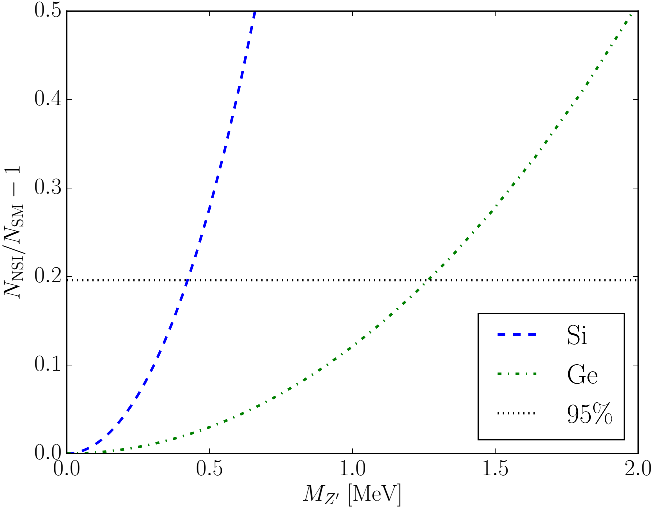
Reactor Sensitivity for CONUS



$\bar{\nu}_e$ only $\Rightarrow$ LMA-Dark at $x=0$ only

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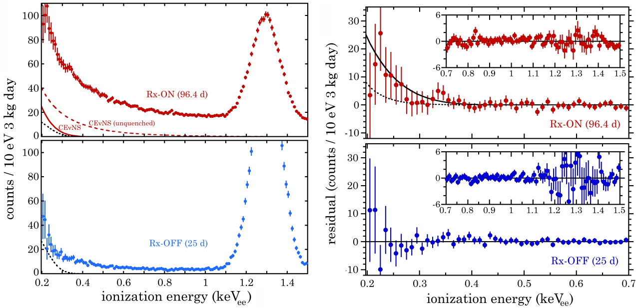
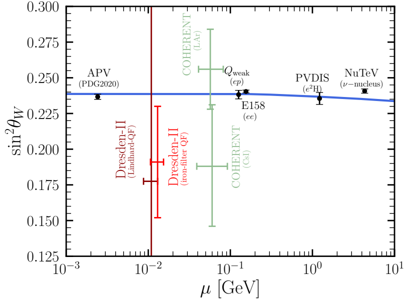
Reactor CEvNS data



Dresden-II 2202.09672



D. Sierra, V. De Romeri, D. Papoulias 2203.02414

Quenching factors?