LMA-Dark: Large New Physics Effects in Neutrino Oscillations

Peter B. Denton

BNL Friday Lunch Discussion

February 28, 2020

BROOKHAVEN NATIONAL LABORATORY

Brookhaven NDI Neutrino Discovery Initiative

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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. BBN and CMB cover light mediators ☺
9. LMA-Dark, light mediator, diagonal degeneracy restore the degeneracy ☹

1. Oscillation Degeneracies ☹

Since neutrinos oscillate there are 7+ new parameters in the SM
Oscillations are sensitive to 6 of them

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

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

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

That is, it is impossible to determine either mass ordering

A. de Gouvea, A. Friedland, H. Murayama hep-ph/0002064

P. Bakhti and Y. Farzan, 1403.0744

P. Coloma, T. Schwetz 1604.05772

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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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

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

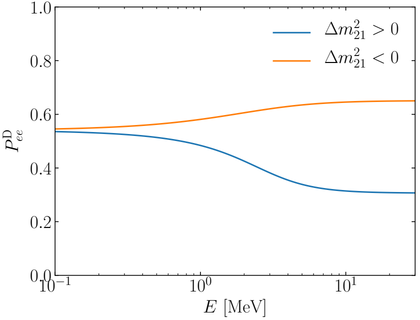
2. Solar Neutrinos ☺

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



We know $\Delta m^2_{21}>0$ so degeneracy is broken by matter effects.
Measuring the atmospheric mass ordering in DUNE would also break this degeneracy.

Unless ...

3. New Physics ☹

In matter

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

This factor of -2 restores the degeneracy in matter as well.

New physics like this is called neutrino non-standard interactions: NSIs, the ϵ's.

L. Wolfenstein, PRD 17 (1978)

Recent overview: PBD, et al. 1907.00991

NSI at the Lagrangian Level

EFT Lagrangian:

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

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

Simplified model Lagrangian:

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

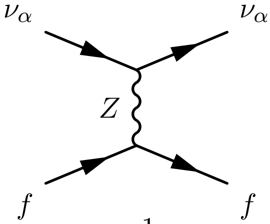
which gives a potential

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

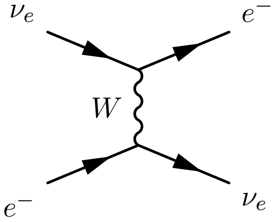
Models with large NSIs consistent with CLFV:

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

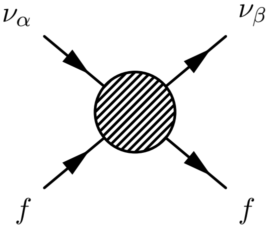
Matter Effects in Feynman Diagrams



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

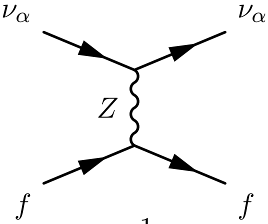


$$V_{\rm CC} = \pm\sqrt{2}G_F n_e$$



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

Matter Effects in Feynman Diagrams



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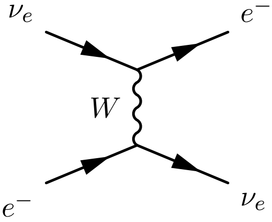

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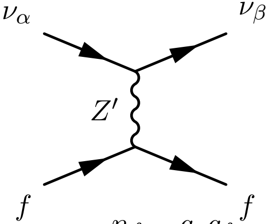

$$V_{\rm NSI} = \frac{n_f}{2}\frac{g_\nu g_f}{q^2+m_{Z'}^2}$$

NSI at the Hamiltonian Level

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

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

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

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

LMA-Dark in Matter

Even in matter the LMA-Dark degeneracy is still exact

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

$$\epsilon_{ee} \to \epsilon_{ee} - 2 \quad , \qquad \epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha\beta \neq ee)$$

NSI: The Epsilons

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

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

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

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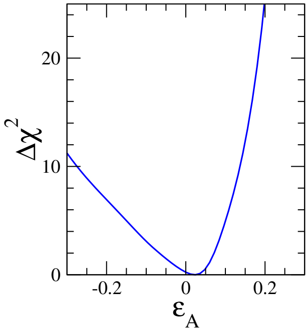


- Axial is not constrained by oscillations, only scattering

  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

Search or A

(Help | Advance

High Energy Physics - Phenomenology

Are solar neutrino oscillations robust?

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

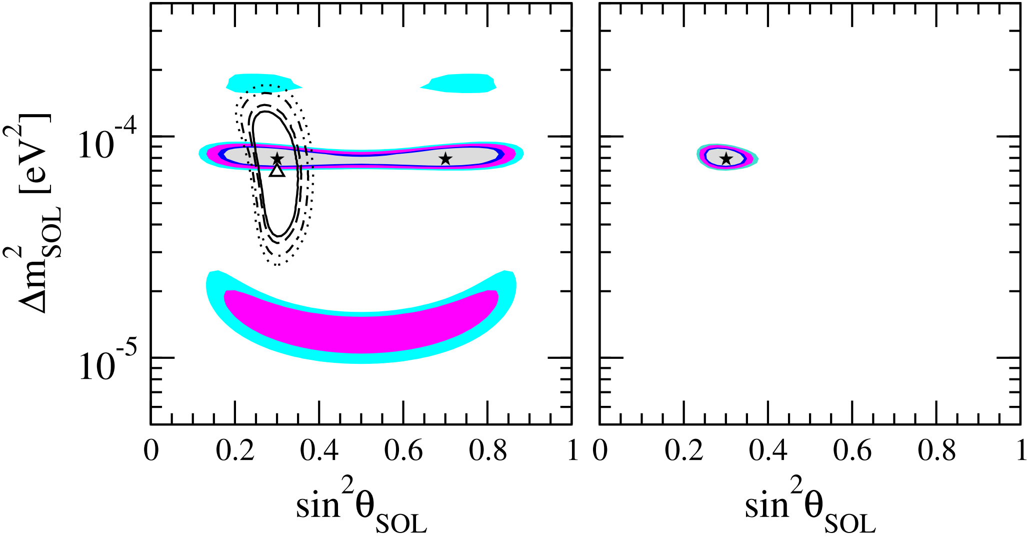
(Submitted on 24 Jun 2004 (v1), last revised 7 Sep 2006 (this version, v3))

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

Best Fit Assuming Standard Neutrino Physics

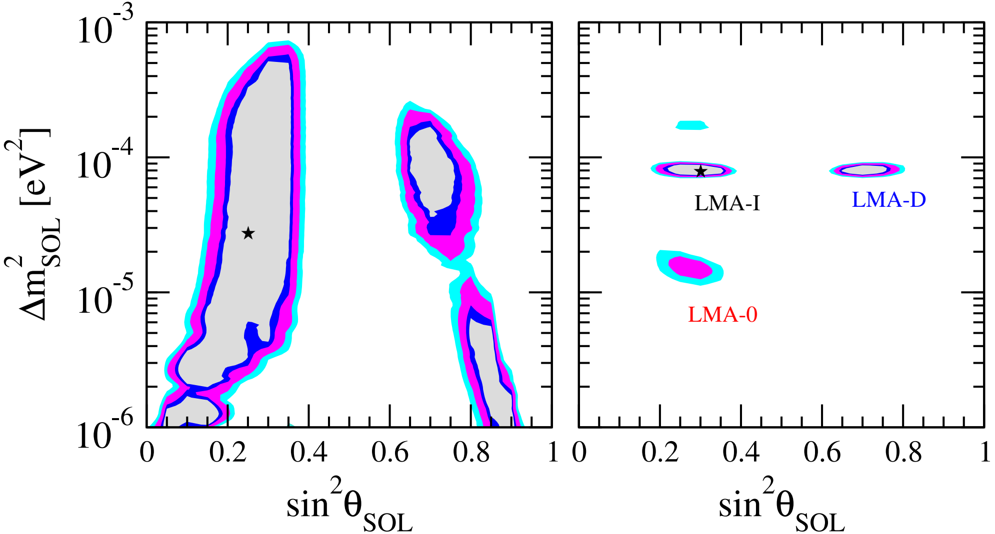


90%, 95%, 99% and 99.73% CL

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

KamLAND (color), solar (black)

Best Fit Assuming Standard Neutrino Physics

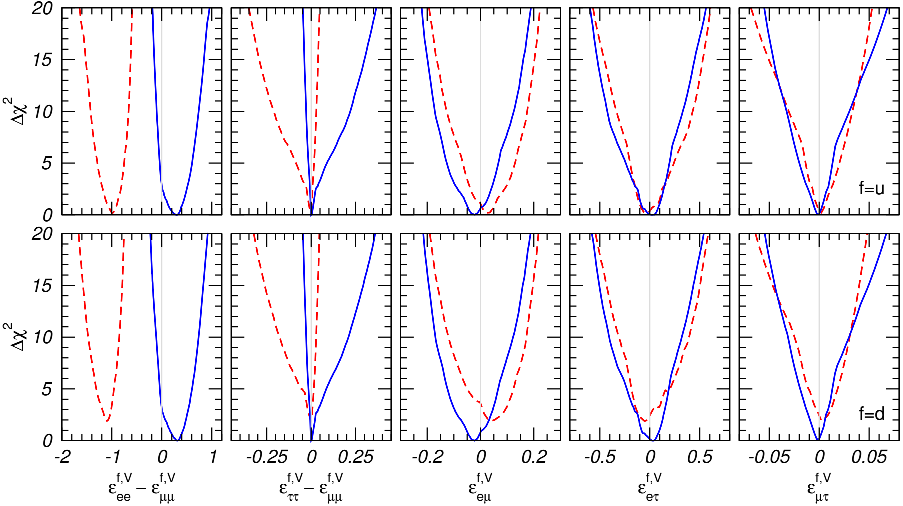


90%, 95%, 99% and 99.73% CL

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

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

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

A Global Fit Reveals

A 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

4. 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 detectable!

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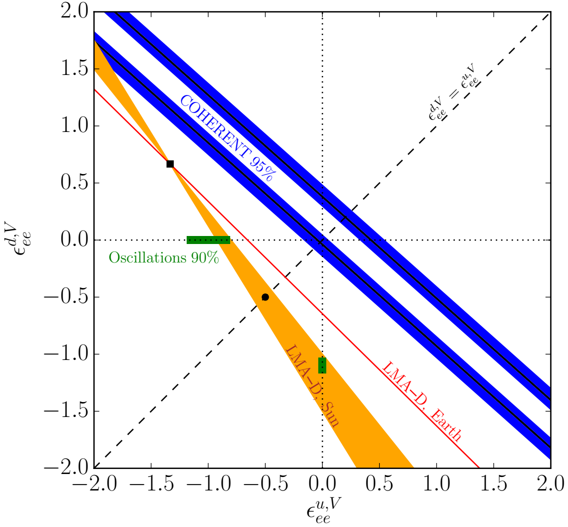
Matter effect has only been measured in the sun,
DUNE will make a $\sim 30\%$ measurement.

K. Kelly, S. Parke 1802.06784

5. 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 $m_{Z'}^*$

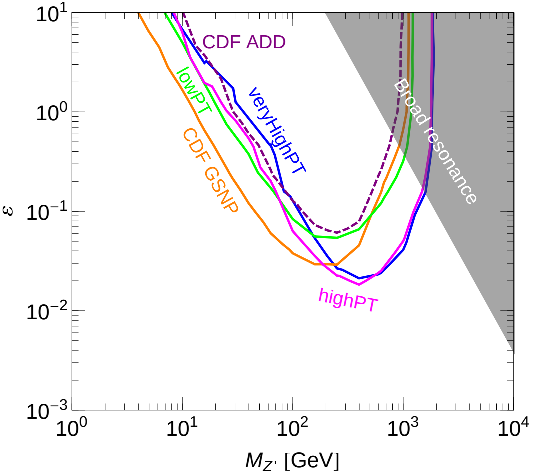
*See e.g. M. Wise, Y. Zhang 1803.00591

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

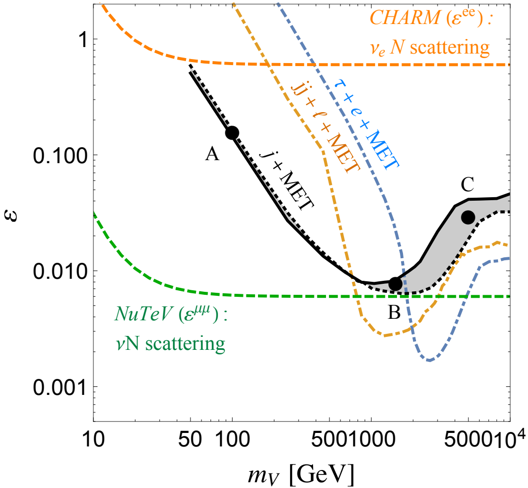
Regime	$m_{Z'}$
Tevatron/LHC	$\gtrsim 10 - 100$ GeV
CHARM/NuTeV (DIS)	$\gtrsim 1$ GeV
COHERENT (CEvNS)	$\gtrsim 10$ MeV
Early universe	$\lesssim 5$ MeV
Reactor CEvNS	$\gtrsim 1$ MeV
Oscillation	Any

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

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,

$$R_{\mathrm{NC/CC}} = (\tilde{g}_e^L)^2 + (\tilde{g}_e^R)^2 = 0.406 \pm 0.140$$

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

CHARM Collaboration, PLB180 (1986)

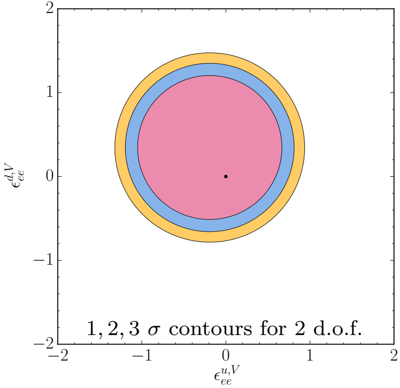
$$(\tilde{g}_e^P)^2 = \sum_{q=u,d} \left[(g_q^P + \epsilon_{ee}^{q,P})^2 + \sum_{\alpha \neq e} |\epsilon_{e\alpha}^{q,P}|^2 \right]$$

2-loop radiative corrections for SM couplings

J. Erler, S. Su, 1303.5522

$R_{e,\mathrm{SM}} = 0.333$ for $q^2 \sim 20$ GeV^2.

PBD, et al., 1701.04828



NuTeV

NuTeV measured NC and CC ν_μ and $\bar{\nu}_\mu$ cross sections with nuclei.

$$R_\mu^\nu = \frac{\sigma(\nu_\mu X \to \nu_\mu X)}{\sigma(\nu_\mu X \to \mu X)} = (\tilde{g}_\mu^L)^2 + r(\tilde{g}_\mu^R)^2 = 0.3919 \pm 0.0013$$

$$R_\mu^{\bar{\nu}} = \frac{\sigma(\bar{\nu}_\mu X \to \bar{\nu}_\mu X)}{\sigma(\bar{\nu}_\mu X \to \bar{\mu} X)} = (\tilde{g}_\mu^L)^2 + \frac{1}{r}(\tilde{g}_\mu^R)^2 = 0.4050 \pm 0.0027$$

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 $\chi^2_{\text{NuTeV,SM}} \sim 9$ 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

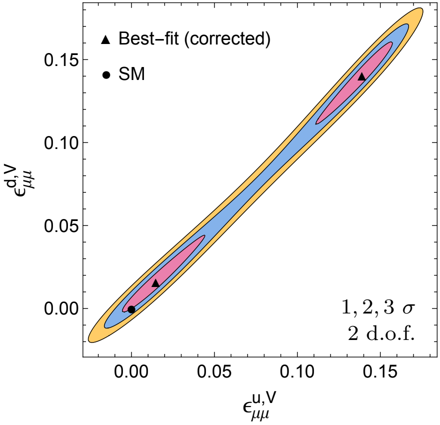
NNPDF Collaboration, 0906.1958

W. Bentz, et al., 0908.3198

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

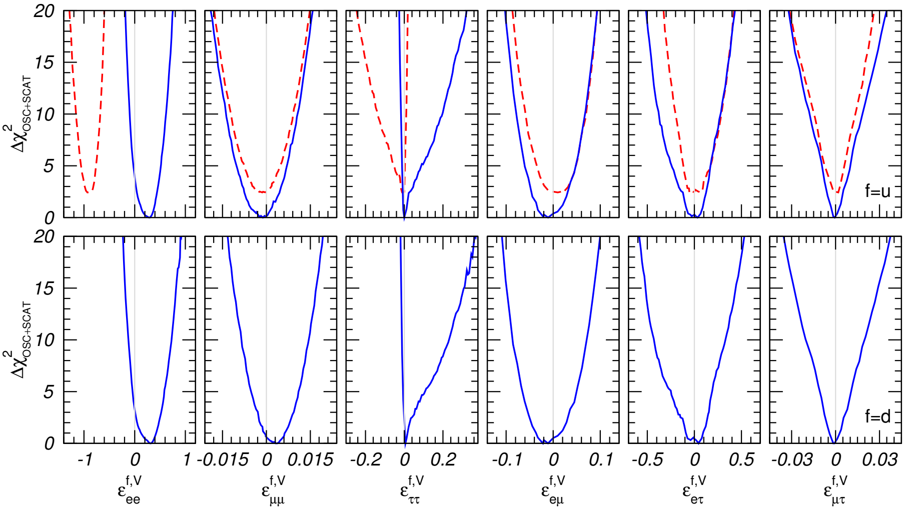
$$R_{\mathrm{exp,true}} = R_{\mathrm{exp,orig}} + \delta R$$

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



PBD, et al., 1701.04828

Heavy NSI Constraints



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

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)

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Thanks to DM direct detection efforts, this is now possible.

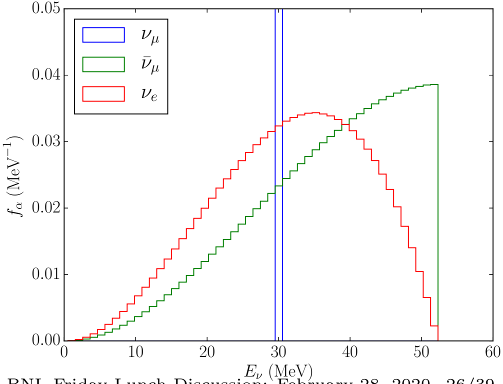
COHERENT

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

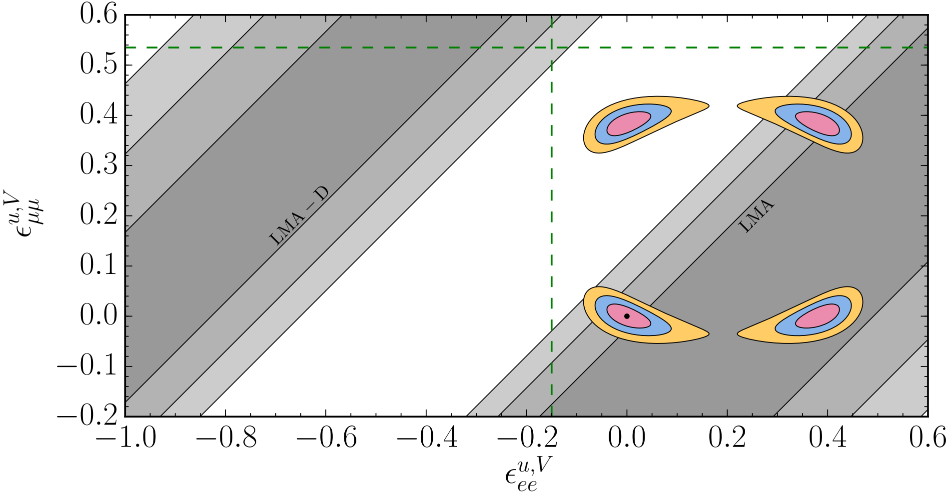
- The ν_μ from the π^+ decay forms the prompt signal.
- The ν_e and $\bar{\nu}_\mu$ form the delayed signal.
- Probability that the muon decays within the pulse width,

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

- We expect ~ 100 prompt and ~ 200 delayed.

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

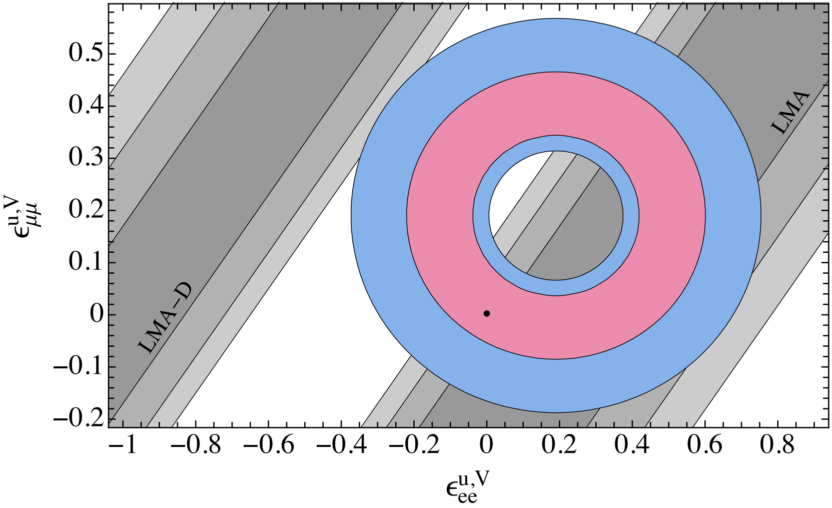
COHERENT Sensitivity to Exclude LMA-Dark



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

PBD, et al., 1701.04828

6. COHERENT Excludes LMA-Dark ☺



Counts only, no timing

P. Coloma, et al., 1708.02899

Recap: Oscillations and the Diagonal Terms

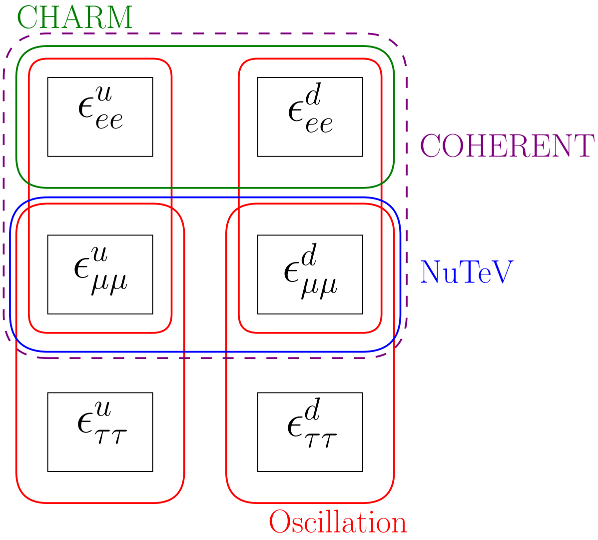
Solar
Chlorine, Gallex/GNO, SAGE,
Super-K, Borexino, and SNO.

Atmospheric
Super-K, MINOS, and T2K.

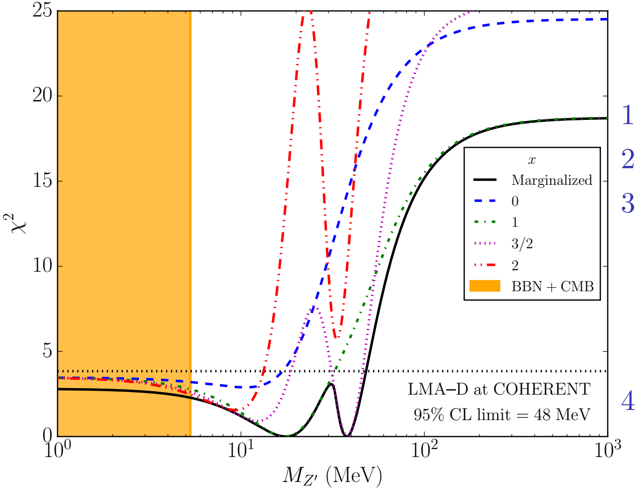
Reactor
CHOOZ, Palo Verde, Double CHOOZ,
Daya Bay, and RENO.

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

Global fit to oscillation data



7. General LMA-Dark Constraints from COHERENT ☹



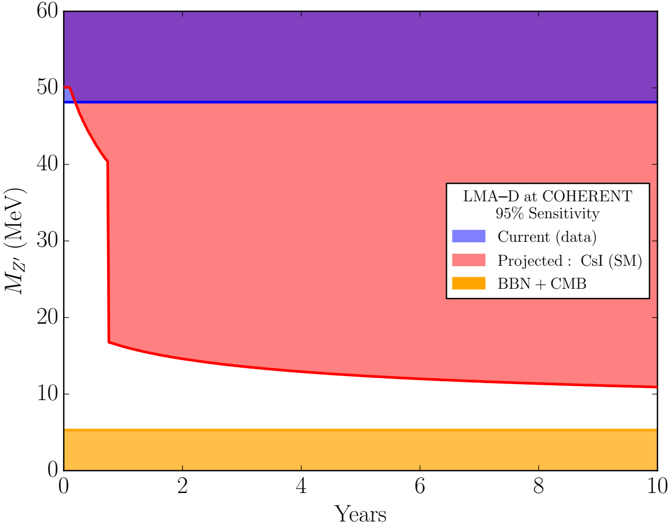
PBD, Y. Farzan, I. Shoemaker, 1804.03660

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

Future LMA-Dark Sensitivity at COHERENT



← Gap?

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Light Mediator Coverage

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

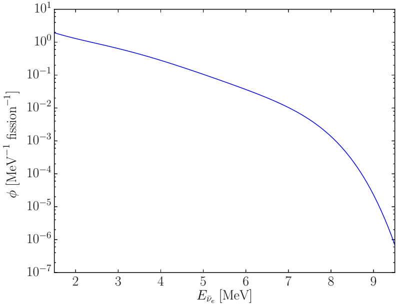
   $N_{\rm eff}$-BBN measurements require $\boldsymbol{m_{Z'} > 5.3}$ **MeV** and $g_\nu < 10^{-9}\frac{m_{Z'}}{\rm MeV}$

   A. Kamada, H. Yu, 1504.00711

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

Reactor CEvNS Experiments

Upcoming program of measuring CEvNS with reactors:



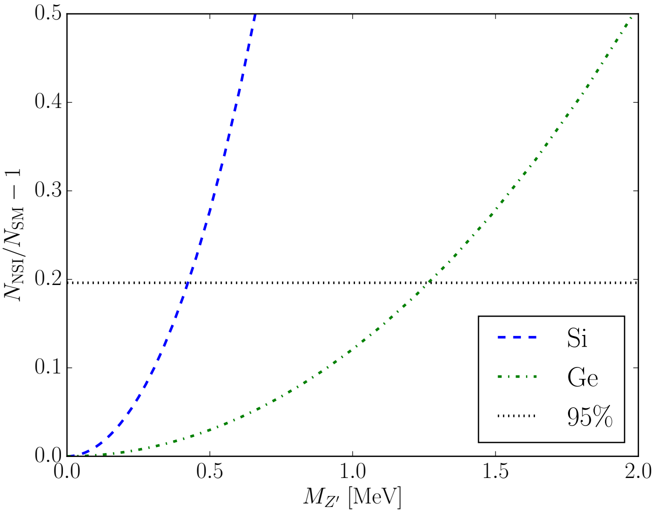
- High statistics
- Low $q^2 \Rightarrow$ "more coherent"
  - Less form factor uncertainty
- Flux uncertainty
  - Reactor anti-neutrino anomaly
  - 5 MeV bump

Experimental program includes:

- NOSTOS — hep-ex/0503031
- TEXONO — hep-ex/0511001
- GEMMA — 1411.2279
- νGeN — JINST 10 (2015)
- CONNIE — 1604.01343
- MINER — 1609.02066
- CONUS — 1612.04150
- Ricochet — 1612.09035
- ν-cleus — 1704.04320

$\vdots$

8. Reactor Sensitivity for CONUS ☺



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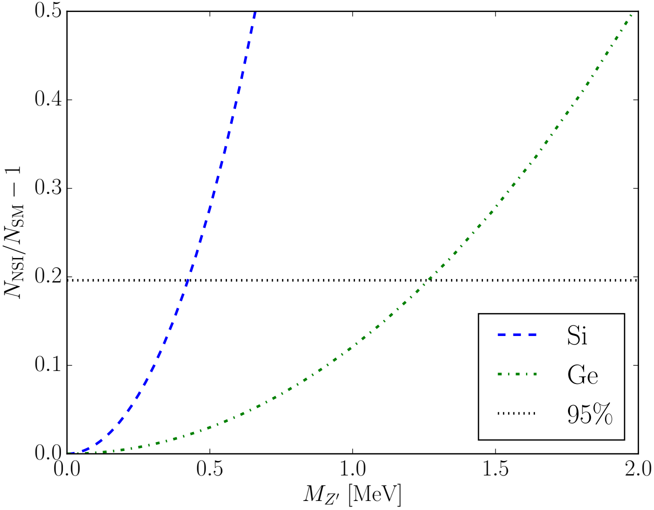
8. Reactor Sensitivity for CONUS ☺



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

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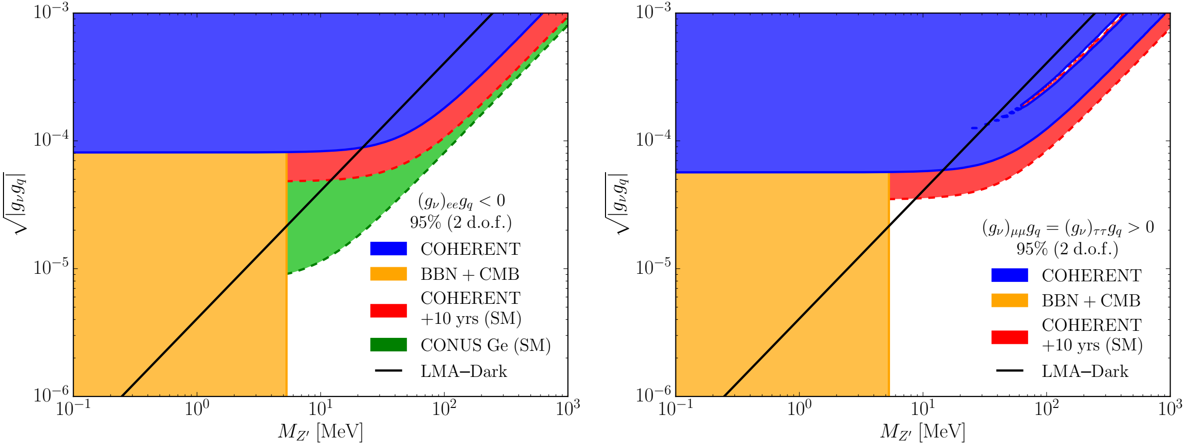
9. Present and Future LMA-Dark Bounds ☹



ϵ_{ee} only

$x = 0$

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

$x = 2$

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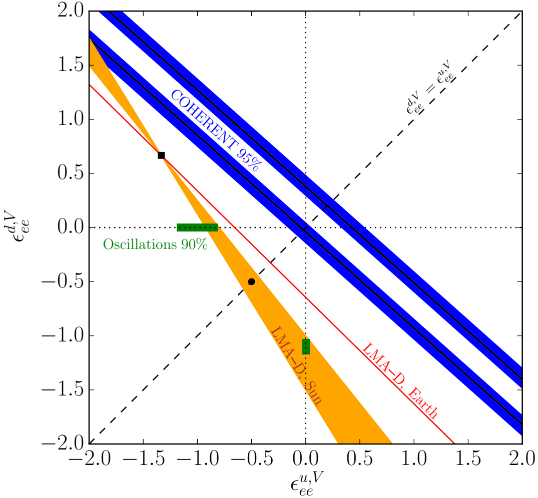
Experimental Connections

1. All oscillation experiments
   - Solar neutrinos in particular
2. CHARM and NuTeV
3. COHERENT
4. Early universe
5. CONUS and other reactor CEvNS
6. DUNE (matter effect) or COHERENT with different materials



COHERENT constraints for large $m_{Z'}$.

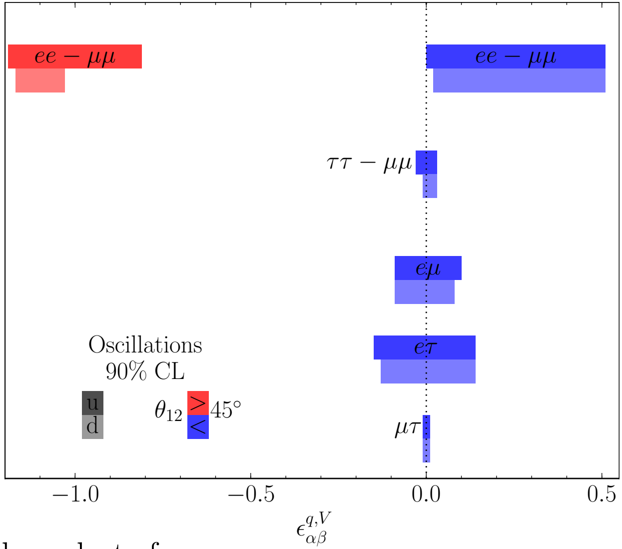
PBD, Y. Farzan, I. Shoemaker 1804.03660

Summary

- Exact degeneracies will be present in every oscillation experiment
- Measuring the sign of Δm^2_{ij} *requires* the matter effect
- New physics (NSIs) makes probing the mass ordering impossible
- 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
- Gap will be covered by reactor CEvNS experiments
- LMA-Dark + diagonal: $(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) \simeq (0, 2, 2)$ with $\epsilon^u \simeq 4/3$ and $\epsilon^d \simeq -2/3$ and $m_{Z'} \in [5, 50]$ MeV may never be probable

Backups

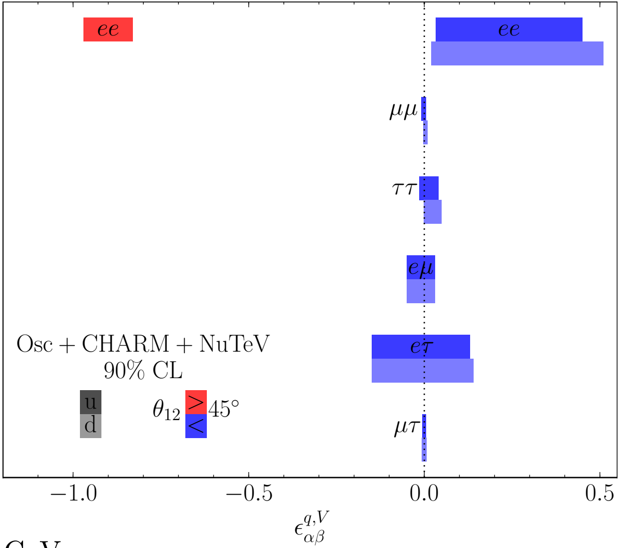
NSI Global Fit: Oscillations



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

PBD, et al., 1701.04828

Heavy NSI Global Fit: CHARM & NuTeV

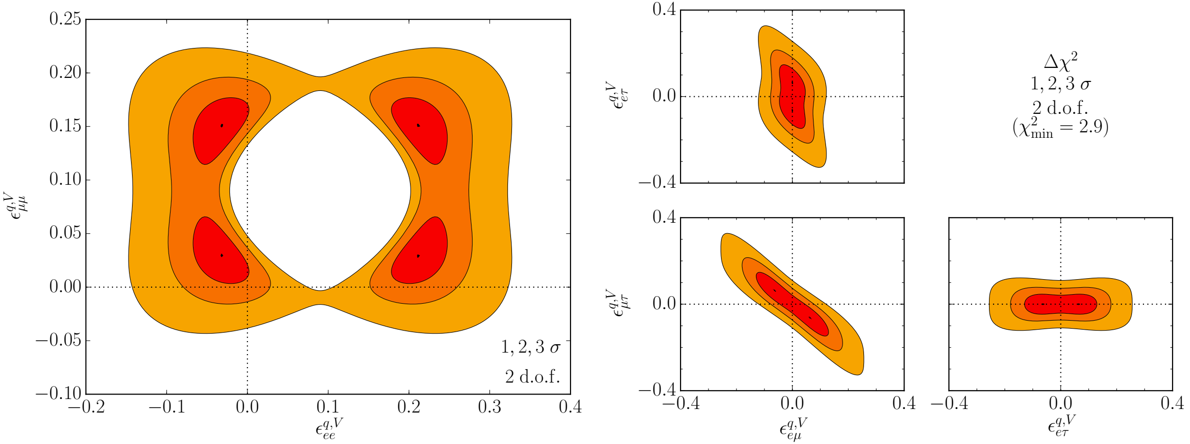


Heavy $\Rightarrow m_{Z'} \gtrsim 1$ GeV.

PBD, et al., 1701.04828

NSI Projections: COHERENT

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



Diagonal

Off-Diagonal

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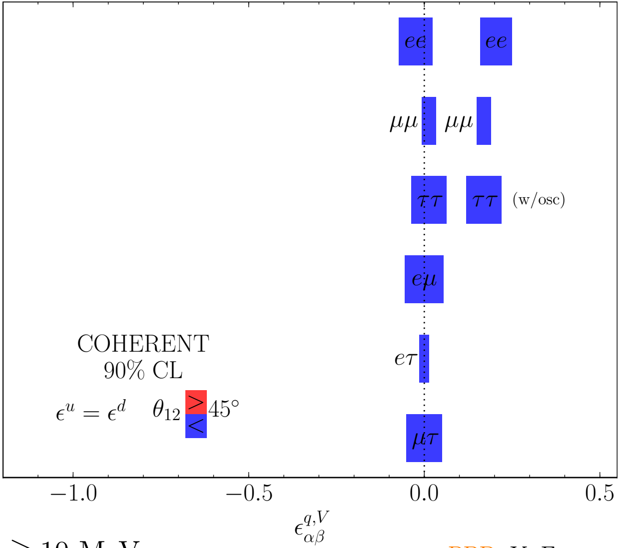
NSI Constraints: COHERENT



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

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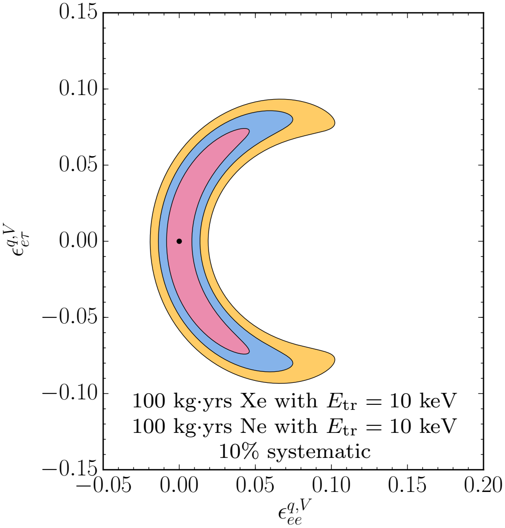
Looking to the COHERENT Future

Interference of different materials is powerful.



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

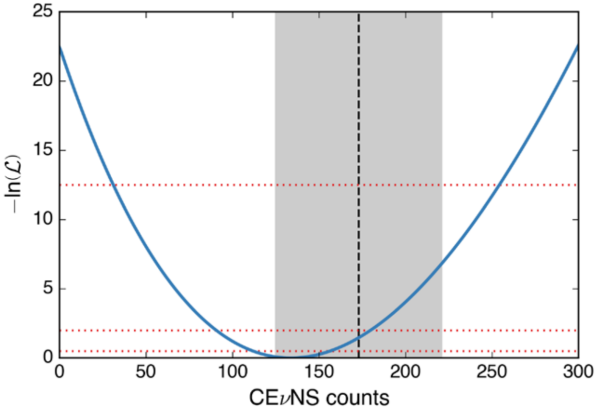
$$Y_n \in [1, 1.43]$$

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

Solar upturn?

COHERENT Results Last Year

COHERENT measured CEvNS at 6.7σ.
14.6 kg CsI (Na doped) for 15 months.



COHERENT Collaboration, 1708.01294 Science

Further LMA-Dark Degeneracy

There is a further exact degeneracy with scattering.

$$Q_{w\alpha}^2 \propto (X_q - \epsilon_{\alpha\alpha}^{q,V})^2\,,$$

with

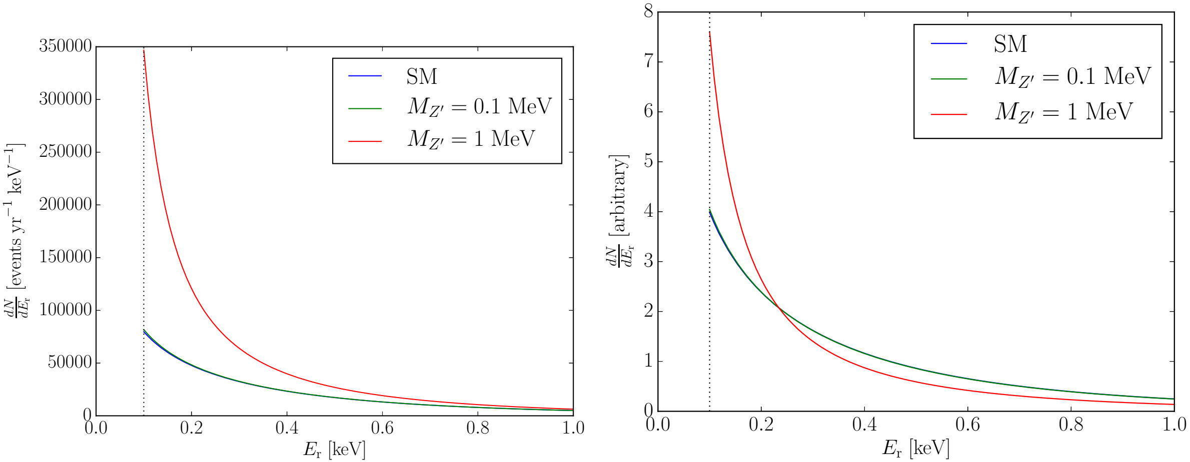
$$X_u = -\frac{Zg_p^V + Ng_n^V}{2Z+N}\,, X_d = -\frac{Zg_p^V + Ng_n^V}{Z+2N}\,.$$

This leads to an exact degeneracy at

$$\epsilon_{ee}^{u,V} = \begin{cases} -0.15 \\ 0.842 \end{cases}\,, \quad \epsilon_{ee}^{d,V} = \begin{cases} -0.224 \\ 0.886 \end{cases}\,.$$

- In this case a scattering experiment cannot break the degeneracy.
- Multiple materials can break this degeneracy in theory, in practice this is hard.
- Best fit points seem to be far from these points, so there is no problem.

Reactor Spectrum Shape Analysis



LMA-Dark $x = 0$ shape sensitivity down to ~ 1 MeV.