Abstract

In presence of non-standard neutrino interactions the neutrino flavor evolution equation is affected by a degeneracy which leads to the so-called LMA-Dark solution. It requires a solar mixing angle in the second octant and implies an ambiguity in the neutrino mass ordering. Non-oscillation experiments are required to break this degeneracy. We perform a combined analysis of data from oscillation experiments with the neutrino scattering experiments CHARM and NuTeV. We find that the degeneracy can be lifted if the non-standard neutrino interactions take place with down quarks, but it remains for up quarks. However, CHARM and NuTeV constraints apply only if the new interactions take place through mediators not much lighter than the electroweak scale. For light mediators we consider the possibility to resolve the degeneracy by using data from future coherent neutrino-nucleus scattering experiments such as COHERENT. We find that, for an experiment using a stopped-pion neutrino source, the LMA-Dark degeneracy will either be resolved, or the presence of new interactions in the neutrino sector will be established with high significance.

COHERENT and the LMA-Dark NSI Solution

Peter B. Denton

NUFACT 2017 Uppsala

September 29, 2017

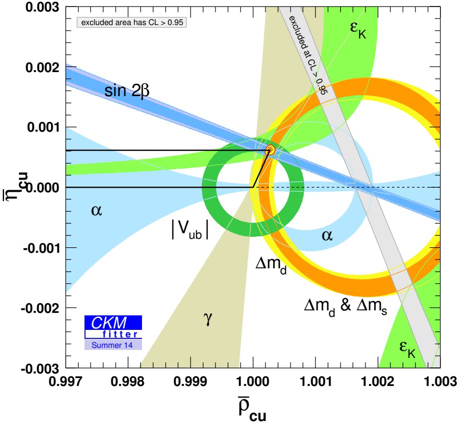
1701.04828 JHEP

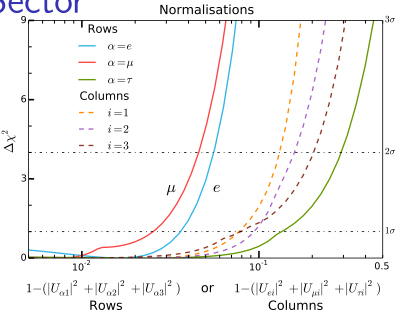
with P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz

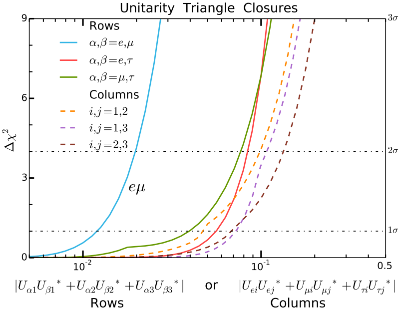
The Niels Bohr International Academy

VILLUM FONDEN

Over Constrain the Neutrino Sector







J. Charles, et. al., 1501.05013

S. Parke, M. Ross-Lonergan, 1508.05095

Not Just Under Constrained

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

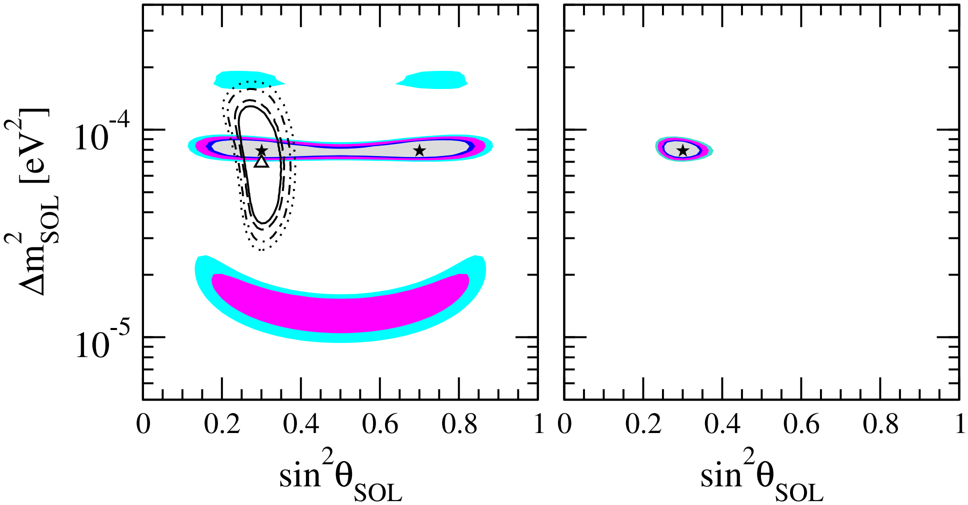
(Submitted on 24 Jun 2004 (v1), last revised 7 Sep 2006 (this version, v3))

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

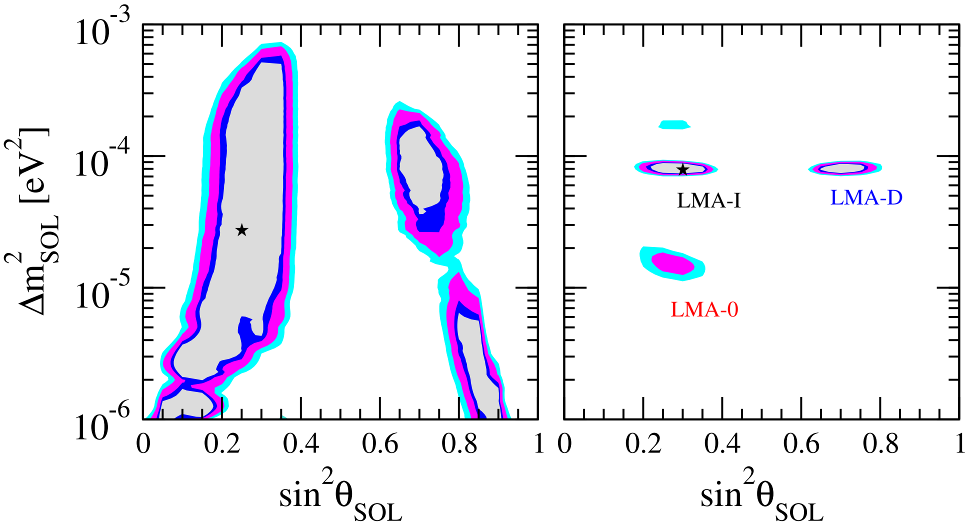
Best Fit Assuming Standard Neutrino Physics



90%, 95%, 99% and 99.73% C.L. O. Miranda, M. Tórtola, J. Valle, hep-ph/0406280

KamLAND (color), solar (black).

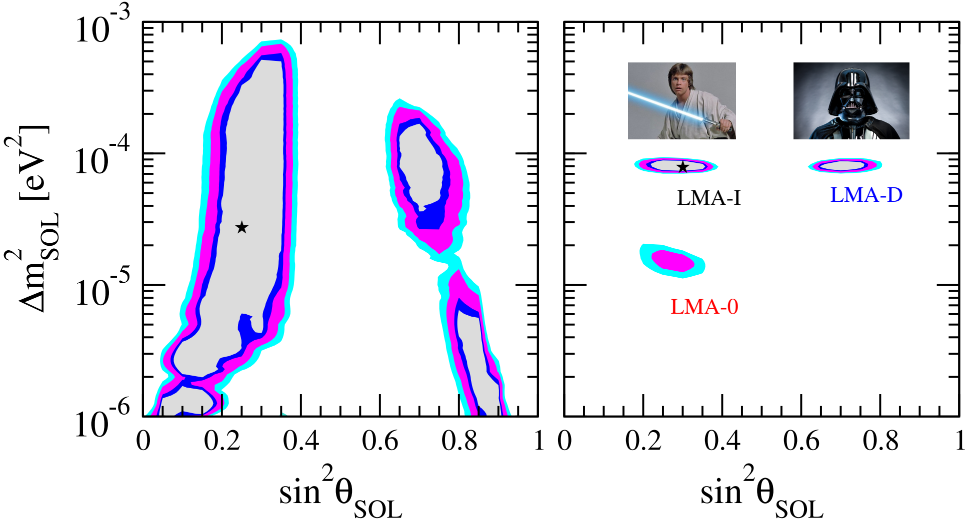
Allowing For New Neutrino Interactions



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

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

Allowing For New Neutrino Interactions



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

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

New Physics: Phenomenology

The simplest/clearest phenomenological description of NSI is,

$$H_\nu = H_\nu^{\rm vac} + H_\nu^{\rm mat}\,,$$

with

$$H_\nu^{\rm vac} = \frac{1}{2E} U_{\rm PMNS} \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U_{\rm PMNS}^\dagger$$

$$H_\nu^{\rm mat} = H_\nu^{\rm mat,SM} + H_\nu^{\rm mat,NSI}$$

$$H_\nu^{\rm mat,SM} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

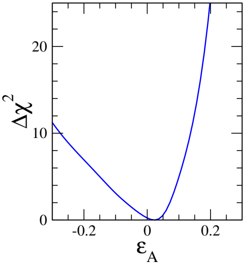
$$H_\nu^{\rm mat,NSI} = \sqrt{2} G_F n_e \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

NSI: The Epsilons

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

with

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



- We constrain ourselves to only consider vector NSI.
- Generically, axial-vector NSI may exist as well.
- This doubles the number of free parameters.
- Axial-vector is not constrained by oscillations, only scattering.

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

Lagrangian

EFT Lagrangian:

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

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

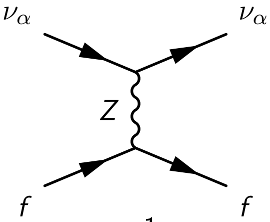
Simplified model Lagrangian:

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

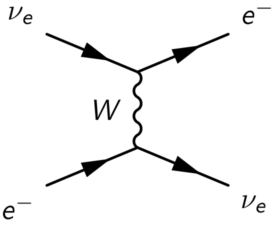
which gives a potential

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

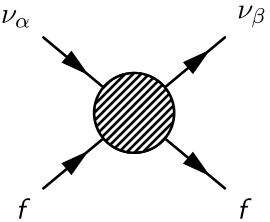
Matter Effects in Feynman Diagrams



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

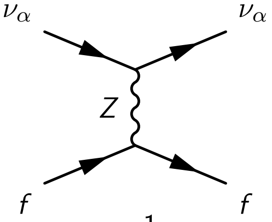


$$V_{\mathrm{CC}} = \pm\sqrt{2}G_F n_e$$

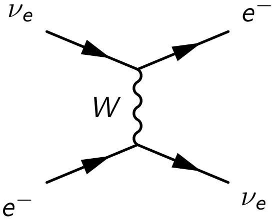


$$V_{\mathrm{NSI}} = \pm\epsilon_{\alpha\beta}^{f,X}\sqrt{2}G_F n_f$$

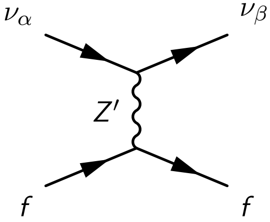
Matter Effects in Feynman Diagrams



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



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



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

Generalized Mass Ordering Degeneracy (GMOD)

CPT symmetry $\Rightarrow$ that oscillations are invariant under $H \to -H^*$.

In vacuum, change:

- Switch mass ordering: $\Delta m^2_{31} \to -\Delta m^2_{32}$,
- $\sin\theta_{12} \to \cos\theta_{12}$,
- $\delta \to \pi - \delta$.

In vacuum, this degeneracy is exact.

In matter, the degeneracy can be restored with NSI with changes,

- $\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta}$,
- $\epsilon_{ee} \to -\epsilon_{ee} - 2 \Rightarrow \epsilon_{ee} = -2$.

This can be broken by varying or different neutron densities.
The degeneracy can be restored by setting $\epsilon^u_{\alpha\beta} = -2\epsilon^d_{\alpha\beta}$.
Setting $\epsilon^u_{ee} = -4/3$ and $\epsilon^d_{ee} = 2/3$ yields an exact degeneracy in any neutron density.

P. Coloma, T. Schwetz, 1604.05772

NSI in Scattering Experiments Probe Different NSI Scales

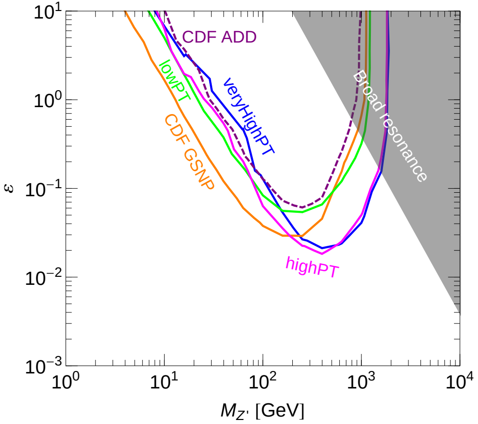
NSI affects:

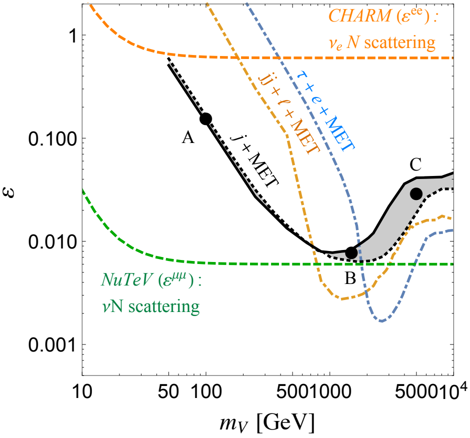
- Oscillation: $q^2 = 0$, the effect is valid for any $M_{Z'}$.
- Scattering: the NSI potential is suppressed if $q^2 > M_{Z'}^2$.

Method	$M_{Z'}$
CHARM/NuTeV (DIS)	$\gtrsim 1$ GeV
COHERENT (CEνNS)	$\gtrsim 10$ MeV
Oscillation	Any

Above ~ 1 TeV, $\epsilon \sim \mathcal{O}(1)$ is no longer perturbative.

LHC Constraints at High Energy





A. Friedland, M. Graesser, I. Shoemaker, and L. Vecchi, 1111.5331

D. Franzosi, M. Frandsen, and I. Shoemaker, 1507.07574

Oscillations

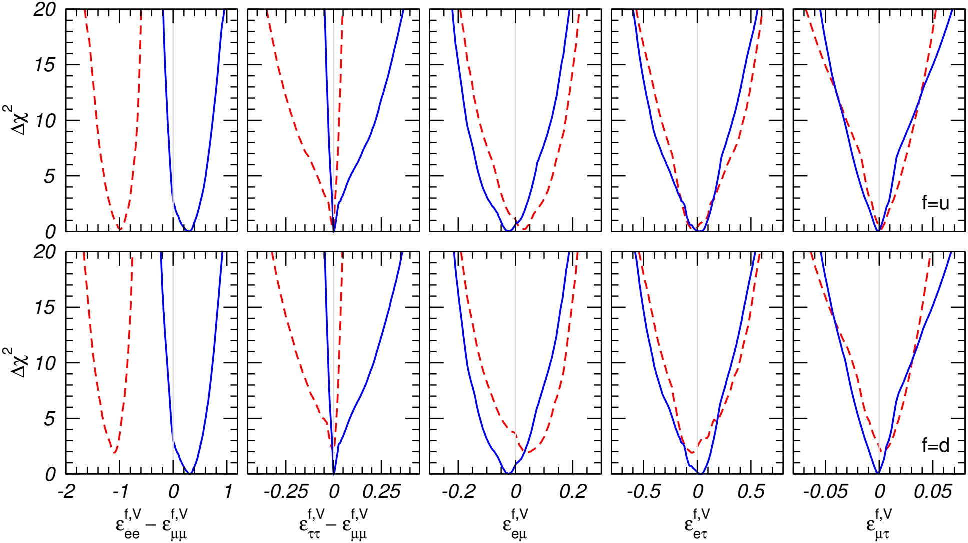
Global fit of oscillation parameters.
Marginalize over all vacuum parameters and
NSI parameters assuming:

- $\epsilon^e_{\alpha\beta} = 0$.
- Vector only $L + R$ (no axial).
- $\epsilon \in \mathbb{R}$.

Solar data from
Chlorine, Gallex/GNO, SAGE, Super-K, Borexino, and SNO.
Atmospheric data from
Super-K, MINOS, and T2K.
Reactor data from
CHOOZ, Palo Verde, Double CHOOZ, Daya Bay, and RENO.
Short baseline data from
Bugey, ROVNO, Krasnoyarsk, ILL, Gösgen, and SRP.

M.C. Gonzalez-Garcia, M. Maltoni, 1307.3092

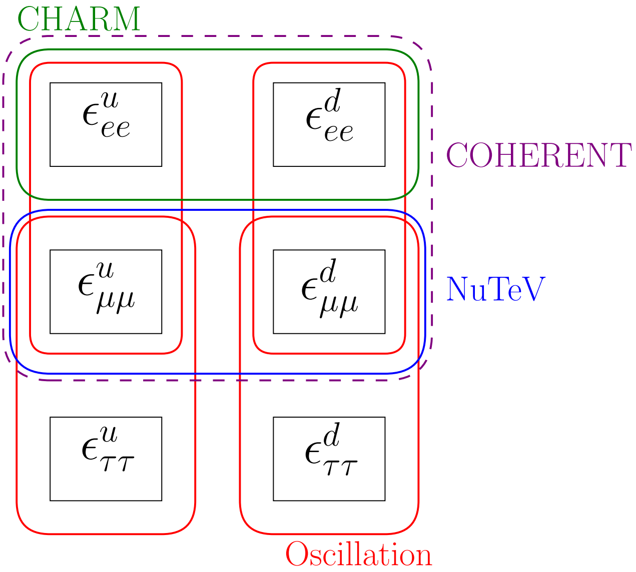
Pre-COHERENT Light NSI Constraints



LMA: blue, LMA-D: red dashed. No absolute diagonal sensitivity

Oscillation data is applicable for any NSI mass scale.

Constraining the Diagonal NSI Terms



CHARM

CHARM measured NC and CC ν_e and $\bar{\nu}_e$ cross sections with nuclei.

$$R_e = \frac{\sigma(\nu_e X \to \nu_e X) + \sigma(\bar{\nu}_e X \to \bar{\nu}_e X)}{\sigma(\nu_e X \to e X) + \sigma(\bar{\nu}_e X \to \bar{e} X)} = 0.406 \pm 0.140\,.$$

CHARM Collaboration, PLB180 (1986)

We can express this ratio in terms of couplings,

$$R_e = (\tilde{g}_e^L)^2 + (\tilde{g}_e^R)^2\,,$$

where effective couplings are SM + NSI,

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

with SM parameters,

$$g_u^L = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W\,, \quad g_u^R = -\frac{2}{3}\sin^2\theta_W\,,$$
$$g_d^L = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W\,, \quad g_d^R = \frac{1}{3}\sin^2\theta_W\,.$$

CHARM

Radiative corrections through two loops give SM values,

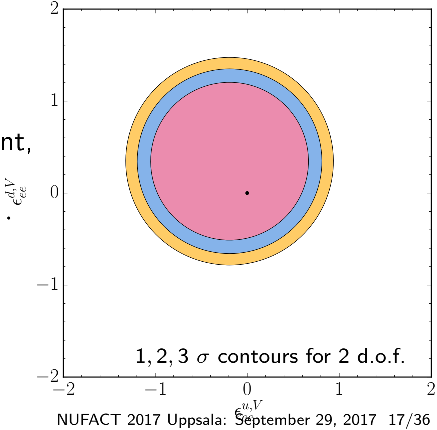
$$g_u^L = 0.3457\,, \quad g_u^R = 0.1553\,,$$
$$g_d^L = 0.4288\,, \quad g_d^R = 0.0777\,,$$

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

J. Erler, S. Su, 1303.5522

We calculate the χ^2 between an NSI parameterization and the measurement,

$$\chi^2_{\mathrm{CHARM}} = \left(\frac{R_{e,\mathrm{NSI}} - R_{e,\mathrm{CHARM}}}{\sigma_{\mathrm{CHARM}}}\right)^2 .$$



NuTeV

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

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

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

where

$$r = \frac{\sigma(\bar{\nu}_\mu X \to \bar{\mu} X)}{\sigma(\nu_\mu X \to \mu X)}\,.$$

$$R_{\mu,\mathrm{exp}}^\nu = 0.3919 \pm 0.0013\,,$$

$$R_{\mu,\mathrm{exp}}^{\bar{\nu}} = 0.4050 \pm 0.0027\,,$$

with correlation coefficient $\rho = 0.636$.
This includes statistical, systematical, and theory uncertainties.

NuTeV Collaboration, hep-ex/0110059

G. P. Zeller PhD thesis

NuTeV

The correct way to interpret this data is to use fitted effective couplings,

$$(g^L_{\rm eff,exp})^2 = 0.30005 \pm 0.00137\,, \quad (g^R_{\rm eff,exp})^2 = 0.03076 \pm 0.00110\,,$$

with correlation coefficient $\rho = -0.017$.

G. P. Zeller PhD thesis

We then define the χ^2 with correlation between L and R as,

$$\chi^2_{\rm NuTeV} = (\vec{X} - \vec{X}_{\rm exp})^T V_X^{-1} (\vec{X} - \vec{X}_{\rm exp})$$

where

$$\vec{X} = \begin{pmatrix} g^L_{\rm eff} \\ g^R_{\rm eff} \end{pmatrix},$$

$$V_X = \begin{pmatrix} \sigma(g^L_{\rm eff,exp})^2 & \sigma(g^L_{\rm eff,exp})\sigma(g^R_{\rm eff,exp})\rho \\ \sigma(g^L_{\rm eff,exp})\sigma(g^R_{\rm eff,exp})\rho & \sigma(g^R_{\rm eff,exp})^2 \end{pmatrix}.$$

This leads to $\chi^2_{\rm NuTeV,SM} \sim 9$ which is the NuTeV anomaly.

NuTeV Anomaly

Several corrections to the NuTeV analysis have been applied in an attempt to understand this anomaly.

Corrections to the measurements are applied because,

- Improved nuclear models,
- Iron is not isoscalar,
- Updated PDF's including the strange quark.

These lead to,

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

where $R_{\mathrm{exp,true}} = R_{\mathrm{exp,orig}} + \delta R$.
Convert to effective couplings by $\delta\vec{X} = J^{-1}\delta\vec{R}$.

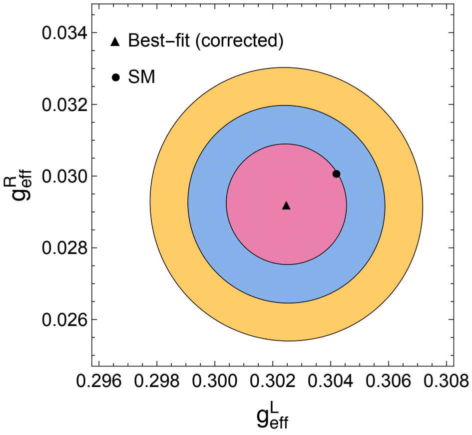
$$\delta g^{L}_{\mathrm{eff,exp}} = 0.00242\,, \quad \delta g^{R}_{\mathrm{eff,exp}} = -0.00155\,,$$

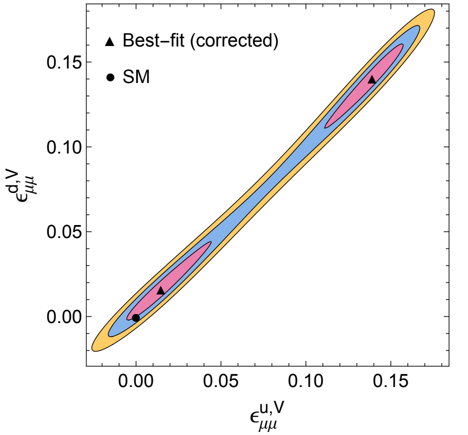
leading to a corrected $\chi^2_{\mathrm{NuTeV,SM}} \sim 2.3$.

NNPDF Collaboration, 0906.1958

W. Bentz, I. C. Cloet, J. T. Londergan, A. W. Thomas, 0908.3198

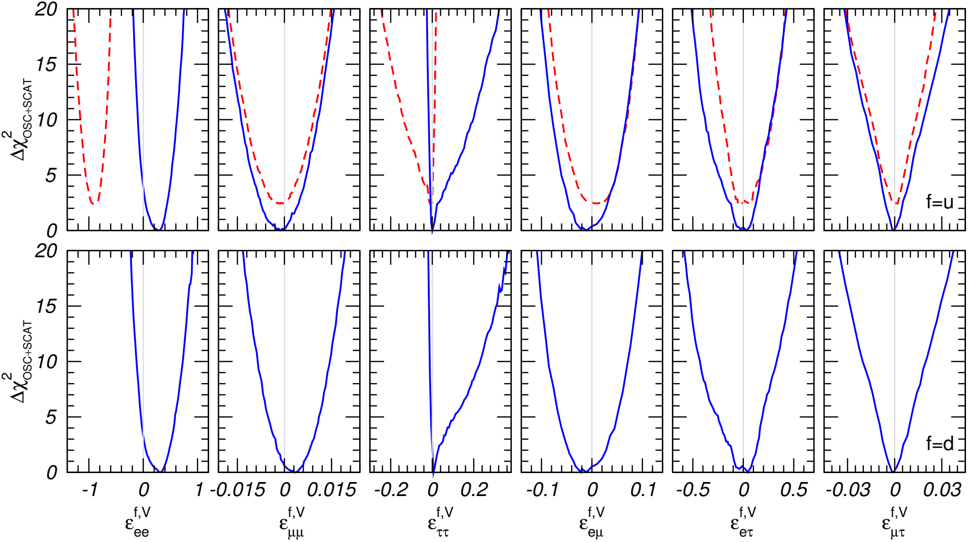
NuTeV Constraints





$1, 2, 3\ \sigma$ contours for 2 d.o.f.

Pre-COHERENT Heavy NSI Constraints



Heavy $\Rightarrow M'_Z \gtrsim 1$ GeV.

All oscillation experiments, CHARM, and NuTeV.

COHERENT

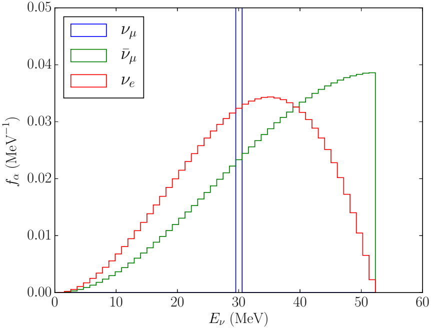
Spallation Neutron Source at Oak Ridge National Laboratory in a π-DAR configuration.

K. Scholberg's plenary yesterday.

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:

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

$Z = 32,\ N = 44.$

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

COHERENT Beam Details

Calculating contamination:

- The ν_μ from the π^+ decay forms the prompt signal.
- The ν_e and $\bar{\nu}_\mu$ form the delayed signal.
- Pulse width is 0.695 μs.
- μ lifetime is $\Gamma\tau = 2.283$ μs.
- Probability that the muon decays within the pulse width,

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

- Prompt and delayed counts:

$$N_p = N_{\nu_\mu} + P_c(N_{\nu_e} + N_{\bar{\nu}_\mu}) \,,$$

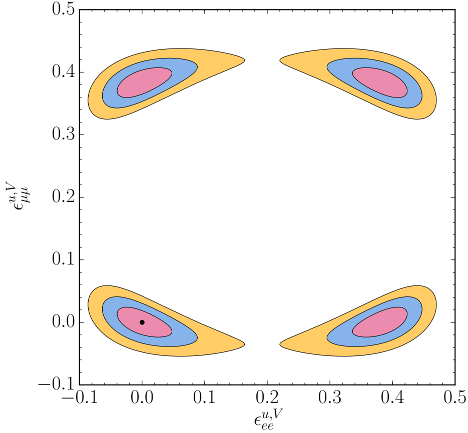
$$N_d = (1 - P_c)(N_{\nu_e} + N_{\bar{\nu}_\mu}) \,.$$

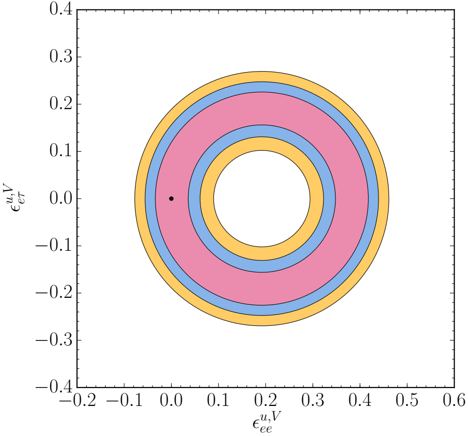
- We expect $\sim$ 113 prompt and $\sim$ 200 delayed.

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

COHERENT Sensitivity

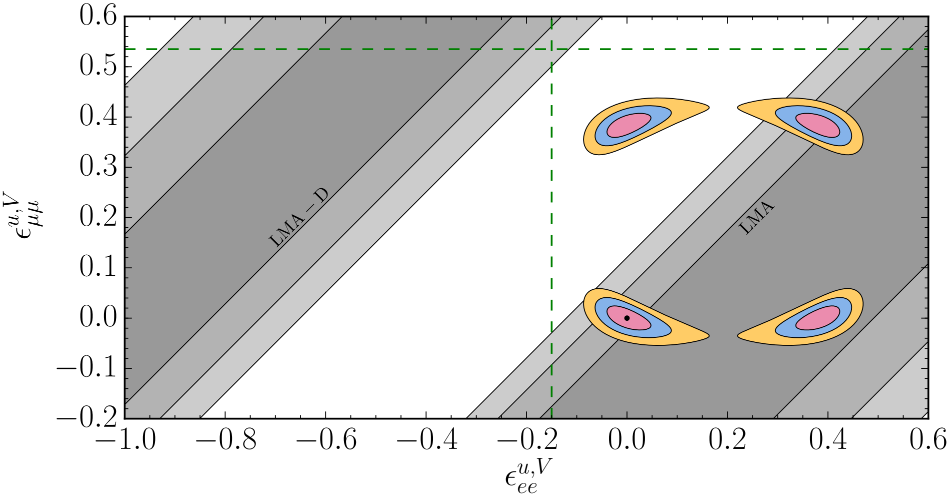
Recall that $\epsilon_{e\tau}$ is poorly constrained.





Predicted sensitivity measuring SM with 10 kg·yrs of ^{76}Ge.
LHS shape is due to prompt + delayed.

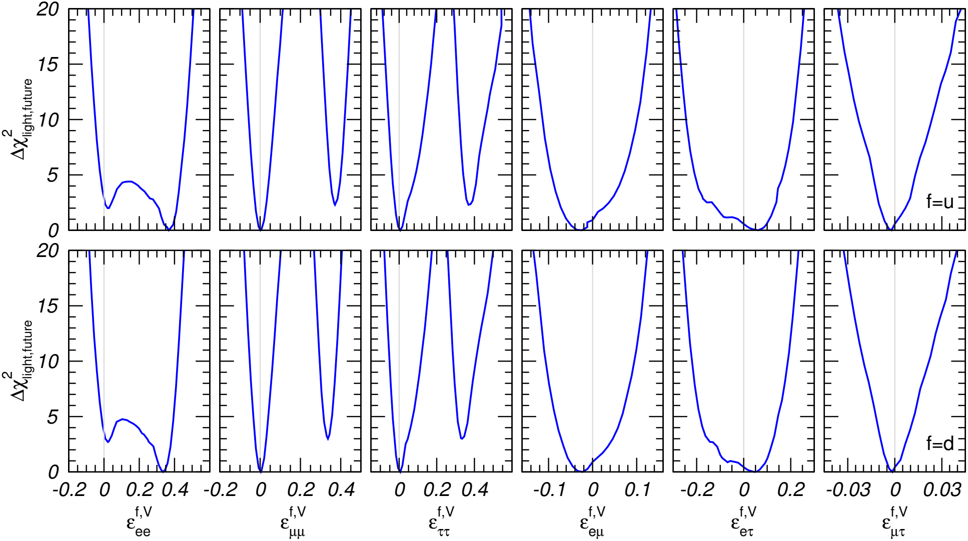
COHERENT Sensitivity to Exclude LMA-D



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

Dashed lines are the locations of another exact degeneracy.

Predicted Light NSI Constraints

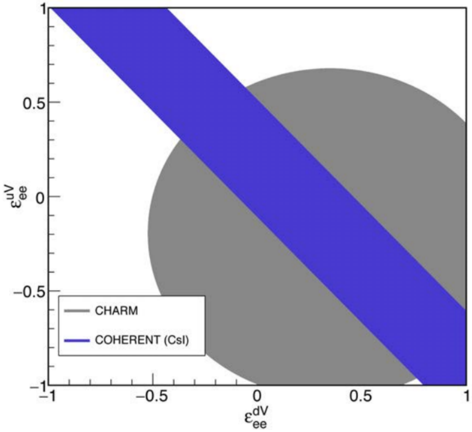


Assume that COHERENT measures SM: $\epsilon = 0$.

Oscillation plus COHERENT (no CHARM or NuTeV).

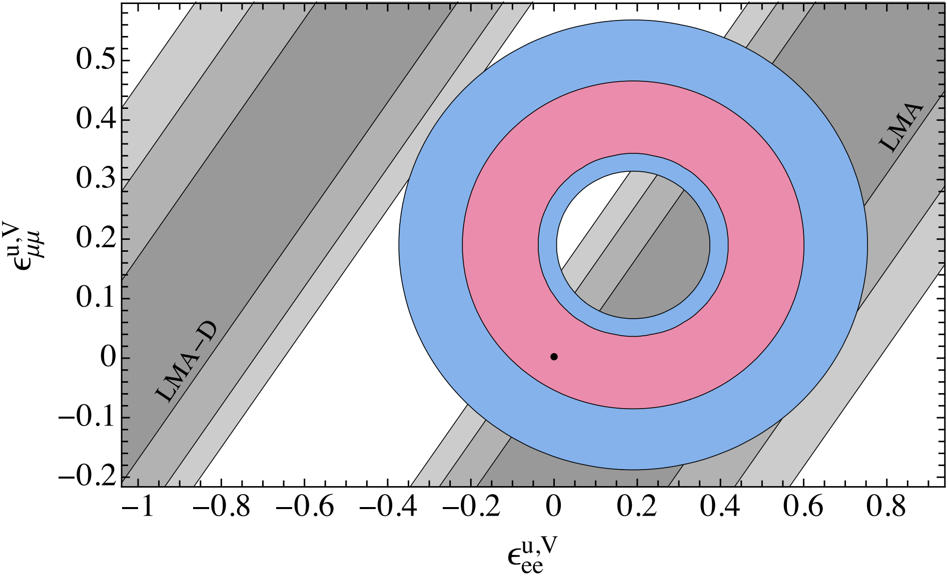
New Limits

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



COHERENT Collaboration, 1708.01294 Science

Latest Light NSI Constraints



P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, 1708.02899

NSI Constraints for All Masses
Oscillations

$\epsilon_{ee}^{u,V} - \epsilon_{\mu\mu}^{u,V}$	$[-1.19, -0.81] \oplus [0.00, 0.51]$
$\epsilon_{\tau\tau}^{u,V} - \epsilon_{\mu\mu}^{u,V}$	$[-0.03, 0.03]$
$\epsilon_{e\mu}^{u,V}$	$[-0.09, 0.10]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.14]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.01, 0.01]$
$\epsilon_{ee}^{d,V} - \epsilon_{\mu\mu}^{d,V}$	$[-1.17, -1.03] \oplus [0.02, 0.51]$
$\epsilon_{\tau\tau}^{d,V} - \epsilon_{\mu\mu}^{d,V}$	$[-0.01, 0.03]$
$\epsilon_{e\mu}^{d,V}$	$[-0.09, 0.08]$
$\epsilon_{e\tau}^{d,V}$	$[-0.13, 0.14]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.01, 0.01]$

90% CL

NSI Constraints for Heavy Mediators
Oscillations + CHARM + NuTeV

$\epsilon_{ee}^{u,V}$	$[-0.97, -0.83] \oplus [0.033, 0.450]$
$\epsilon_{\mu\mu}^{u,V}$	$[-0.008, 0.005]$
$\epsilon_{\tau\tau}^{u,V}$	$[-0.0015, 0.04]$
$\epsilon_{e\mu}^{u,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.13]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.006, 0.005]$
$\epsilon_{ee}^{d,V}$	$[0.02, 0.51]$
$\epsilon_{\mu\mu}^{d,V}$	$[-0.003, 0.009]$
$\epsilon_{\tau\tau}^{d,V}$	$[-0.001, 0.05]$
$\epsilon_{e\mu}^{d,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{d,V}$	$[-0.15, 0.14]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.007, 0.007]$

90% CL

NSI Predictions for Heavy Mediators
Oscillations + CHARM + NuTeV + COHERENT(SM)

$\epsilon_{ee}^{u,V}$	$[0.014, 0.032] \oplus [0.24, 0.41]$
$\epsilon_{\mu\mu}^{u,V}$	$[-0.007, 0.005]$
$\epsilon_{\tau\tau}^{u,V}$	$[-0.006, 0.04]$
$\epsilon_{e\mu}^{u,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.13]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.006, 0.004]$
$\epsilon_{ee}^{d,V}$	$[0.26, 0.38]$
$\epsilon_{\mu\mu}^{d,V}$	$[-0.003, 0.009]$
$\epsilon_{\tau\tau}^{d,V}$	$[-0.001, 0.05]$
$\epsilon_{e\mu}^{d,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{d,V}$	$[-0.15, 0.14]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.007, 0.007]$

90% CL

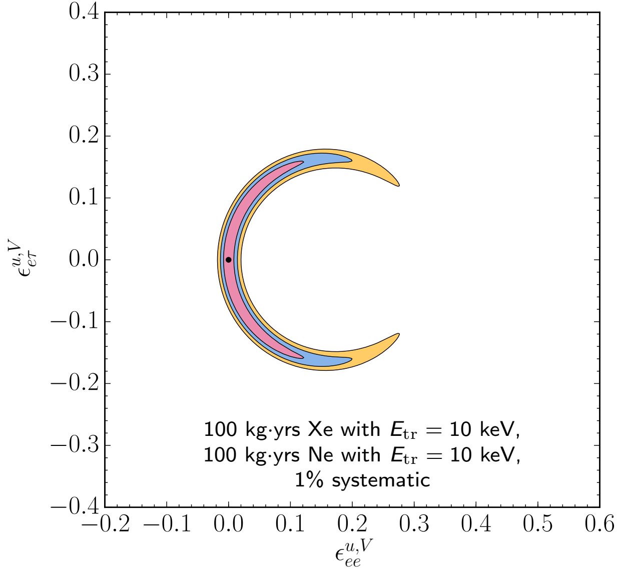
NSI Constraints for Light Mediators Oscillations + COHERENT(data)

$\epsilon_{ee}^{u,V}$	$[0.028, 0.60]$
$\epsilon_{\mu\mu}^{u,V}$	$[-0.088, 0.37]$
$\epsilon_{\tau\tau}^{u,V}$	$[-0.090, 0.38]$
$\epsilon_{e\mu}^{u,V}$	$[-0.073, 0.044]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.13]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.01, 0.009]$
$\epsilon_{ee}^{d,V}$	$[0.03, 0.55]$
$\epsilon_{\mu\mu}^{d,V}$	$[-0.075, 0.33]$
$\epsilon_{\tau\tau}^{d,V}$	$[-0.075, 0.33]$
$\epsilon_{e\mu}^{d,V}$	$[-0.07, 0.04]$
$\epsilon_{e\tau}^{d,V}$	$[-0.13, 0.12]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.009, 0.008]$

90% CL from P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, 1708.02899

Looking to the COHERENT Future

Interference of different materials is powerful.

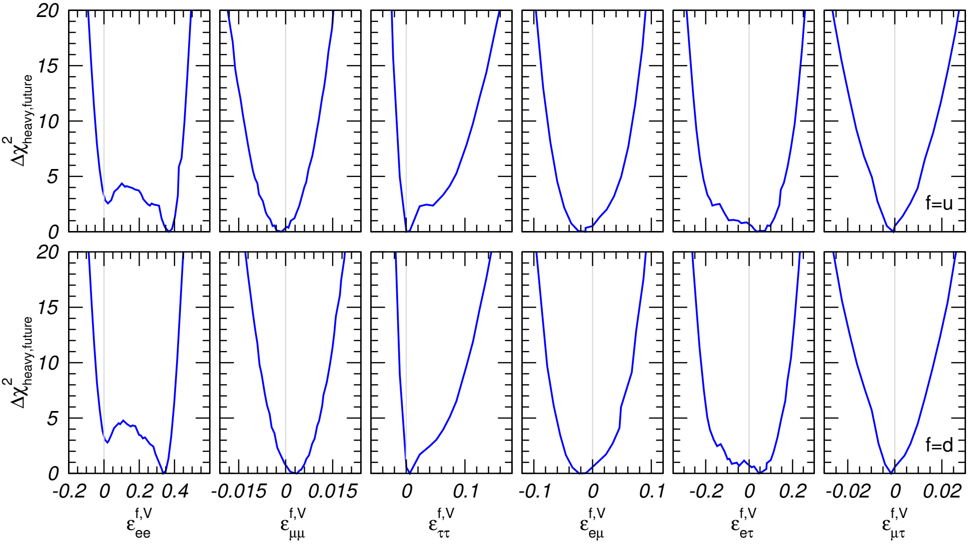


Wrap-up

- NSI parameterizes generic BSM phenomenology in the neutrino sector.
- Large NSI $\mathcal{O}$(electroweak) consistent with oscillation data.
- Scattering experiments are crucial to measure diagonal NSI.
- For heavy mediators $M'_Z \gtrsim 1$ GeV,
  - CHARM and NuTeV apply.
  - LMA-D is ruled out for d quarks.
  - With COHERENT LMA-D is completely ruled out.
- For light mediators $M'_Z \gtrsim 10$ MeV,
  - CHARM and NuTeV are suppressed, but COHERENT applies.
  - With COHERENT LMA-D is completely ruled out.
- Anticipate future COHERENT results.
- Making progress on constraining BSM ν physics.

Backups

Predicted Heavy NSI Constraints



Heavy $\Rightarrow M'_Z \gtrsim 1$ GeV. All oscillation experiments, CHARM, and NuTeV. Assumes COHERENT measures SM: $\epsilon = 0$.

COHERENT χ^2

The COHERENT χ^2,

$$\chi^2_{\text{COH}} = \min_{\xi} \sum_{k=p,d} \left(\frac{(1+\xi)N_{k,\text{NSI}} - N_{k,\text{obs}}}{\sqrt{N_{k,\text{obs}} + 0.2N_{k,\text{obs}}}} \right)^2 + \left(\frac{\xi}{0.1} \right)^2 ,$$

where 20% is the background rate and 10% is a normalization uncertainty covering various systematics including fast neutrons and CR and radioactive backgrounds.

Further LMA-D Degeneracy

There is a further exact degeneracy with scattering.

$$Q^2_{w\alpha} \propto (X_q - \epsilon^{q,V}_{\alpha\alpha})^2\,,$$

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

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

- 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.