Multiple Probes of Lorentz Violation with Reactor Antineutrinos

Joshua Spitz
DPF, 8/16/2013

Based on: Phys. Rev. D 86 112009 (2012) and arXiv:1307.5789 [hep-ex] (2013)

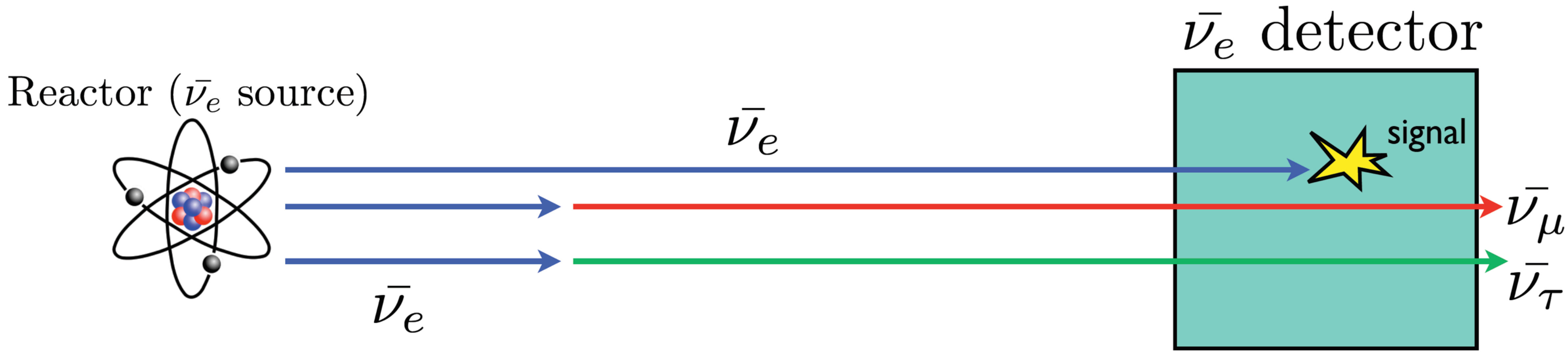
Outline

- Introduction to Double Chooz
- Introduction to Lorentz violation

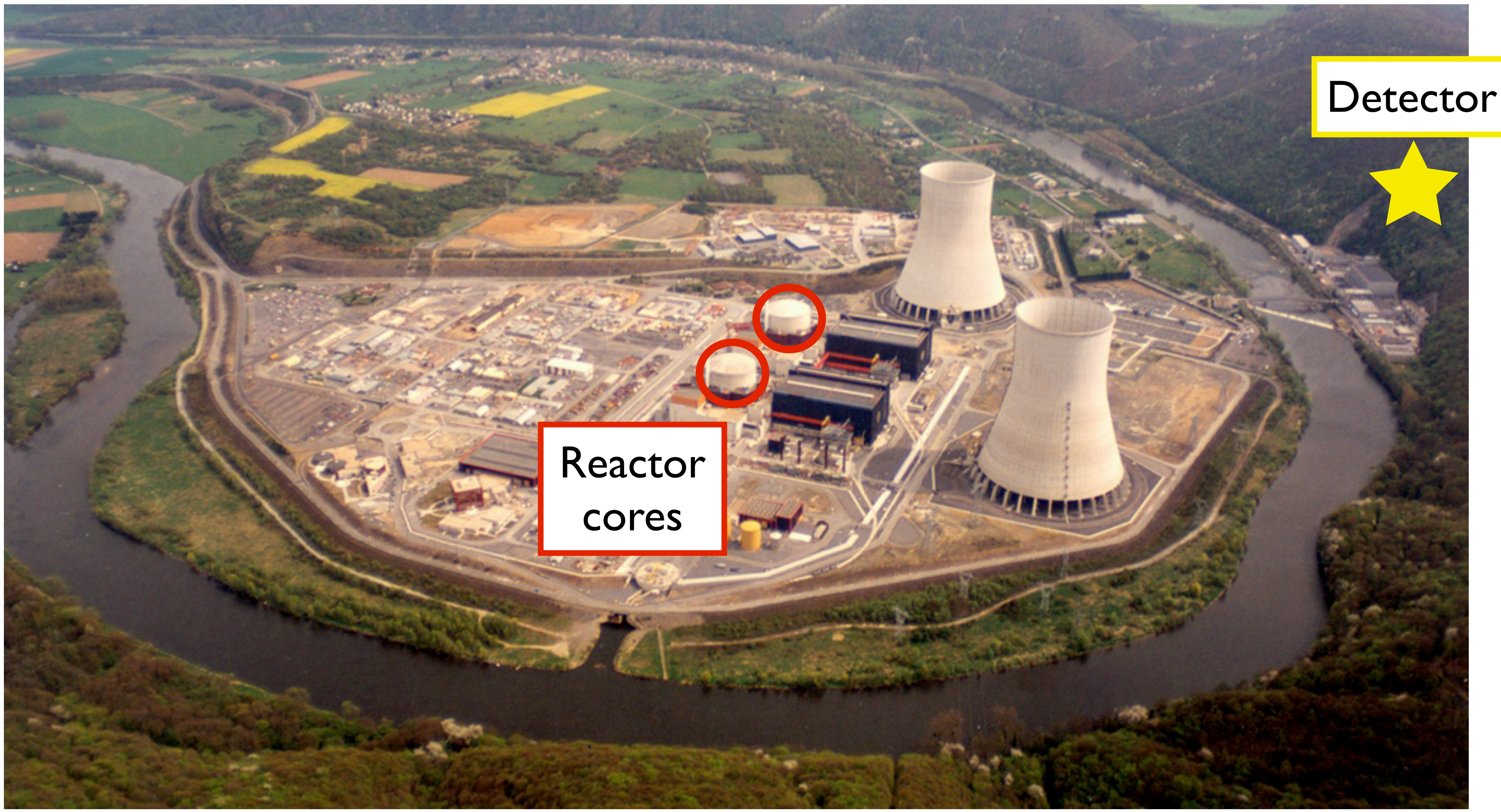
- A search for a time-dependent oscillation signal
- A search for neutrino-antineutrino mixing

Double Chooz

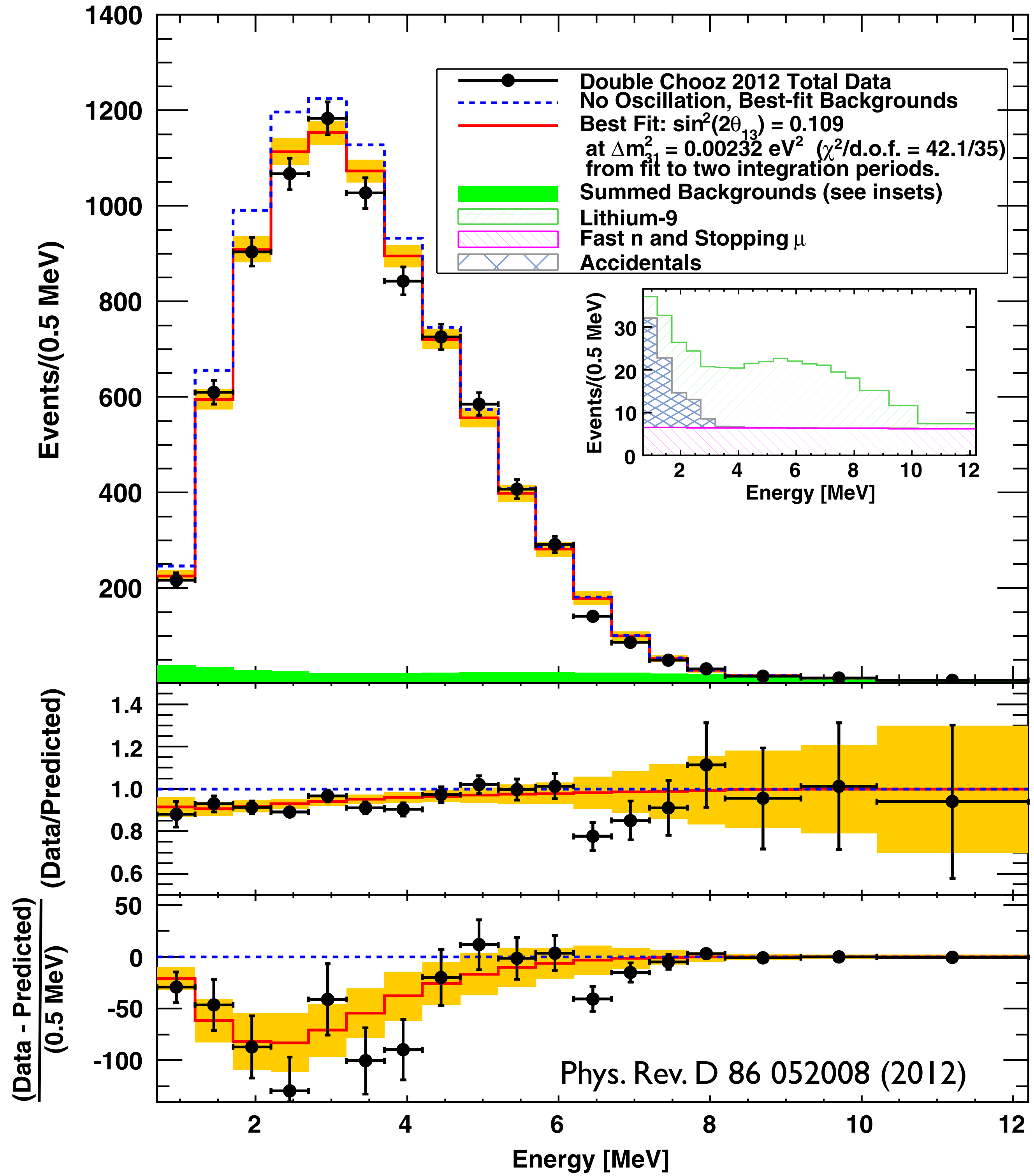
(The north of France, a few miles from Belgium)

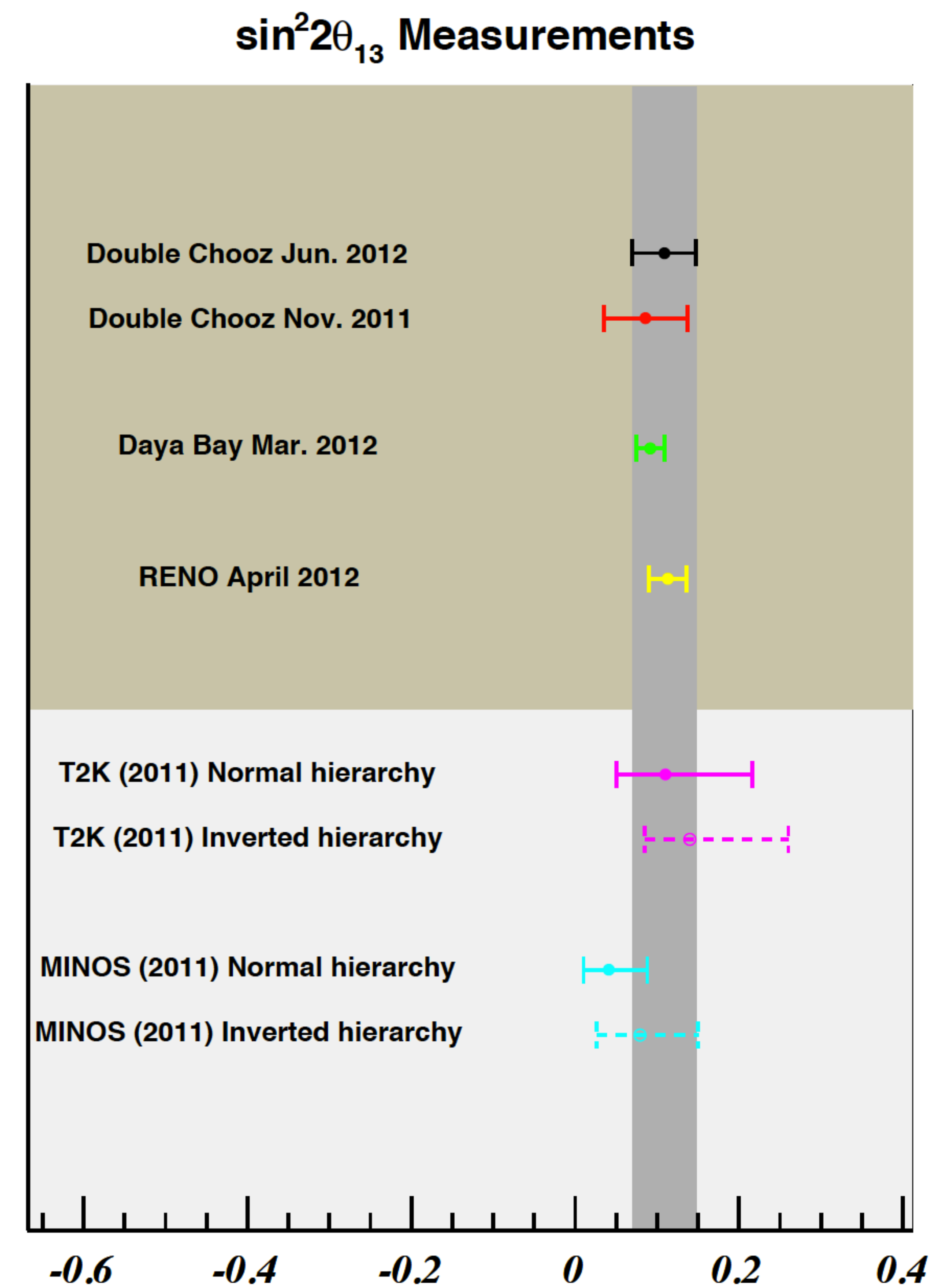


In a *disappearance experiment*, we look for a deficit of antineutrinos



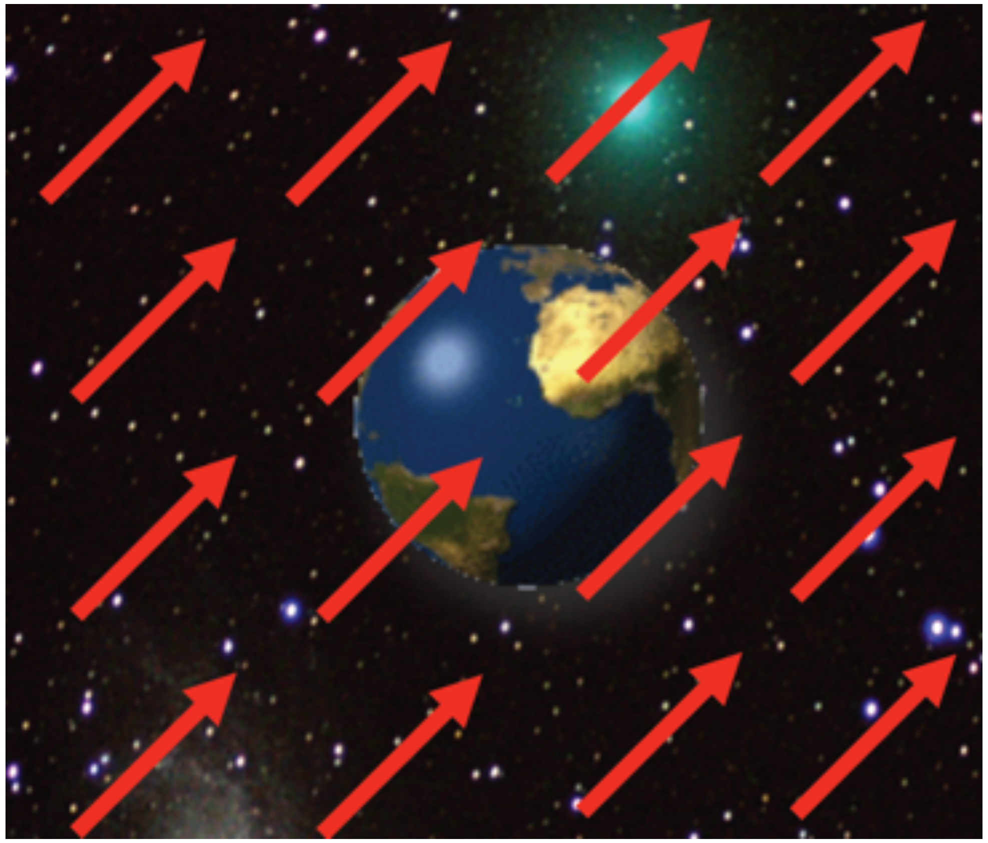
The last mixing angle



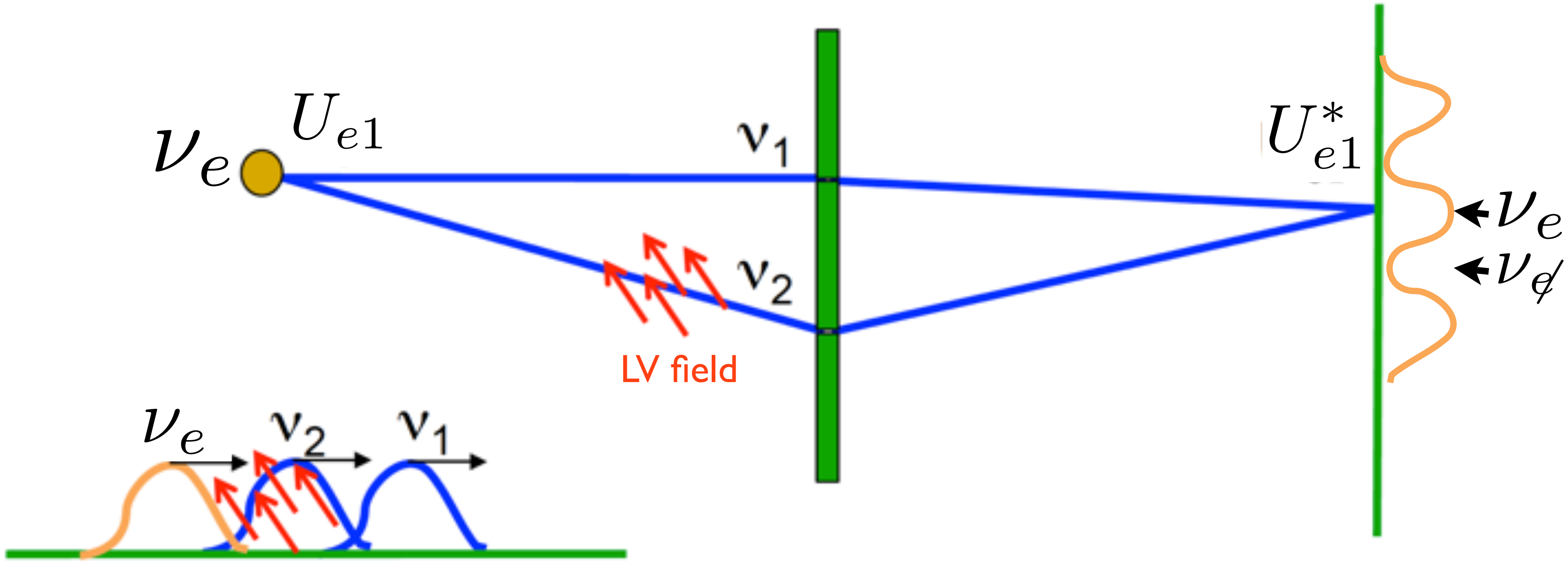


What is Lorentz violation?

- Lorentz invariance requires that the behavior of a particle is independent of its direction or boost velocity.
- Basically, LV means that the universe has a preferred direction.
- Our SM particles can couple to this background field and create observable effects.
- LV has never been seen.



Neutrino oscillation and LV



Neutrino oscillations are natural interferometers!

If the mass eigenstates have different couplings to a Lorentz violating field, the oscillation pattern will be affected.

Neutrino eigenvalue difference is comparable to the target scale of Lorentz violation (Planck scale)....$<10^{-19}$ GeV

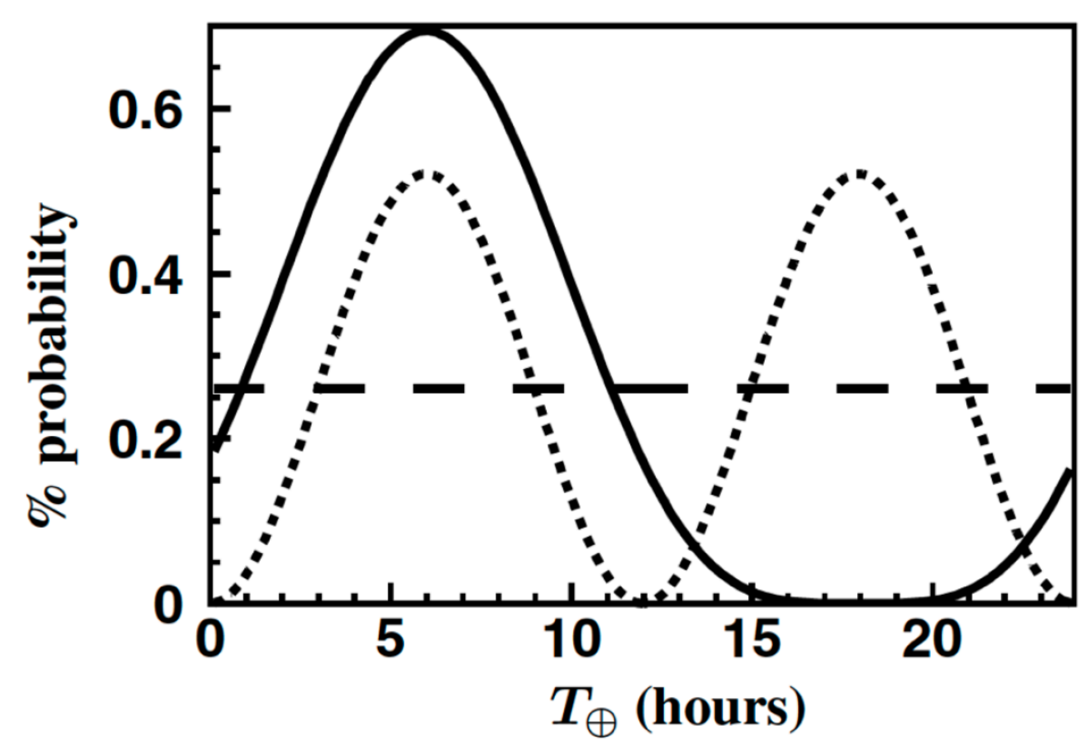
Is there any hope of ever seeing LV with neutrinos?

- First and foremost, "You can't see if you don't look".
- Note that neutrinos generally do not provide the best sensitivity to LV. Measurements of gamma ray burst photons set the best limits.
  - Gamma rays from GRBs all seem to arrive at the same time, despite having different energies/frequencies and traveling a very long way.
- Neutrinos are special because they only feel the weak force and thus can avoid QED constraints.
- Neutrinos are also special because we don't understand them very well.

How to look for it?

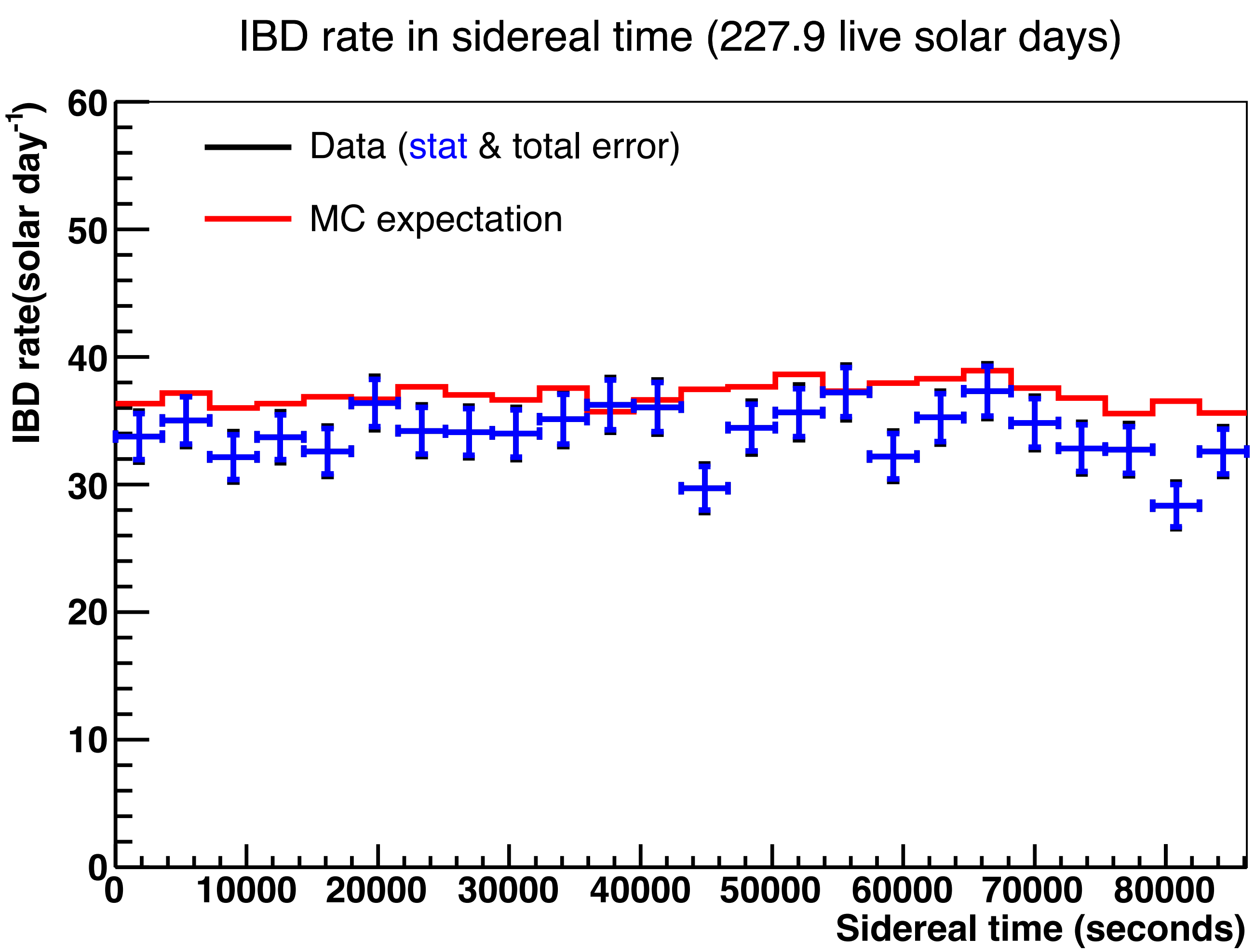
- Strange energy dependence (i.e. non-L/E behavior).
- CPT violation (differences between neutrinos and antineutrinos).
- Neutrino-antineutrino mixing.
- Periodicity (in time) of neutrino oscillation.

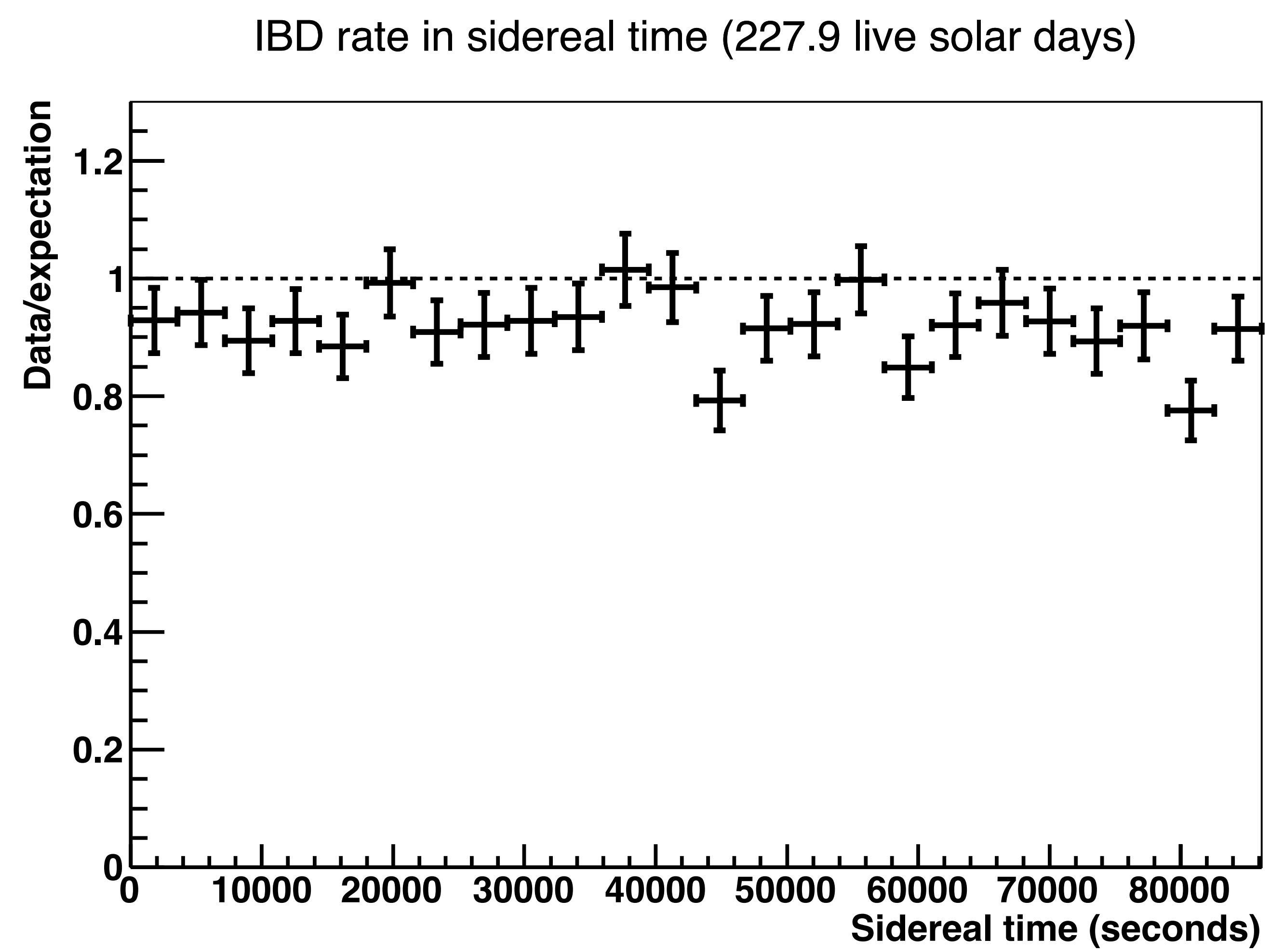
An example of a sidereal dependence
of oscillation probability



Rate and time

We search for a sidereal modulation among the 8249 electron antineutrino candidates





$$\mathrm{IBD} = \overline{\nu}_e p \rightarrow e^+ n$$

What to fit?

The Standard Model Extension (SME) is a framework for all possible types of Lorentz violation and separates the different experimental effects that may be seen.

The full SME equation for electron antineutrino disappearance:

Kostelecký & Mewes, PRD **69**, 016005 (2004)
Kostelecký & Mewes, PRD **85**, 096005 (2012)

$$
\begin{aligned}
P_{\bar{\nu}_e\to\bar{\nu}_e} &\simeq 1 - P_{\bar{\nu}_e\to\bar{\nu}_\mu} - P_{\bar{\nu}_e\to\bar{\nu}_\tau} \\
&= 1 - \frac{|(h_{\rm eff})_{\bar{e}\bar{\mu}}|^2 L^2}{(\hbar c)^2} - \frac{|(h_{\rm eff})_{\bar{e}\bar{\tau}}|^2 L^2}{(\hbar c)^2} \\
&= 1 - \frac{L^2}{(\hbar c)^2}\big[\,|\,(\mathcal{C})_{\bar{e}\bar{\mu}} + (\mathcal{A}_s)_{\bar{e}\bar{\mu}} \sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\mu}} \cos\omega_\oplus T_\oplus \\
&\quad + (\mathcal{B}_s)_{\bar{e}\bar{\mu}} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\bar{e}\bar{\mu}} \cos 2\omega_\oplus T_\oplus\,|^2 \\
&\quad - |\,(\mathcal{C})_{\bar{e}\bar{\tau}} + (\mathcal{A}_s)_{\bar{e}\bar{\tau}} \sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\tau}} \cos\omega_\oplus T_\oplus \\
&\quad + (\mathcal{B}_s)_{\bar{e}\bar{\tau}} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\bar{e}\bar{\tau}} \cos 2\omega_\oplus T_\oplus\,|^2\,\big]
\end{aligned}
$$

contains 28 SME coefficients

10 params.

We perform the following fits:

Assume e-μ terms are zero:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2}[\,|\,(\mathcal{C})_{\bar{e}\bar{\tau}} + (\mathcal{A}_s)_{\bar{e}\bar{\tau}} \sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\tau}} \cos\omega_\oplus T_\oplus + (\mathcal{B}_s)_{\bar{e}\bar{\tau}} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\bar{e}\bar{\tau}} \cos 2\omega_\oplus T_\oplus\,|^2\,]$$

5 params.

Assume e-τ terms are zero:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2}[|(\mathcal{C})_{\bar{e}\bar{\mu}} + (\mathcal{A}_s)_{\bar{e}\bar{\mu}} \sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\mu}} \cos\omega_\oplus T_\oplus|^2]$$

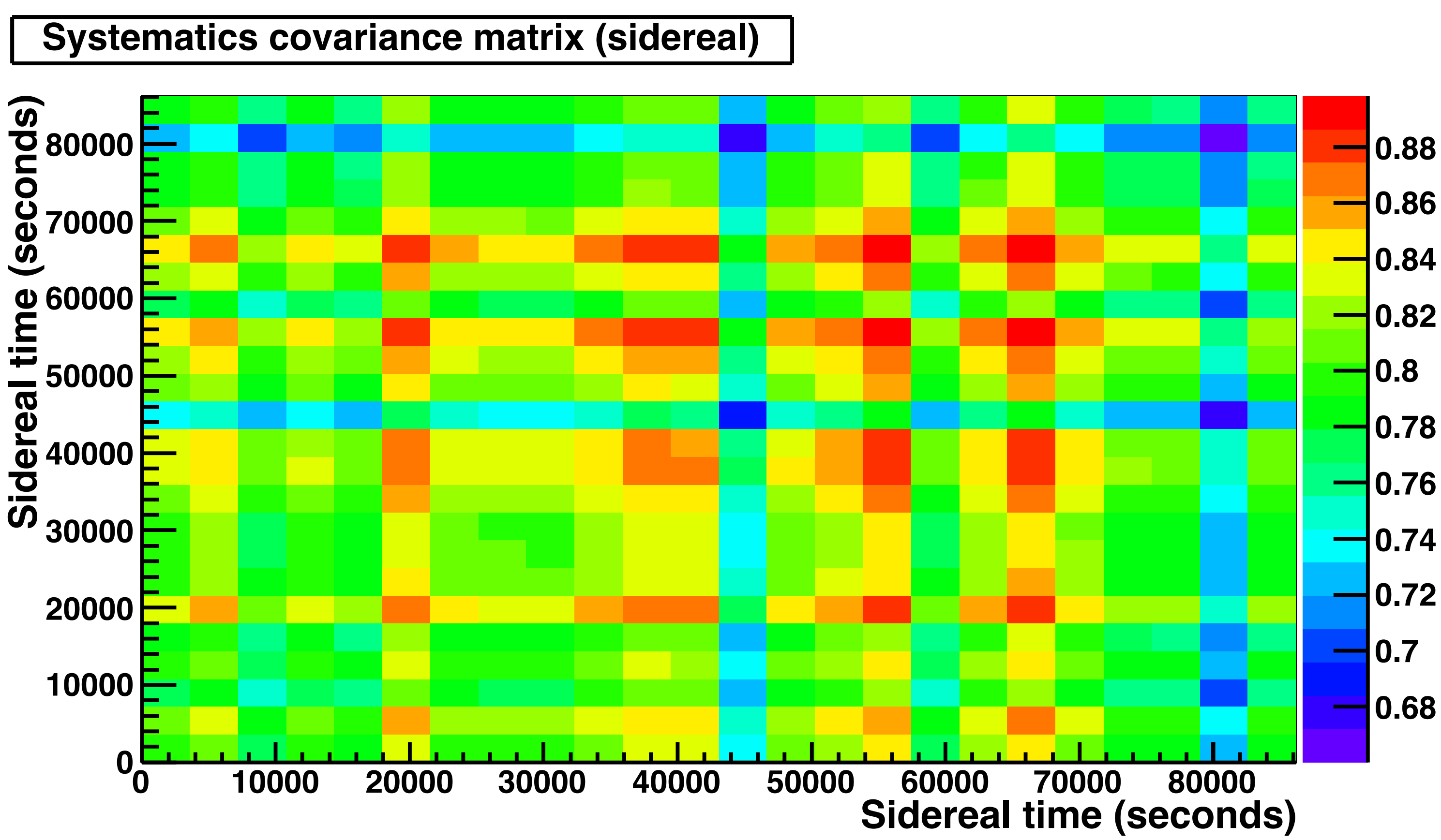
3 params.

Fit technique

- We use a least squares fitting technique to extract the best fit parameters.

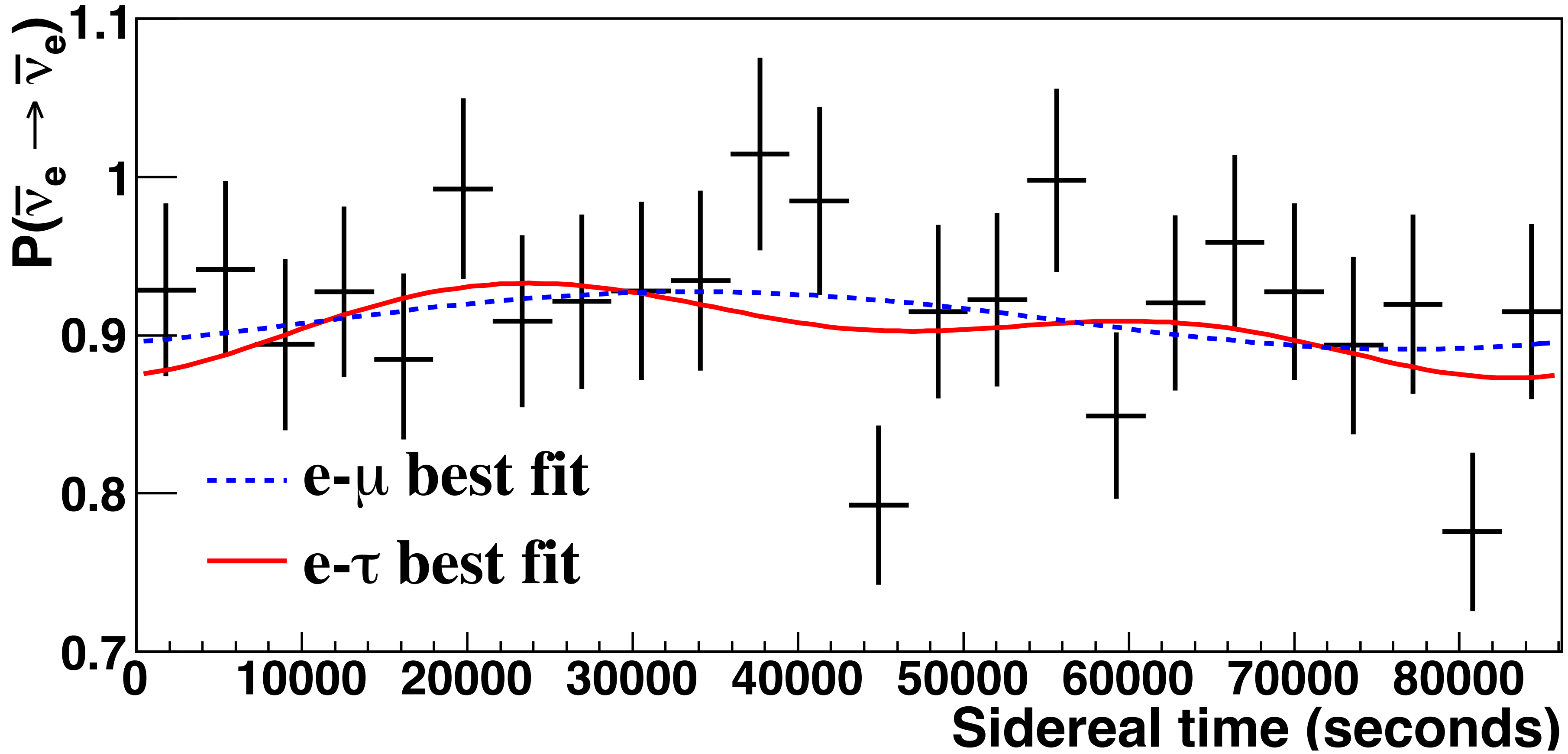
$$X^2 = \sum_{ij}^{N} [r_{i,data} - P_{\bar{\nu}_e \to \bar{\nu}_e}(t, SME) \cdot r_{i,MC}] \cdot M_{ij}^{-1} [r_{j,data} - P_{\bar{\nu}_e \to \bar{\nu}_e}(t, SME) \cdot r_{j,MC}]$$

full covariance matrix



Source	Variance wrt data
Stats.	1.10%
MC correction	1.01%
Background	1.69%
Reactor+detector	1.75%
Total	2.85%

Best fit results



$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2}[|(\mathcal{C})_{\bar{e}\bar{\mu}} + (\mathcal{A}_s)_{\bar{e}\bar{\mu}} \sin \omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\mu}} \cos \omega_\oplus T_\oplus|^2]$$

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2}[\,|\,(\mathcal{C})_{\bar{e}\bar{\tau}} + (\mathcal{A}_s)_{\bar{e}\bar{\tau}} \sin \omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\tau}} \cos \omega_\oplus T_\oplus$$
$$+ (\mathcal{B}_s)_{\bar{e}\bar{\tau}} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\bar{e}\bar{\tau}} \cos 2\omega_\oplus T_\oplus\,|^2\,]$$

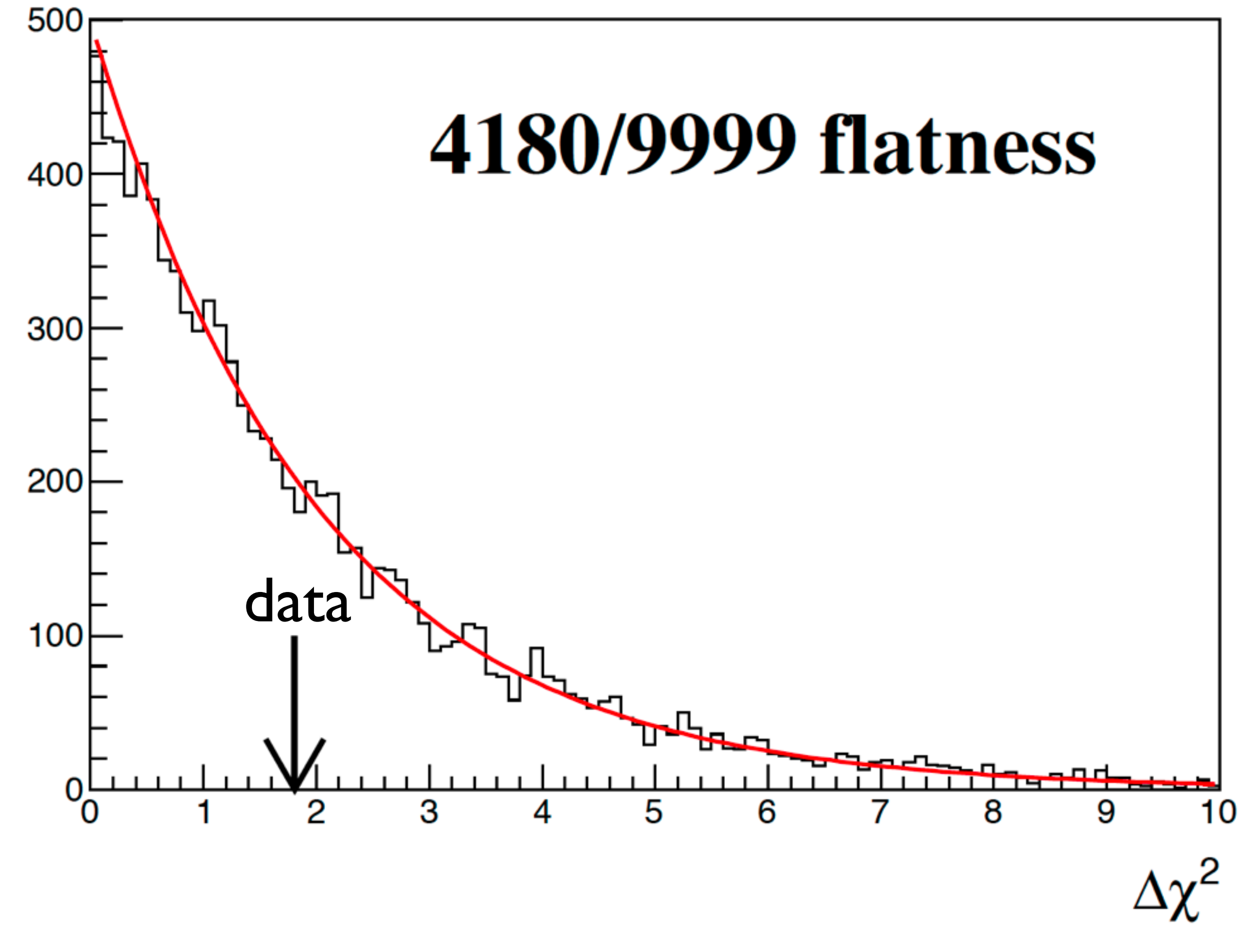
Is oscillation probability independent of time?

A frequentist study is used to determine the significance of the results

$\Delta\chi^2 = \chi^2$ (1 parameter fit) – χ^2 (3 parameter fit)

Sidereal time independent　　Sidereal time dependent

Fake data Δchi^2 distribution



Data Δchi^2 is in the middle of the fake data Δchi^2 distribution.
In other words, the data is consistent with a flat hypothesis.

No Lorentz violation is seen!

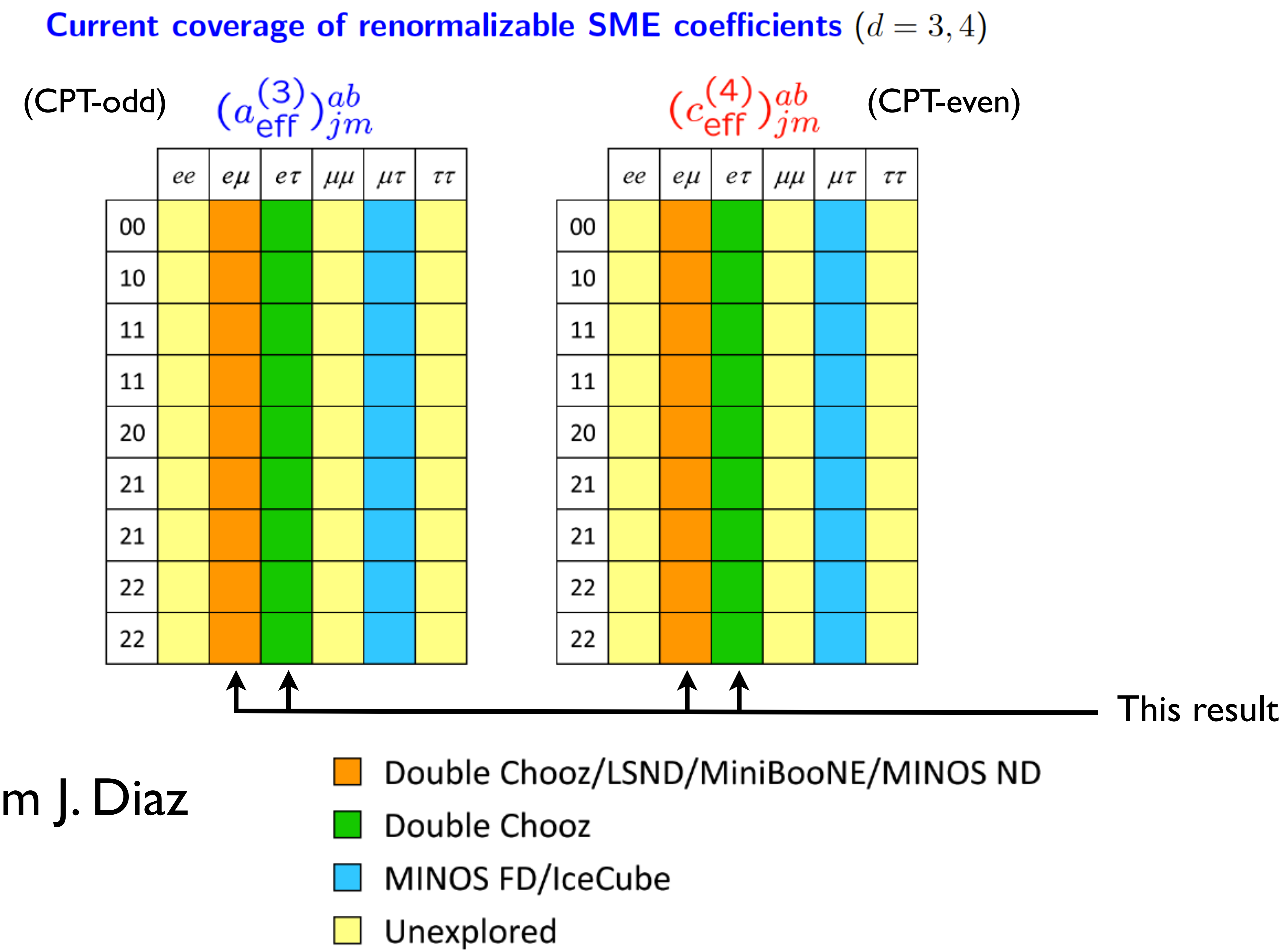
Limits on SME coefficients

With no sidereal time dependence apparent, we proceed to set limits on the relevant SME coefficients

2σ limits

SME coefficients	$e-\tau$ fit	$e-\mu$ fit
$\mathrm{Re}(a_L)^T$ or $\mathrm{Im}(a_L)^T$	7.8×10^{-20} GeV	—
$\mathrm{Re}(a_L)^X$ or $\mathrm{Im}(a_L)^X$	4.4×10^{-20} GeV	1.6×10^{-21} GeV
$\mathrm{Re}(a_L)^Y$ or $\mathrm{Im}(a_L)^Y$	9.0×10^{-20} GeV	6.1×10^{-20} GeV
$\mathrm{Re}(a_L)^Z$ or $\mathrm{Im}(a_L)^Z$	2.7×10^{-19} GeV	—
$\mathrm{Re}(c_L)^{XY}$ or $\mathrm{Im}(c_L)^{XY}$	3.4×10^{-18}	—
$\mathrm{Re}(c_L)^{XZ}$ or $\mathrm{Im}(c_L)^{XZ}$	1.8×10^{-17}	—
$\mathrm{Re}(c_L)^{YZ}$ or $\mathrm{Im}(c_L)^{YZ}$	3.8×10^{-17}	—
$\mathrm{Re}(c_L)^{XX}$ or $\mathrm{Im}(c_L)^{XX}$	3.9×10^{-17}	—
$\mathrm{Re}(c_L)^{YY}$ or $\mathrm{Im}(c_L)^{YY}$	3.9×10^{-17}	—
$\mathrm{Re}(c_L)^{ZZ}$ or $\mathrm{Im}(c_L)^{ZZ}$	4.9×10^{-17}	—
$\mathrm{Re}(c_L)^{TT}$ or $\mathrm{Im}(c_L)^{TT}$	1.3×10^{-17}	—
$\mathrm{Re}(c_L)^{TX}$ or $\mathrm{Im}(c_L)^{TX}$	5.2×10^{-18}	—
$\mathrm{Re}(c_L)^{TY}$ or $\mathrm{Im}(c_L)^{TY}$	1.1×10^{-17}	—
$\mathrm{Re}(c_L)^{TZ}$ or $\mathrm{Im}(c_L)^{TZ}$	3.2×10^{-17}	—

Neutrino coverage of LV



From J. Diaz

Physics statements

Phys. Rev. D 86 112009 (2012)

- Double Chooz's second publication disappearance result by itself rules out a number of alternative oscillation models motivated by Lorentz violation.
- Double Chooz finds no evidence of Lorentz violation. We set the first limits on fourteen of the SME coefficients associated with e-tau transitions and set two competitive limits on coefficients associated with e-mu transitions.

NEW!

A search for neutrino-antineutrino oscillations

(work with J. Diaz, T. Katori, and J. Conrad)

arXiv:1307.5789 [hep-ex] (2013), Submitted to Phys. Lett. B

- Lorentz violation can lead to the coupling of neutrinos and antineutrinos.
- Neutrino-antineutrino mixing would lead to enhanced disappearance as well as an unconventional energy dependence of the events.

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = P^{(0)}_{\bar{\nu}_e \to \bar{\nu}_e} - P^{(2)}_{\bar{\nu}_e \to \nu_x}$$

$$1 - \sin^2 2\theta_{13} \sin^2(1.267\Delta m^2_{\rm atm} L/E)$$

(conventional mass-based oscillations)

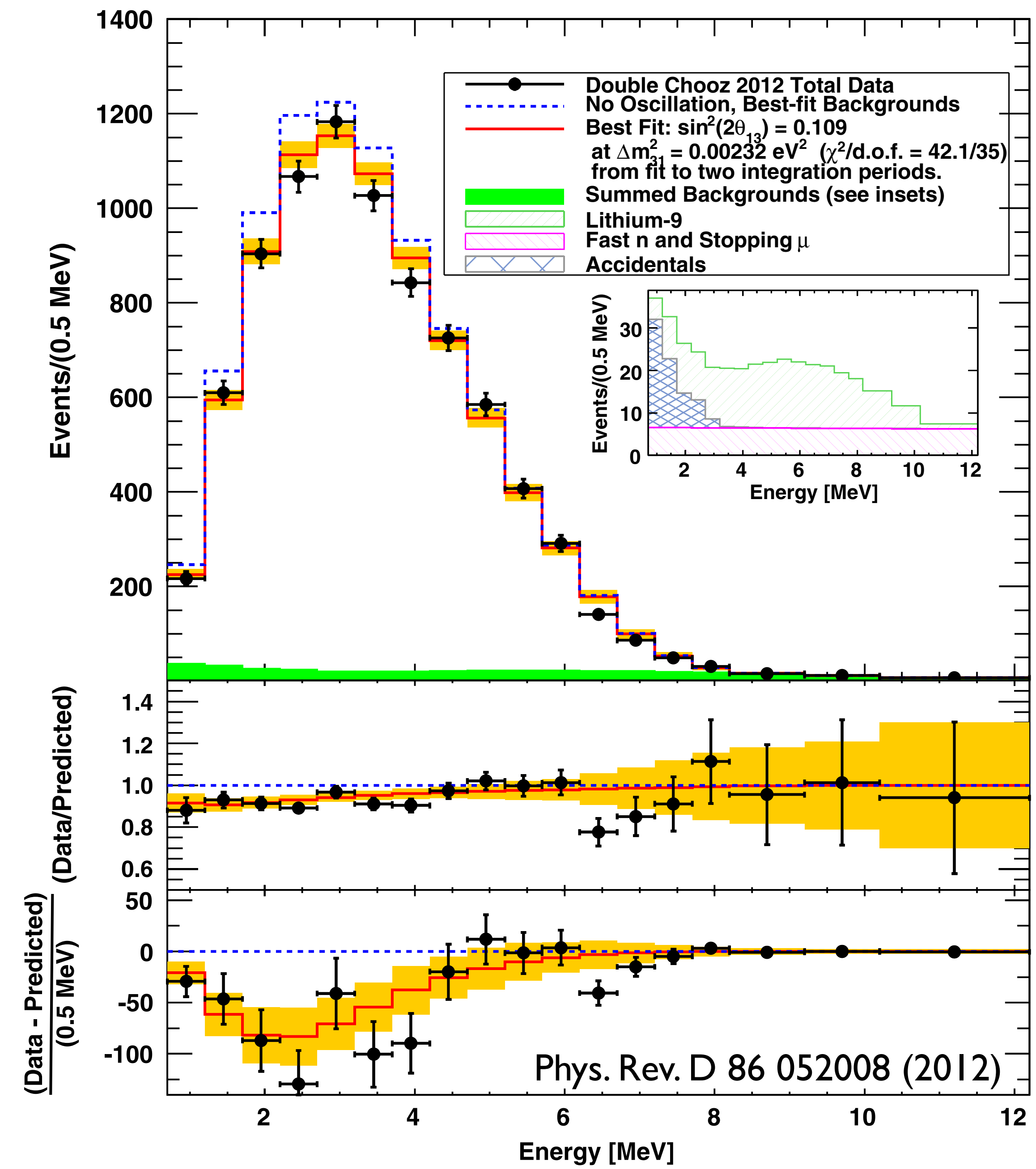
has terms containing E and E^2

Double Chooz spectral info

- We explore the possibility that the observed reactor antineutrino disappearance in Double Chooz may have two components: mass-based oscillations and neutrino-antineutrino oscillations due to Lorentz violation.

- Double Chooz has provided a public data release which includes energy spectra data, prediction, and background(s). Covariance matrices and software to analyze the information are also given.

http://doublechooz.in2p3.fr/Scientific/Data_release



What to fit?

$$P^{(2)}_{\bar{\nu}_e\to\nu_x} = L^2 \left| \sum_{c=e,\mu\tau} \sum_{\bar{d}=\bar{e},\bar{\mu}\bar{\tau}} (\mathcal{M}^{(1)}_{x\bar{e}})_{c\bar{d}} \; \delta h_{c\bar{d}} \right|^2$$

factors depend on conventional oscillation parameters as well as experimental parameters including location, orientation, baseline, and energy

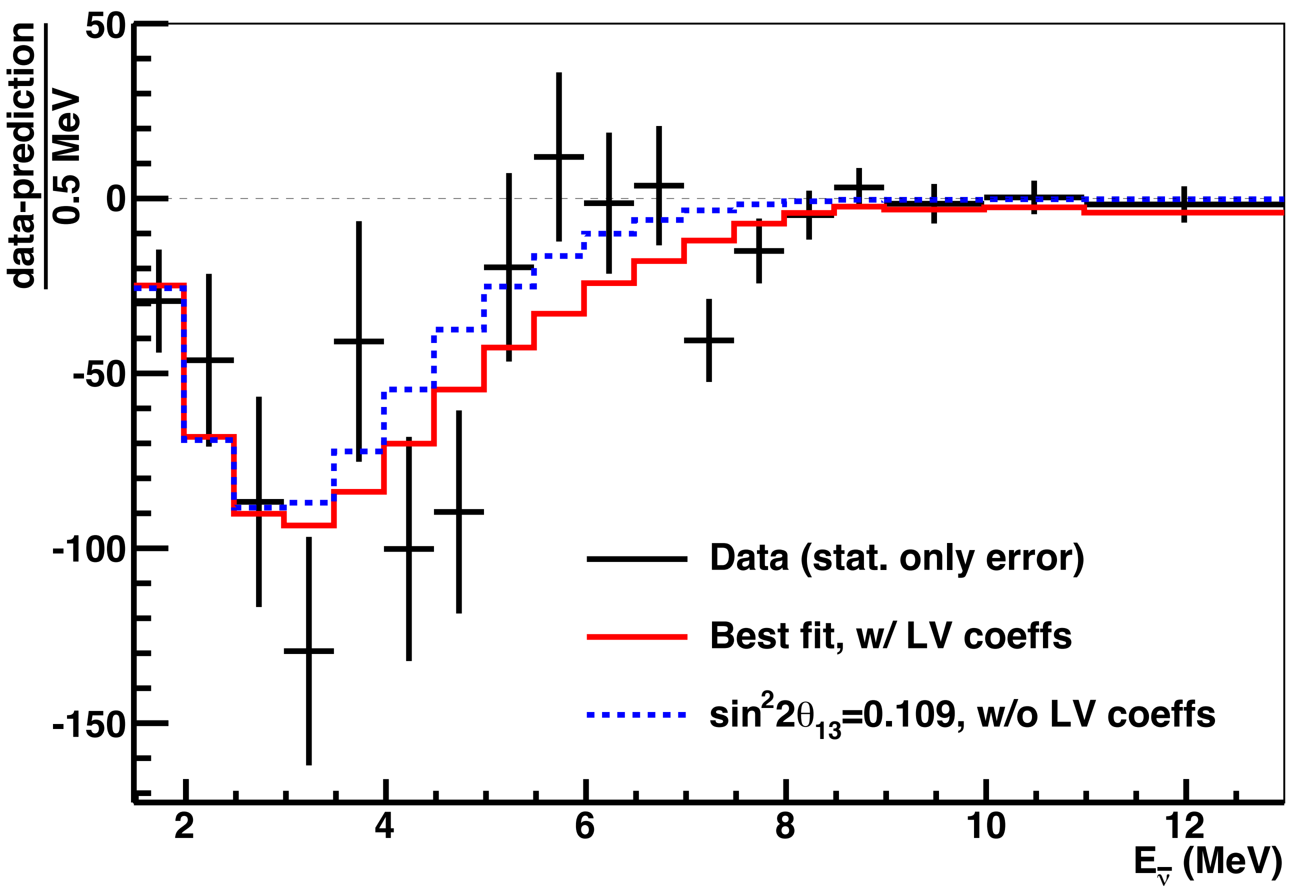
encodes the coefficients controlling Lorentz Violation; parameterized as:

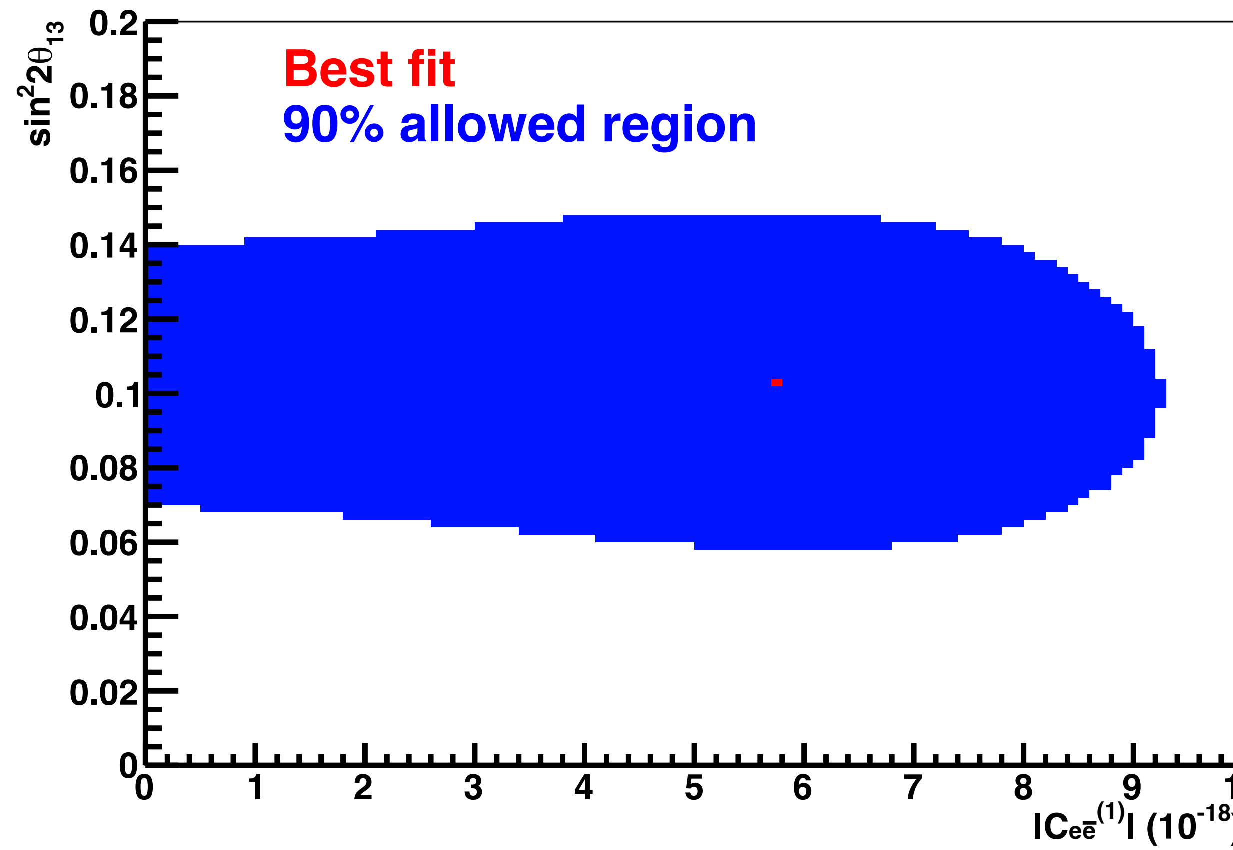
$$\delta h_{c\bar{d}} = \mathrm{C}^{(0)}_{c\bar{d}} + \mathrm{C}^{(1)}_{c\bar{d}} E$$

A fit to the energy spectrum can potentially distinguish between L/E (mass-based) oscillations and (LV) oscillations that grow with E^2.

The fit

- The technique is basically identical to the sidereal-time one. We employ a least squares fitting technique for comparing the Monte Carlo prediction plus background expectation and the data and extracting the best fit parameters.
- After minimization, a confidence region map is formed and then checked with a frequentist study.
- Six different fits are performed, for each of the $c\bar{d}$ terms.





Results

- We find no evidence for Lorentz violating neutrino-antineutrino oscillations.
- We set limits on 15 previously unexplored SME coefficients.
- This work completes the coverage of operators in the minimal SME producing neutrino-antineutrino mixing.

–	$\lvert\widetilde{g}^{ZT}_{e\bar{e}}\rvert < 9.7 \times 10^{-18}$	$\lvert\widetilde{g}^{ZZ}_{e\bar{e}}\rvert < 3.3 \times 10^{-17}$
–	$\lvert\widetilde{g}^{ZT}_{\mu\bar{\mu}}\rvert < 2.3 \times 10^{-16}$	$\lvert\widetilde{g}^{ZZ}_{\mu\bar{\mu}}\rvert < 8.1 \times 10^{-16}$
–	$\lvert\widetilde{g}^{ZT}_{\tau\bar{\tau}}\rvert < 2.3 \times 10^{-16}$	$\lvert\widetilde{g}^{ZZ}_{\tau\bar{\tau}}\rvert < 8.1 \times 10^{-16}$
$\lvert\widetilde{H}^{Z}_{e\bar{\mu}}\rvert < 1.4 \times 10^{-19}$	$\lvert\widetilde{g}^{ZT}_{e\bar{\mu}}\rvert < 2.7 \times 10^{-17}$	$\lvert\widetilde{g}^{ZZ}_{e\bar{\mu}}\rvert < 9.3 \times 10^{-17}$
$\lvert\widetilde{H}^{Z}_{e\bar{\tau}}\rvert < 1.4 \times 10^{-19}$	$\lvert\widetilde{g}^{ZT}_{e\bar{\tau}}\rvert < 2.7 \times 10^{-17}$	$\lvert\widetilde{g}^{ZZ}_{e\bar{\tau}}\rvert < 9.3 \times 10^{-17}$
$\lvert\widetilde{H}^{Z}_{\mu\bar{\tau}}\rvert < 1.7 \times 10^{-18}$	$\lvert\widetilde{g}^{ZT}_{\mu\bar{\tau}}\rvert < 4.4 \times 10^{-16}$	$\lvert\widetilde{g}^{ZZ}_{\mu\bar{\tau}}\rvert < 1.5 \times 10^{-15}$

Limits at 90% C.L. for the 15 independent SME coefficients that produce neutrino-antineutrino oscillations. The coefficients for CPT-conserving Lorentz violation $\widetilde{H}^{Z}_{c\bar{d}}$ are given in units of GeV and the coefficients for CPT-violating Lorentz violation $\widetilde{g}^{\alpha\beta}_{c\bar{d}}$ are dimensionless.

Last words

- As a community, we have lots of neutrinos and antineutrinos in the book. Let's spend some (perhaps small) fraction of our time (thoroughly) looking for the unexpected.
- Maybe our ~~proton decay~~ θ_{13} experiment(s) will discover ~~neutrino oscillations~~ Lorentz violation. ~~Supernova~~ Sterile neutrinos wouldn't be so bad either.

Double Chooz

Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC
ULB/VUB

Germany
EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München
U. Hamburg

Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst Tech.

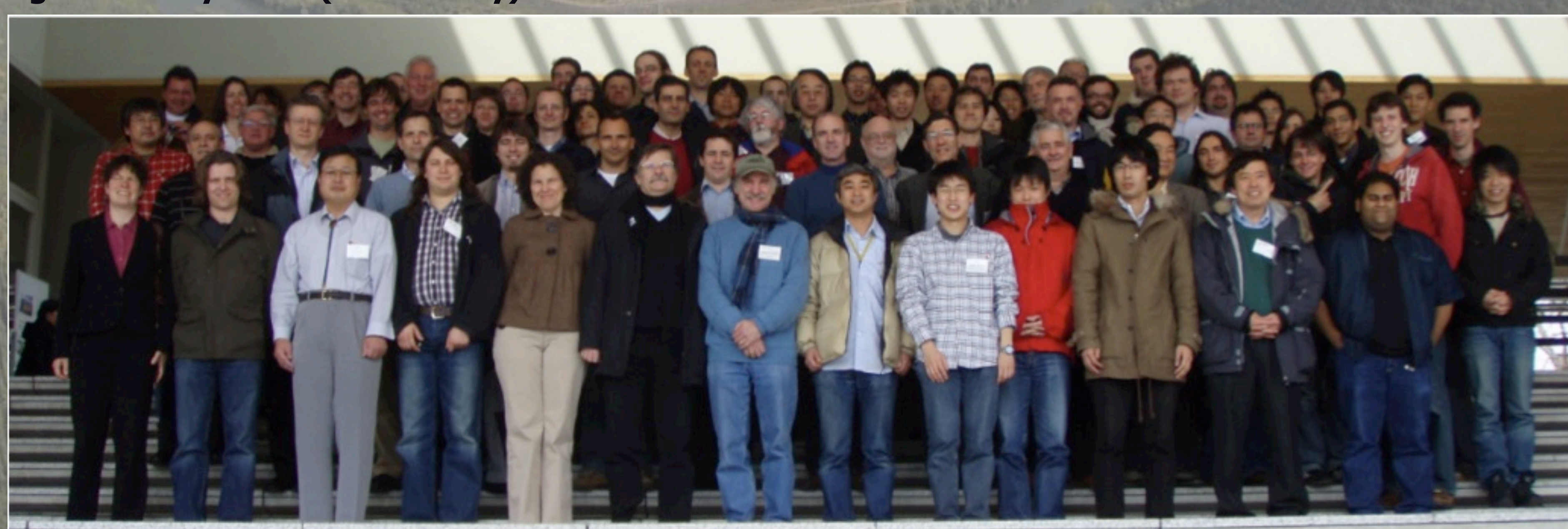
Russia
INR RAS
IPC RAS
RRC Kurchatov

Spain
CIEMAT-Madrid

USA
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
Kansas State
LLNL
MIT
U. Notre Dame
Sandia National Laboratories
U. Tennessee

Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.org/



θ_{13} and Lorentz violation

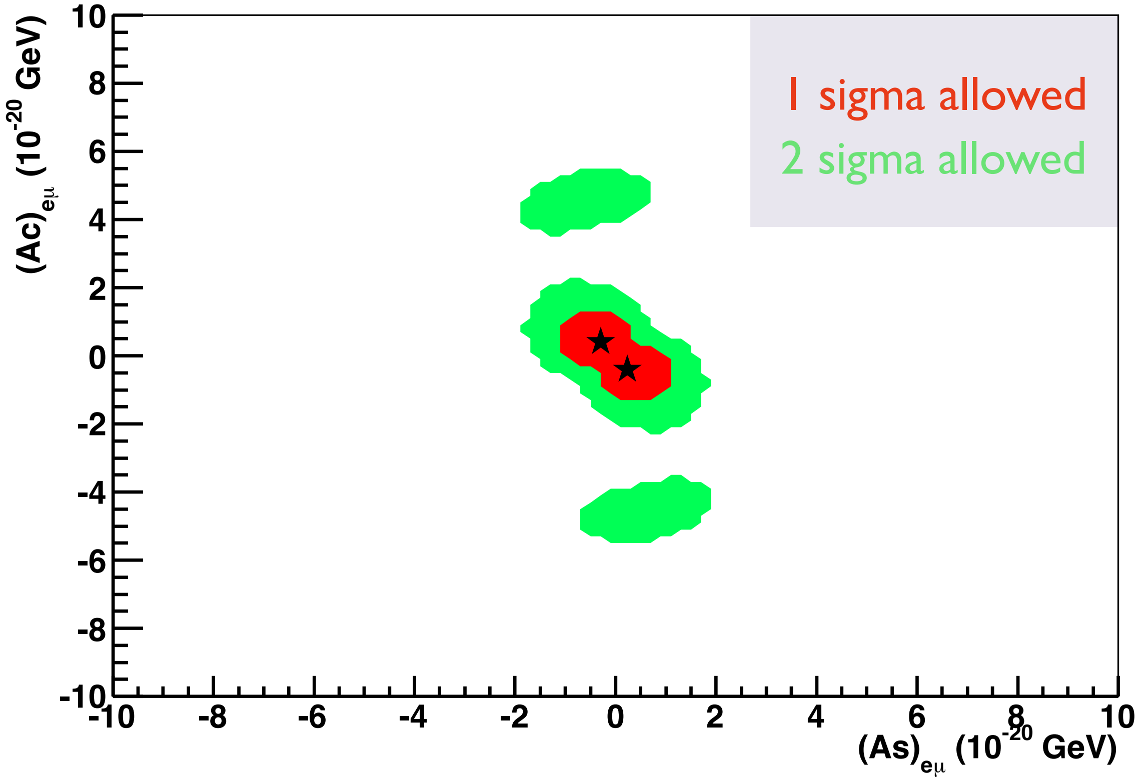
All measured time dependent parameters are consistent with zero.
However, the time independent parameter is non-zero at 2.1 sigma.

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2}\left((\mathcal{C})^2_{\bar{e}\bar{\tau}} + (\mathcal{C})^2_{\bar{e}\bar{\mu}}\right)$$

A normalization-only fit finds $(\mathcal{C})^2_{\bar{e}\bar{\tau}} + (\mathcal{C})^2_{\bar{e}\bar{\mu}} = 34.2 \pm 9.2$

Generally we interpret the sidereal time independent disappearance observed (consistent with the Double Chooz second publication) as due to θ_{13} in the 3 flavor neutrino oscillation framework rather than LV.

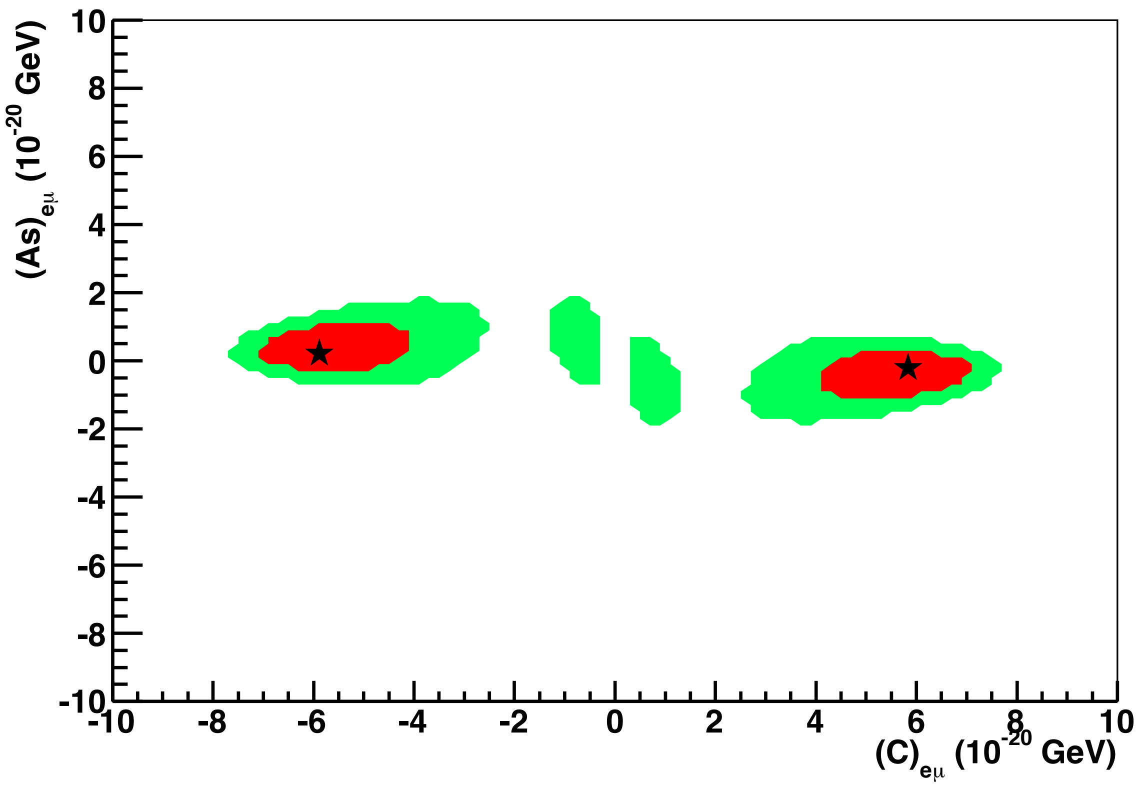
Three parameter fit

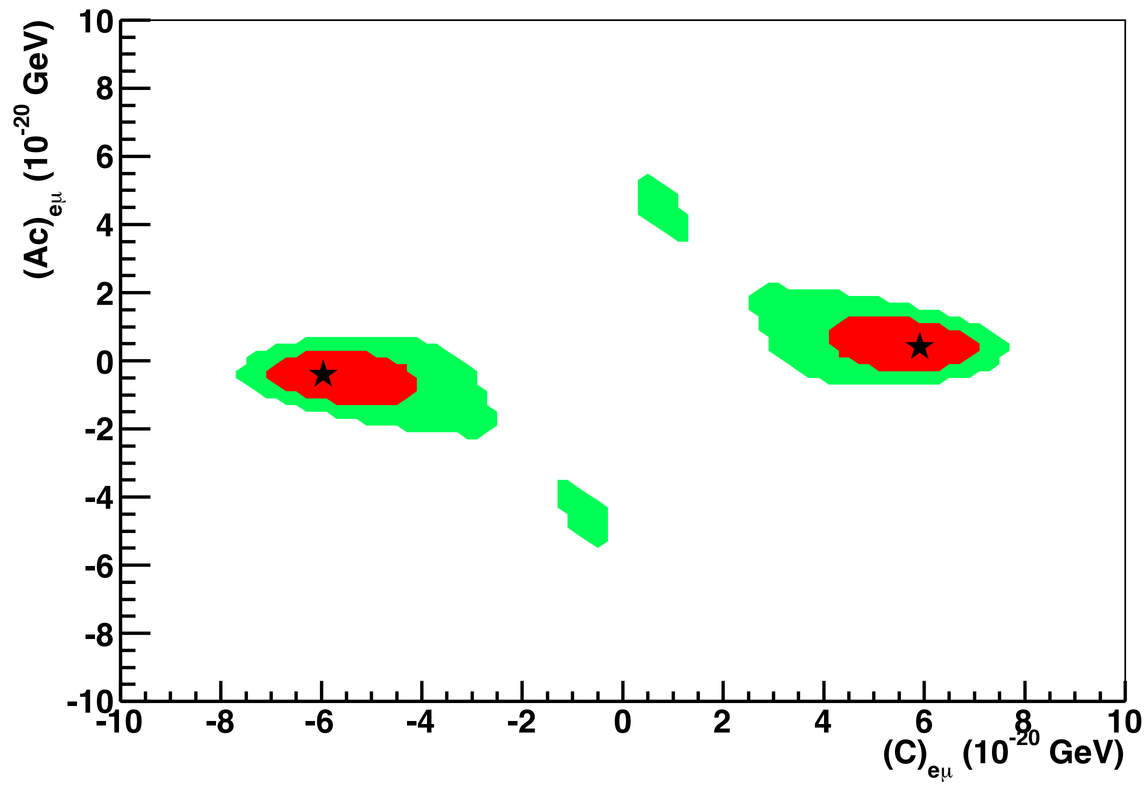


$$P_{\bar{\nu}_e\to\bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2}[|(\mathcal{C})_{\bar{e}\bar{\mu}} + (\mathcal{A}_s)_{\bar{e}\bar{\mu}}\sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\mu}}\cos\omega_\oplus T_\oplus|^2]$$

The time dependent parameters are consistent with zero.

The time independent parameter is non-zero at 2.1 sigma.





Rate and (solar) time