Superluminal neutrinos in long baseline experiments and SN1987a

Luca Panizzi

IPN Lyon

G. Cacciapaglia, A. Deandrea, LP, arXiv: 1109.4980

Outline

1. Lorentz violation and the neutrino sector
2. Power Law Lorentz Violation
   - Bounds from Supernova 1987a
   - Bounds from MINOS and OPERA
3. Alternative LV parametrisations

Outline

1. Lorentz violation and the neutrino sector
2. Power Law Lorentz Violation
   - Bounds from Supernova 1987a
   - Bounds from MINOS and OPERA
3. Alternative LV parametrisations

Lorentz invariance

Physical laws must not change when passing from a reference frame to another through Lorentz transformations

The poles of the propagator give us the LI dispersion relation

$$p^2 = E^2 - \vec{p}^2 = m^2$$

The velocity law is:

$$\vec{v} = \frac{\partial E}{\partial \vec{p}} = \frac{\vec{p}}{\sqrt{m^2 + \vec{p}^2}} \simeq \frac{\vec{p}}{|\vec{p}|}\left(1 - \frac{m^2}{2\vec{p}^2}\right)$$

and saturates at the speed of light when $|\vec{p}| \gg m$

Stringent bounds on LV operators coming from experiments on

photons, electrons or nucleons

(non-zero deviations of Lorentz symmetry at weak confidence levels)

V. A. Kostelecky, N. Russell, Rev. Mod. Phys. **83** (2011) 11

Neutrinos and Lorentz violation

OPERA

T. Adam *et al.* [OPERA Collaboration], [arXiv:1109.4897 [hep-ex]].

$$\delta_t = -60.7 \pm 6.9(\text{stat}) \pm 7.4(\text{sys})\ \text{ns} \quad 68\%\ \text{C.L.}$$

corresponding to: $\beta_\nu - 1 = (2.48 \pm 0.41) \times 10^{-5}$ 68% C.L., consistent with c at 6σ

No energy dependence in the effect

MINOS

P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. D **76** (2007) 072005.

$$\delta_t = -126 \pm 32(\text{stat}) \pm 64(\text{sys})\ \text{ns} \quad 68\%\ \text{C.L.}$$

corresponding to: $\beta_\nu - 1 = (5.1 \pm 3.9) \times 10^{-5}$ 68% C.L., consistent with c at $< 1.8\sigma$

No energy dependence in the effect

- Stringent bound from high energy ν ($< E_\nu > \sim 80$ GeV) at Fermilab

  $|\beta_\nu - 1| < 4 \times 10^{-5}$ G. R. Kalbfleisch *et al.*, Phys. Rev. Lett. **43** (1979) 1361.

- Very stringent bounds from SN1987a

Is this real new physics?

Minos anomaly was at less than 2σ, but Opera results are at 6σ!

Neutrinos and Lorentz violation

- LVs are not (yet?!) described by a unique and well established theory

Neutrinos and Lorentz violation

- LVs are not (yet?!) described by a unique and well established theory
- nothing in principle forbids LVs to affect **only a class of particles**
  - $\rightarrow$ right-handed neutrinos are not charged under SM gauge groups
  - $\rightarrow$ nevertheless loop effects must be taken into account

Neutrinos and Lorentz violation

- LVs are not (yet?!) described by a unique and well established theory
- nothing in principle forbids LVs to affect **only a class of particles**

  $\rightarrow$ right-handed neutrinos are not charged under SM gauge groups
  $\rightarrow$ nevertheless loop effects must be taken into account

- properties of neutrinos known with limited accuracy:

  $\rightarrow$ no experimental evidence for right handed neutrinos
  $\rightarrow$ Dirac or Majorana particles?
  $\rightarrow$ mass hierarchies (normal, inverted, degenerate)
  $\rightarrow$ only upper bound on their masses (from tritium decay)

  they are suitable candidates for searches of **new physics**

Neutrinos and Lorentz violation

- LVs are not (yet?!) described by a unique and well established theory
- nothing in principle forbids LVs to affect **only a class of particles**

  $\rightarrow$ right-handed neutrinos are not charged under SM gauge groups
  $\rightarrow$ nevertheless loop effects must be taken into account

- properties of neutrinos known with limited accuracy:

  $\rightarrow$ no experimental evidence for right handed neutrinos
  $\rightarrow$ Dirac or Majorana particles?
  $\rightarrow$ mass hierarchies (normal, inverted, degenerate)
  $\rightarrow$ only upper bound on their masses (from tritium decay)

  they are suitable candidates for searches of **new physics**

- significant amount of **experimental data** on neutrinos already collected and hopefully even more will be added in the future

Neutrinos and Lorentz violation

- LVs are not (yet?!) described by a unique and well established theory
- nothing in principle forbids LVs to affect **only a class of particles**
  - $\rightarrow$ right-handed neutrinos are not charged under SM gauge groups
  - $\rightarrow$ nevertheless loop effects must be taken into account
- properties of neutrinos known with limited accuracy:
  - $\rightarrow$ no experimental evidence for right handed neutrinos
  - $\rightarrow$ Dirac or Majorana particles?
  - $\rightarrow$ mass hierarchies (normal, inverted, degenerate)
  - $\rightarrow$ only upper bound on their masses (from tritium decay)

  they are suitable candidates for searches of **new physics**
- significant amount of **experimental data** on neutrinos already collected and hopefully even more will be added in the future

A complete and careful analysis of Lorentz violation signatures in the neutrino sector is strongly motivated!

Lorentz violation

Modified dispersion relation

$$E^2 - \vec{p}^2 = m^2 \pm f_{LV}(E, \vec{p}^2, m, M)$$

LV effects may not derive from a Lagrangian description!

The modified velocity law becomes (at very high energies, when $E \sim |\vec{p}|$):

$$\vec{v} = \frac{\partial E}{\partial \vec{p}} = \frac{2\vec{p} \pm \partial f_{LV}/\partial \vec{p}}{2\sqrt{\vec{p}^2 + m^2 \pm f_{LV}}} \simeq \frac{\vec{p}}{|\vec{p}|}\left(1 - \frac{m^2}{2\vec{p}^2} \mp \frac{f_{LV}}{2\vec{p}^2} \pm \frac{\partial f_{LV}/\partial |\vec{p}|}{2|\vec{p}|}\right)$$

and the speed of light is not necessarily the upper bound!

Parametrising the LV term

Phenomenological approach

Any deviation from the usual velocity law can be parametrized as:

$$v = 1 - \frac{m^2}{2E^2} \pm \Delta_{LV}(E)$$

where Δ_{LV} is linked to the LV term in the dispersion relation as:

$$\Delta_{LV}(E) = \mp \frac{f_{LV}}{2E^2} \pm \frac{\partial f_{LV}/\partial E}{2E}$$

Power Law parametrisation

LV in the dispersion relation

$$E^2 - \vec{p}^2 \pm E^2 \left(\frac{E}{M}\right)^\alpha = m^2$$

Velocity of neutrinos

$$v \simeq 1 \pm \left(\frac{E}{2M}\right)^\alpha$$

New physics at scale M, but which value of α?

- α=1,2: operators of dimension 5 or 6 in the effective Lagrangian
  $\rightarrow$ **Quantum Gravity** inspired
- **more general** analysis with non-integer α
  ($\rightarrow$ it is possible to build a toy model inspired by **unparticles**)

Outline

1. Lorentz violation and the neutrino sector

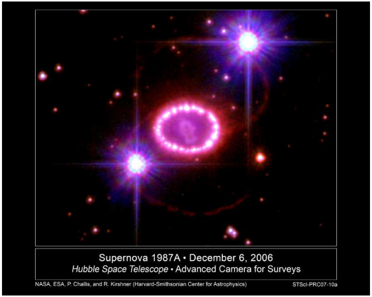
2. Power Law Lorentz Violation
   - Bounds from Supernova 1987a
   - Bounds from MINOS and OPERA

3. Alternative LV parametrisations

Outline

1. Lorentz violation and the neutrino sector
2. Power Law Lorentz Violation
   - Bounds from Supernova 1987a
   - Bounds from MINOS and OPERA
3. Alternative LV parametrisations

What we have seen



Distance of the SN

$51.33 \pm 1.2\ kpc$

Detected neutrinos

- Baksan: 5 events within $\sim$ 9 sec
- IMB: 8 events within $\sim$ 5 sec
- Kamiokande II: 16 events within $\sim$ 23 sec

Time gap between neutrinos and photons: $\delta t_{\gamma\nu} = 0 \pm 10\ h$

L. Stodolsky, Phys. Lett. **B201** (1988) 353

Three sets of data

Baksan

t_i (s)	E_i (MeV)	σ_i (MeV)
$\equiv 0.0$	12.0	2.4
0.435	17.9	3.6
1.710	23.5	4.7
7.687	17.6	3.5
9.099	20.3	4.1

IMB

t_i (s)	E_i (MeV)	σ_i (MeV)
$\equiv 0.0$	38	7
0.412	37	7
0.650	28	6
1.141	39	7
1.562	36	9
2.684	36	6
5.010	19	5
5.582	22	5

Kamiokande II

t_i (s)	E_i (MeV)	σ_i (MeV)
$\equiv 0.0$	20	2.9
0.107	13.5	3.2
0.303	7.5	2.0
0.324	9.2	2.7
0.507	12.8	2.9
0.686	6.3	1.7
1.541	35.4	8.0
1.728	21.0	4.2
1.915	19.8	3.2
9.219	8.6	2.7
10.433	13.0	2.6
12.439	8.9	1.9
17.641	6.5	1.6
20.257	5.4	1.4
21.355	4.6	1.3
23.814	6.5	1.6

Events with energies $E_i < 7.5$ MeV are discarded, being too close to the background peak

Further information:

- Relative arrival times not known $\Longrightarrow t \equiv 0$ for the first event in each data set
- Uncertainties on times negligible wrt uncertainties on energies
- Neutrinos detected through absorption process:

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \Longrightarrow \quad E_\nu = E_i + Q \quad \text{with} \quad Q = 1.29\ MeV$$

Neutrinos from SN

Different mechanisms (cooling models, accretion models, mixed mechanisms . . .)

Crucial parameters

- **Interval of time** during which neutrinos are emitted
  - prompt emission (ν emitted at the same time) — disfavoured by SN models
  - delayed emission (with interval $\delta t^{SN}_{\nu_i \nu_f}$) — favoured by SN models
- **Offset in time** between the emission of neutrinos and photons ($\delta t^{SN}_{\gamma\nu}$)

Neutrinos from SN

Different mechanisms (cooling models, accretion models, mixed mechanisms . . .)

Crucial parameters

- **Interval of time** during which neutrinos are emitted
  - prompt emission (ν emitted at the same time) — disfavoured by SN models
  - delayed emission (with interval $\delta t^{SN}_{\nu_i \nu_f}$) — favoured by SN models
- **Offset in time** between the emission of neutrinos and photons ($\delta t^{SN}_{\gamma\nu}$)

If LV is energy-dependent. . .

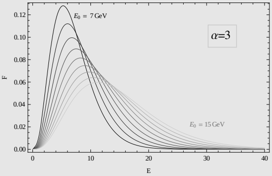
. . . we also need to parametrize the energy spectrum of emitted neutrinos:

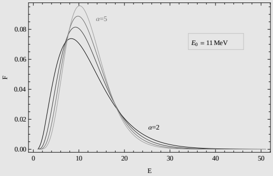
$$F \sim E^{\alpha_z} e^{-(1+\alpha_z)E/E_0}$$

C. Lunardini and A. Y. Smirnov, Astropart. Phys. **21** (2004) 703

Ranges for the parameters:

$$\begin{cases} 2 \lesssim \alpha_z \lesssim 5 \\ 7\ MeV \lesssim E_0 \lesssim 15\ MeV \end{cases}$$





Propagation of neutrinos

Lorentz-conserving hypothesis

Observables at detector

- **Shift** in time between photons and the first detected neutrinos:

$$\delta t_{\gamma\nu} = \delta t^{SN}_{\gamma\nu} + \frac{L}{c}\left(\frac{c}{v_{\nu_i}(m, E_i)} - 1\right)$$

For $m_\nu \sim 1eV$ and $E_{\nu_i} \sim 7MeV$: $\delta t_{\gamma\nu} \simeq \delta t^{SN}_{\gamma\nu} + 0.05sec$

- **Spread** in the arrival times of neutrinos:

$$\delta t_{\nu_i\nu_f} = \delta t^{SN}_{\nu_i\nu_f} + L\left(\frac{1}{v_{\nu_i}(m, E_i)} - \frac{1}{v_{\nu_f}(m, E_f)}\right)$$

For $m_\nu \sim 1eV$, $E_{\nu_i} \sim 7MeV$ and $E_{\nu_f} \sim 40MeV$: $\delta t_{\nu_i\nu_f} \simeq \delta t^{SN}_{\nu_i\nu_f} + 0.05sec$

Propagation of neutrinos

the effect of Lorentz violation

Observables **at the detector** receive a contribution from $\Delta_{LV}(E)$

- **Shift** in time between photons and the first detected neutrinos:

$$\delta t_{\gamma\nu} = \delta t^{SN}_{\gamma\nu} + \frac{L}{c}\left(\frac{c}{v_{\nu_i}(m, E_i, \Delta_{LV}(E_i))} - 1\right)$$

- **Spread** in the arrival times of neutrinos:

$$\delta t_{\nu_i \nu_f} = \delta t^{SN}_{\nu_i \nu_f} + L\left(\frac{1}{v_{\nu_i}(m, E_i, \Delta_{LV}(E_i))} - \frac{1}{v_{\nu_f}(m, E_f, \Delta_{LV}(E_f))}\right)$$

Propagation of neutrinos

the effect of Lorentz violation

Observables **at the detector** receive a contribution from $\Delta_{LV}(E)$

- **Shift** in time between photons and the first detected neutrinos:

$$\delta t_{\gamma\nu} = \delta t^{SN}_{\gamma\nu} + \frac{L}{c}\left(\frac{c}{v_{\nu_i}(m, E_i, \Delta_{LV}(E_i))} - 1\right)$$

- **Spread** in the arrival times of neutrinos:

$$\delta t_{\nu_i\nu_f} = \delta t^{SN}_{\nu_i\nu_f} + L\left(\frac{1}{v_{\nu_i}(m, E_i, \Delta_{LV}(E_i))} - \frac{1}{v_{\nu_f}(m, E_f, \Delta_{LV}(E_f))}\right)$$

Possible sources of confusion

- Gravity-induced velocity modification (assumed to be negligible)
- Interaction with dark matter

mean free path: $r = \frac{1}{n_{DM}\sigma_{\nu,DM}} \rightsquigarrow \begin{cases} n_{DM} \sim 3\times 10^{-3} cm^{-3} \\ \sigma_{\nu,DM} \sim 10^{-7} pb \end{cases} \Longrightarrow r \sim 10^{46} cm$

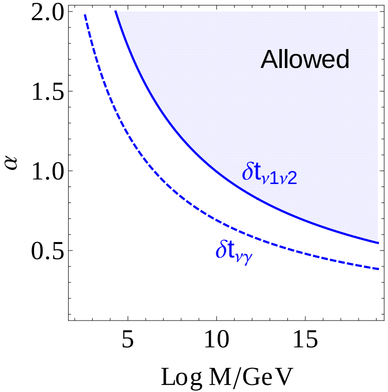
to be compared with the distance of SN 1987a: $L \sim 10^{23} cm$

Bounds on LV parameters

Propagation of **2 sample neutrinos** with energies: $E_{\nu_1} = 7MeV$, $E_{\nu_2} = 40MeV$ emitted at the same time

Conditions to satisfy at the detector

- Shift in time neutrinos-photons: $|\delta t_{\gamma\nu}| < 10$ h
- Spread of the neutrino bunch: $|\delta t_{\nu_1\nu_2}| < 10$ sec



The strongest bound is given by the **time spread** between neutrinos with different energies in the whole range of α and M parameters.

How robust are these estimates?

Numerical simulation to check

An accurate simulation needs just three inputs:

- **recorded data** (with uncertainties)
- assumption on the **energy spectrum** of the neutrinos (which depends very mildly on its parameters)
- **expected number** of neutrinos at detector

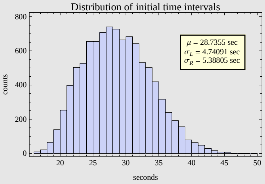
It is not necessary to know the production mechanism
Consistency checks with common SN models can be performed *a posteriori*!

Simulation steps

1. generation of N neutrino bunches at detector. For each bunch:
   - the **number** and **detection times** of neutrinos is the same as those detected
   - the **energies** follow a gaussian distribution around the detected value

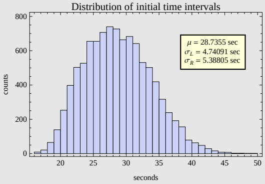
Simulation steps

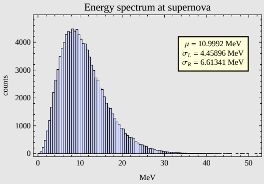
1. generation of N neutrino bunches at detector. For each bunch:
   - the **number** and **detection times** of neutrinos is the same as those detected
   - the **energies** follow a gaussian distribution around the detected value
2. the bunches are evolved backward in time up to the SN source with the LV dispersion relation $\Longrightarrow$ distribution of **initial time dispersions**



Simulation steps

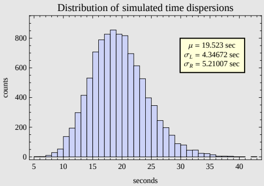
1. generation of N neutrino bunches at detector. For each bunch:
   - the **number** and **detection times** of neutrinos is the same as those detected
   - the **energies** follow a gaussian distribution around the detected value
2. the bunches are evolved backward in time up to the SN source with the LV dispersion relation $\Longrightarrow$ distribution of **initial time dispersions**
3. generation of N neutrino bunches at the SN source. For each bunch:
   - the **number** of neutrinos can be either the same as those detected (**fixed number**) or varying according to a Poisson distribution centered at a certain value n (**varying number**)
   - the **time dispersions** are taken randomly following the distribution obtained in step 2
   - the **energies** are distributed following the assumption on the energy spectrum

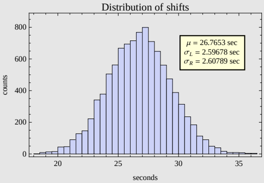




Simulation steps

1. generation of N neutrino bunches at detector. For each bunch:
   - the **number** and **detection times** of neutrinos is the same as those detected
   - the **energies** follow a gaussian distribution around the detected value
2. the bunches are evolved backward in time up to the SN source with the LV dispersion relation $\Longrightarrow$ distribution of **initial time dispersions**
3. generation of N neutrino bunches at the SN source. For each bunch:
   - the **number** of neutrinos can be either the same as those detected (**fixed number**) or varying according to a Poisson distribution centered at a certain value n (**varying number**)
   - the **time dispersions** are taken randomly following the distribution obtained in step 2
   - the **energies** are distributed following the assumption on the energy spectrum
4. the bunches are evolved forward $\Longrightarrow$ distribution of **time dispersions at detector** and **time shifts wrt photons** characterized by **statistical averages** and (in general asymmetric) **standard deviations**.





Analysis of simulation results

Simulation details

- Number of simulated bunches: $N = 10^4$
- Parameters for energy spectrum: $E_0 = 11MeV,\ \alpha_z = 3$

$$F \sim E^3 e^{-\frac{4}{11}E}$$

- Expected neutrinos for Varying Number hypothesis: $n = 10$

Analysis of simulation results

Simulation details

- Number of simulated bunches: $N = 10^4$
- Parameters for energy spectrum: $E_0 = 11 MeV, \ \alpha_z = 3$

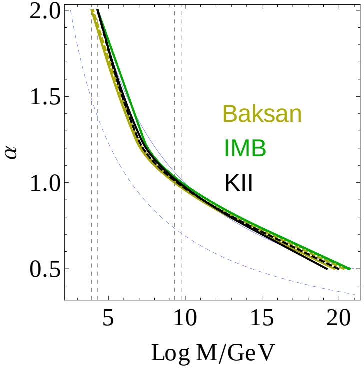
$$F \sim E^3 e^{-\frac{4}{11}E}$$

- Expected neutrinos for Varying Number hypothesis: $n = 10$

Bounds on LV parameters can be obtained from the simulation requiring:

- Shift between neutrinos and photons at detector: $|\delta t_{\gamma\nu}| < 10h$
- The detected time dispersion $\delta t_{\nu_i \nu_f}$ must be in the interval $(\delta t^{\text{sim}}_{\nu_i \nu_f})^{+2\sigma_R}_{-2\sigma_L}$
- (Consistency with SN models $\Longrightarrow$ Initial time dispersion $O(10 sec)$)

Numerical results



Bounds for preferred α values in Quantum Gravity scenarios

$$\alpha = 1 \quad \Longrightarrow \quad M > (2 \div 6) \times 10^9 \; GeV$$
$$\alpha = 2 \quad \Longrightarrow \quad M > (0.8 \div 2) \times 10^4 \; GeV$$

Outline

1. Lorentz violation and the neutrino sector
2. Power Law Lorentz Violation
   - Bounds from Supernova 1987a
   - Bounds from MINOS and OPERA
3. Alternative LV parametrisations

Long baseline experiments vs. SN

Three basic differences between SN and MINOS/OPERA neutrinos

1. **Distance** between source and detector:

$$\left.\begin{array}{lcl} L^{SN} & = & 51.33 \pm 1.2\ kpc \\ L^{MINOS} \sim L^{OPERA} & \sim & 700km \end{array}\right\} \longrightarrow$$

a difference of
16 orders of magnitude

2. **Energy** of neutrinos:

$$\left.\begin{array}{lcl} E_\nu^{SN} & \sim & 10MeV \\ E_\nu^{MINOS} & \sim & 3GeV \\ E_\nu^{OPERA} & \sim & 30GeV \end{array}\right\} \longrightarrow$$

a difference of
2(MINOS) or 3(OPERA) orders of magnitude

3. **Flavour** composition of the beam:

SN: all flavours (with different luminosities: $L_{\nu_e} \sim L_{\bar{\nu}_e} \sim 2L_{\nu_{\mu,\tau},\bar{\nu}_{\mu,\tau}}$)

MINOS and OPERA: only muon neutrinos

Main advantage in long baseline experiments:

Very precise measurement of distance and energy $\Longrightarrow$ model independent interpretation of the results

Estimation of LV effects

at Fermilab 1979, MINOS and OPERA

Condition to satisfy at Fermilab 1979

- LV propagation of a neutrino with energy $E_\nu = 80\ GeV$
- Ratio of neutrino velocity wrt c: $|\beta_\nu - 1| < 4 \times 10^{-5}$

Condition to satisfy at MINOS

- LV propagation of a neutrino with energy $E_\nu = 3\ GeV$
- Shift wrt expected time of flight: $\delta = (-126 \pm 1\sigma) ns$

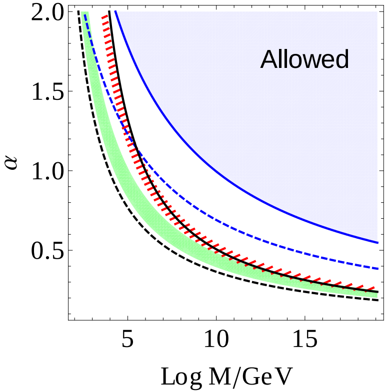
Condition to satisfy at OPERA

- LV propagation of a neutrino with energy $E_\nu = 30\ GeV$
- Shift wrt expected time of flight: $\delta = (-60 \pm 3\sigma) ns$

And compare the results with SN bounds!

Estimation of LV effects

at Fermilab 1979, MINOS and OPERA



- Blue lines: SN bounds
- Solid Black line: Fermilab 1979 bound
- Dashed Black line: MINOS 3σ bound

OPERA and MINOS allowed regions

- Green region: MINOS 1σ
- Red Dashed region: OPERA 3σ

There is tension between the measurements in the whole parameter space

How robust are these estimates?

If Lorentz violation is energy-dependent, it affects
both the shift and the spread of neutrino time profiles
at the Far Detector (MINOS) or Gran Sasso (OPERA)

At present our analysis has been performed only for MINOS data, but the procedure will be exactly the same for OPERA

Measured **time distributions** at ND and FD: **no distortions detected**

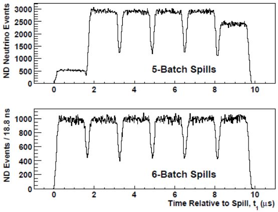


FIG. 1: Neutrino event time distribution measured at the MINOS Near Detector. The top plot corresponds to events in 5-batch spills $P_1^5(t_1)$ while the bottom plot corresponds to 6-batch spills $P_1^6(t_1)$.

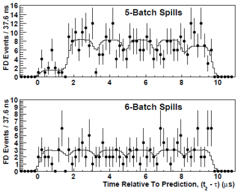


FIG. 2: Time distribution of FD events relative to prediction after fitting the time-of-flight. The top plot shows events in 5-batch spills, the bottom 6-batch spills. The normalized expectation curves $P_2^5(t)$ and $P_2^6(t)$ are shown as the solid lines.

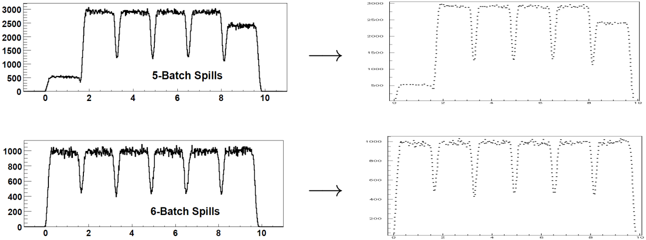
Simulation steps

How to analyse data to search for LV effects:

1. Reproduce MINOS/OPERA results on time shift and spread at FD/GS and check consistency with published data
2. Do the same in the LV hypothesis: consistency with data will provide bounds on LV parameters

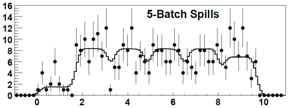
Step 1: reproducing MINOS data

- Reconstruct the **time distribution at ND** through digitization of published figures

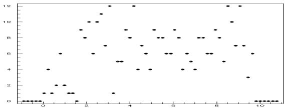


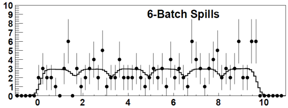
Step 1: reproducing MINOS data

- Reconstruct the **time distribution at ND** through digitization of published figures
- Reconstruct the **data points at FD** through digitization of published figures (63 points in $\sim$12μs: bin size = 188.2ns)

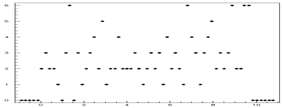


→



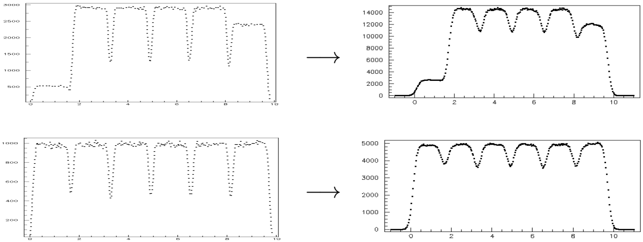


→



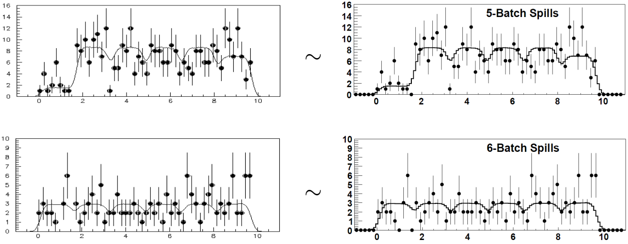
Step 1: reproducing MINOS data

- Reconstruct the **time distribution at ND** through digitization of published figures
- Reconstruct the **data points at FD** through digitization of published figures (63 points in $\sim$12μs: bin size = 188.2ns)
- Compute the **expected time distribution at FD** considering a smearing of $150ns$



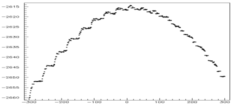
Step 1: reproducing MINOS data

- Reconstruct the **time distribution at ND** through digitization of published figures
- Reconstruct the **data points at FD** through digitization of published figures (63 points in $\sim 12\mu$s: bin size = 188.2ns)
- Compute the **expected time distribution at FD** considering a smearing of $150ns$
- Superposition of data points and **check** with published result

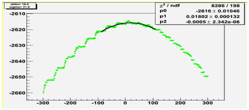


Step 1: reproducing MINOS data

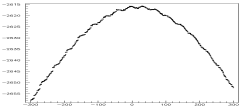
- Reconstruct the **time distribution at ND** through digitization of published figures
- Reconstruct the **data points at FD** through digitization of published figures (63 points in $\sim$12μs: bin size = 188.2ns)
- Compute the **expected time distribution at FD** considering a smearing of $150ns$
- Superposition of data points and **check** with published result
- **Likelihood analysis** for binned and randomly dispersed data in the 188.2ns bin



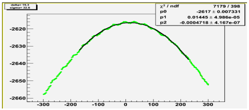
$\longrightarrow$



$\delta = 18.0ns$
$\sigma = 31.6ns$



$\longrightarrow$



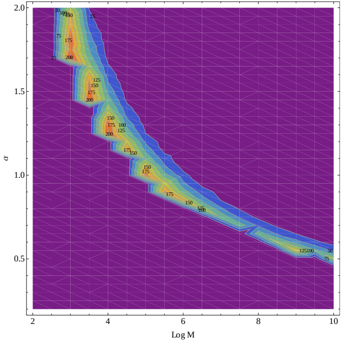
$\delta = 15.3ns$
$\sigma = 32.6ns$

We reproduce the statistical error but not -126ns time shift
consistently with the fact that the data points in the paper are plotted <u>after</u> the fit

Step 2: Bounds on LV hypothesis

Generate predictions for time distributions scanning over α and M

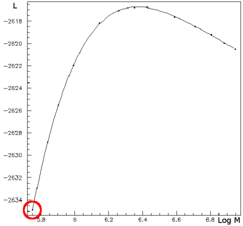
- blind scan on α and M not effective: very sharp passage from excluded region to no-effect region $\Longrightarrow$ useful to have an idea of allowed region for $\{\alpha, m\}$



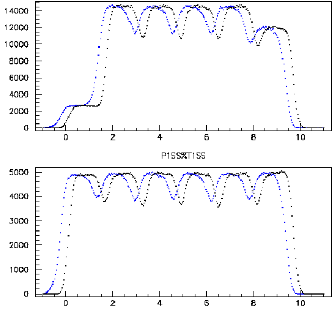
Step 2: Bounds on LV hypothesis

Generate predictions for time distributions scanning over α and M

- blind scan on α and M not effective: very sharp passage from excluded region to no-effect region $\Longrightarrow$ useful to have an idea of allowed region for $\{\alpha, m\}$
- for a given α simulation of a small set of M values around the value which maximises the likelihood



$\longrightarrow$

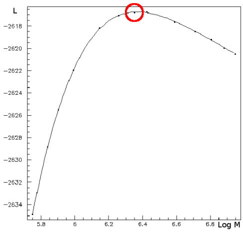


Minimum value for M $\Longrightarrow$ **effect too large**

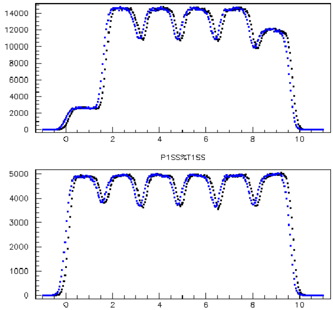
Step 2: Bounds on LV hypothesis

Generate predictions for time distributions scanning over α and M

- blind scan on α and M not effective: very sharp passage from excluded region to no-effect region $\Longrightarrow$ useful to have an idea of allowed region for $\{\alpha, m\}$
- for a given α simulation of a small set of M values around the value which maximises the likelihood



$\longrightarrow$

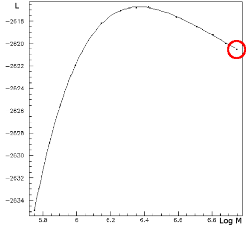


M for max Likelihood $\Longrightarrow$ **-126ns shift**

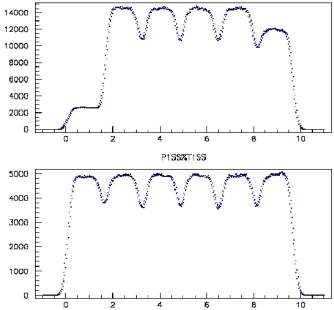
Step 2: Bounds on LV hypothesis

Generate predictions for time distributions scanning over α and M

- blind scan on α and M not effective: very sharp passage from excluded region to no-effect region $\Longrightarrow$ useful to have an idea of allowed region for $\{\alpha, m\}$
- for a given α simulation of a small set of M values around the value which maximises the likelihood



$\longrightarrow$

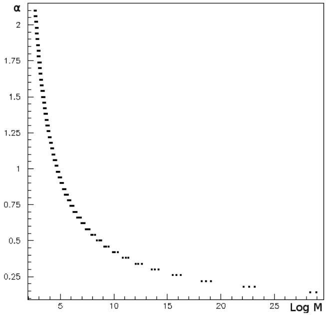


Maximum value for M $\Longrightarrow$ **no effect at all**

Step 2: Bounds on LV hypothesis

Generate predictions for time distributions scanning over α and M

- blind scan on α and M not effective: very sharp passage from excluded region to no-effect region $\Longrightarrow$ useful to have an idea of allowed region for $\{\alpha, m\}$
- for a given α simulation of a small set of M values around the value which maximises the likelihood
- the allowed range on the $\alpha - \log M$ plane is obtained



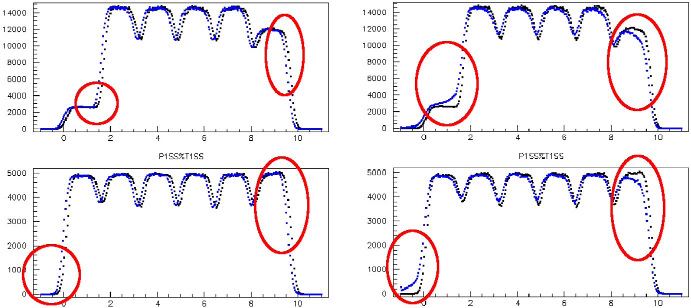
Step 2: Bounds on LV hypothesis

Two effects of energy-dependent LV:

First order: average shift in time

Second order: α-dependent spread in the waveform, <u>not observed</u>

$\alpha = 0.7$ $\alpha = 2.1$

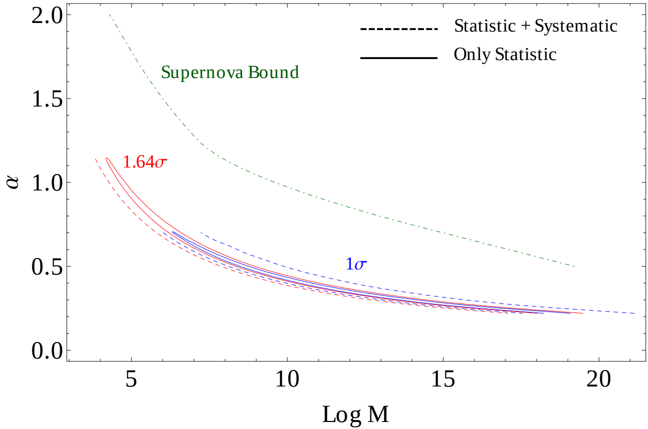


The maximum likelihood value depends on α

The region at low α is favoured at MINOS

Combined results

SN 1987a + MINOS bounds



The tension between SN and MINOS data is confirmed

The values $\alpha = 1$ or 2, justified by quantum gravity, are disfavoured at 1σ!

This tension can just worsen with OPERA data, due to the absence of energy dependence (distortion of the shape of the time distribution)

Why the tension?

SN 1987a + MINOS bounds

Two puzzles (assuming LV)

- The **time shift** of SN neutrinos seems to be almost consistent with 0 sec, while the shift at MINOS is consistent with 0 sec at 1.8σ (and OPERA at 6σ!)
- MINOS does not measure any **distortion in time distribution** and neither does OPERA

How to explain these puzzles?

- **errors in the experimental analysis**: at MINOS it could just be a statistical fluctuation, but the results at OPERA are striking!
- Are LV terms **dependent on energy in a different way** than the power law? How to explain such behaviour in terms of a viable **theoretical model**?

A third way?

Flavour-dependent Lorentz violations

Three major differences between neutrinos from SN and MINOS/OPERA:

- **Distance:** $O(kpc)$ vs. $O(km)$
- **Energy:** $O(MeV)$ vs $O(GeV)$
- **Flavour:** Only electron antineutrinos from SN have been detected, while MINOS and OPERA beams are composed of muon neutrinos

Hypothesis

Lorentz violation may affect only muon neutrinos,
while electron neutrinos would propagate in a Lorentz invariant way

A third way?

Flavour-dependent Lorentz violations

Lorentz violation may affect only muon neutrinos,
while electron neutrinos would propagate in a Lorentz invariant way

Consequences on oscillation

electron neutrino: $|\nu_e\rangle = c_\theta|\nu_1\rangle + s_\theta|\nu_2\rangle$
muon neutrino: $|\nu_\mu\rangle = -s_\theta|\nu_1\rangle + c_\theta|\nu_2\rangle$

Oscillation $|\nu_e\rangle \to |\nu_\mu\rangle$ with a LV flavour-dependent dispersion relation $E_i^2 = p^2 + m_i^2 + \delta_i p^2$:

$$\begin{aligned}
\langle\nu_\mu|\nu(t,x)\rangle &= i\sin(2\theta)\int dp\, f(p)\, e^{-i\left(px+\frac{E_1+E_2}{2}t\right)} \sin\left(\frac{E_1-E_2}{2}t\right) \\
&= i\sin(2\theta)\int dp\, f(p)\, e^{-ip\left(x+t+\frac{m_1^2+m_2^2}{4p^2}t+\frac{\delta_1+\delta_2}{4}t\right)} \sin\left(\frac{\Delta m^2}{4p}t+\frac{\delta_1-\delta_2}{4}pt\right)
\end{aligned}$$

A third way?

Flavour-dependent Lorentz violations

Lorentz violation may affect only muon neutrinos,
while electron neutrinos would propagate in a Lorentz invariant way

Consequences on oscillation

electron neutrino: $|\nu_e\rangle = c_\theta|\nu_1\rangle + s_\theta|\nu_2\rangle$
muon neutrino: $|\nu_\mu\rangle = -s_\theta|\nu_1\rangle + c_\theta|\nu_2\rangle$

Oscillation $|\nu_e\rangle \to |\nu_\mu\rangle$ with a LV flavour-dependent dispersion relation $E_i^2 = p^2 + m_i^2 + \delta_i p^2$:

$$\begin{aligned}
\langle\nu_\mu|\nu(t,x)\rangle &= i\sin(2\theta)\int dp\, f(p)\, e^{-i\left(px+\frac{E_1+E_2}{2}t\right)} \sin\left(\frac{E_1-E_2}{2}t\right) \\
&= i\sin(2\theta)\int dp\, f(p)\, e^{-ip\left(x+t+\frac{m_1^2+m_2^2}{4p^2}t+\frac{\delta_1+\delta_2}{4}t\right)} \sin\left(\frac{\Delta m^2}{4p}t+\frac{\delta_1-\delta_2}{4}pt\right)
\end{aligned}$$

To fit the measured advance it must be $\frac{\delta_1+\delta_2}{4} \sim \delta_1 \sim -10^{-2}$, but this means that:

$$10^{-2} \sim \left|\frac{\delta_1-\delta_2}{4}\right| \gg \frac{\Delta m^2}{4p^2} \sim 10^{-23} \implies$$

the oscillation pattern would be completely different

Outline

Parametrising the LV term

Different possibilities to explore, e.g.:

Power law with fixed mass scale: 2 parameters $\{\delta, \alpha\}$

$$\Delta_{LV}(E) = \delta \left(\frac{E}{M_{Pl}}\right)^{\alpha} \quad \Longrightarrow \quad v \sim 1 \pm \delta \left(\frac{E}{M_{Pl}}\right)^{\alpha}$$

Sensitive to small α, where the energy dependence is milder.

Exponential: 2 parameters $\{\delta, \mu\}$

$$\Delta_{LV}(E) = \delta \left(1 - e^{-\frac{E}{\mu}}\right) \quad \Longrightarrow \quad v \sim 1 \pm \delta \left(1 - e^{-\frac{E}{\mu}}\right)$$

Energy independent at large energies.

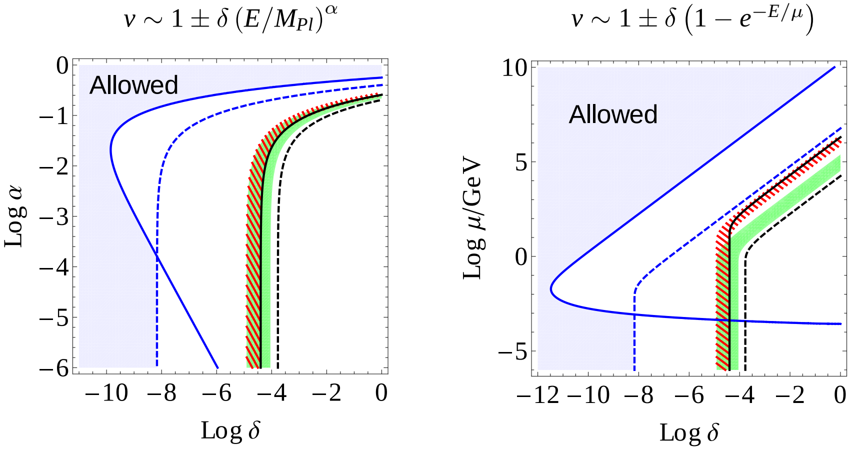
Hyperbolic tangent (step function): 3 parameters $\{\delta, m', \mu\}$

$$\Delta_{LV}(E) = \delta \left(1 + \tanh\left(\frac{E - m'}{\mu}\right)\right) \Longrightarrow \quad v \sim 1 \pm \delta \left(1 + \tanh\left(\frac{E - m'}{\mu}\right)\right)$$

$v_\nu \sim 1$ at low energies and energy independent deviation at large energies.

Estimation of the bounds

power law for low α and exponential



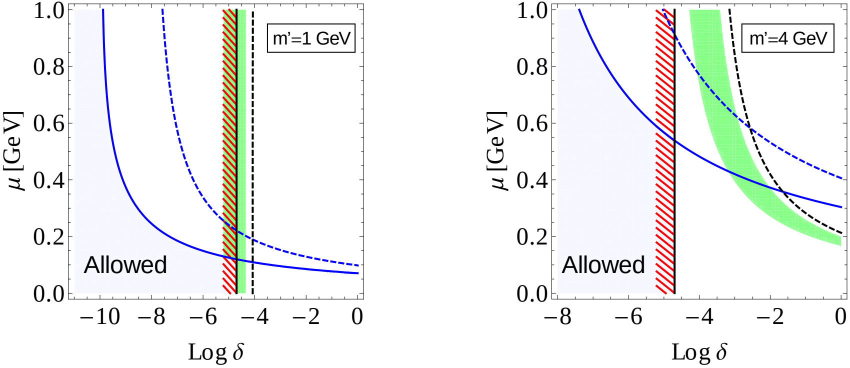
The power law and exponential parametrisations do not remove the tension between SN and MINOS/OPERA

in any region of the parameter space

Estimation of the bounds

hyperbolic tangent, i.e. step function

$$v \sim 1 \pm \delta \left(1 + \tanh\left(\frac{E - m'}{\mu}\right)\right)$$

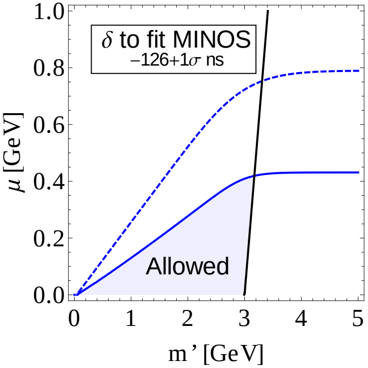


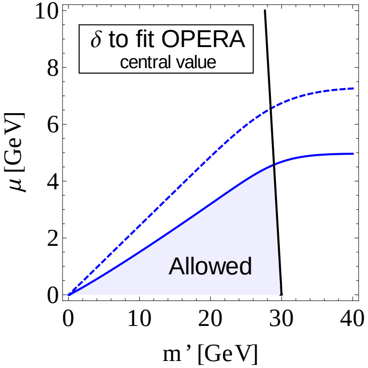
In this parametrisation the tension can be removed, and playing with the parameters only OPERA can be accomodated

Estimation of the bounds

hyperbolic tangent, i.e. step function

Fitting experimental values





More detailed information of allowed parameter ranges

Conclusion and Outlook

- **Violations of Lorentz invariance**, though strongly constrained by experiments, seems to appear in sectors which have not been fully understood yet, such as **neutrino physics**
- Tests on phenomenological parametrizations of energy-dependent Lorentz violation in neutrinos exploiting data from **SN 1987a**, **MINOS** and the very recent 6σ results from **OPERA**

Conclusion and Outlook

- **Violations of Lorentz invariance**, though strongly constrained by experiments, seems to appear in sectors which have not been fully understood yet, such as **neutrino physics**
- Tests on phenomenological parametrizations of energy-dependent Lorentz violation in neutrinos exploiting data from **SN 1987a**, **MINOS** and the very recent 6σ results from **OPERA**

Tension between bounds from supernova and MINOS/OPERA!
for a **power-law** parametrization of LV with non-integer exponent

Conclusion and Outlook

- **Violations of Lorentz invariance**, though strongly constrained by experiments, seems to appear in sectors which have not been fully understood yet, such as **neutrino physics**
- Tests on phenomenological parametrizations of energy-dependent Lorentz violation in neutrinos exploiting data from **SN 1987a**, **MINOS** and the very recent 6σ results from **OPERA**

Tension between bounds from supernova and MINOS/OPERA!
for a **power-law** parametrization of LV with non-integer exponent

Tension removed in alternative parametrisations of LV
with sharp energy dependence

Conclusion and Outlook

- **Violations of Lorentz invariance**, though strongly constrained by experiments, seems to appear in sectors which have not been fully understood yet, such as **neutrino physics**
- Tests on phenomenological parametrizations of energy-dependent Lorentz violation in neutrinos exploiting data from **SN 1987a**, **MINOS** and the very recent 6σ results from **OPERA**

Tension between bounds from supernova and MINOS/OPERA!
for a **power-law** parametrization of LV with non-integer exponent

Tension removed in alternative parametrisations of LV
with sharp energy dependence

Maybe new physics has been found,
but independent experimental confirmation is badly needed!

Backup Slides

Neutrinos in brief

Neutrinos' properties are known to limited accuracy

- no experimental evidence for right handed neutrinos
- Dirac or Majorana particles?
- squared mass differences and mixing angles are known from oscillations:

$$\Delta m^2_{12} = (7.59 \pm 0.21) \times 10^{-5}\ eV^2 \qquad |\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$$

$$\sin^2 2\theta_{12} = 0.861^{+0.026}_{-0.022} \qquad \sin^2 2\theta_{23} > 0.92 \qquad \sin^2 2\theta_{13} < 0.15$$

- various possibilities for their mass hierarchies:

Normal	$m_1 < m_2 \ll m_3$	$m_3 \simeq \sqrt{\Delta m^2_{32}} \sim 0.05\ eV$
Inverted	$m_1 \simeq m_2 \gg m_3$	$m_{1,2} \simeq \sqrt{\Delta m^2_{32}} \sim 0.05\ eV$
Degenerate	$m_1 \simeq m_2 \simeq m_3$	$m_{1,2,3} \gtrsim 0.1\ eV$

- only upper bound on their masses, the most stringent from tritium decay

$$m_\nu < 2eV$$

data taken from K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010)

Numerical results

Power law for $M < M_{Pl}$ at given α

α	t_{SN} (sec)		$\Delta t_{\nu\gamma}$ (sec)		M_{min} (GeV)	
	FN	VN	FN	VN	FN	VN
Baksan						
0.5	$18.4^{+6.2}_{-5.6}$	$11.7^{+3.3}_{-3.0}$	$43.3^{+6.6}_{-7.0}$	$22.2^{+3.1}_{-3.1}$	5×10^{19}	2×10^{20}
1	$18.0^{+6.5}_{-5.6}$	$13.6^{+4.5}_{-4.0}$	$22.1^{+5.0}_{-4.9}$	$14.4^{+3.1}_{-3.0}$	2×10^{9}	3×10^{9}
1.5	$21.0^{+8.6}_{-6.9}$	$14.5^{+5.4}_{-4.5}$	$19.2^{+5.4}_{-4.9}$	$11.4^{+2.9}_{-2.7}$	5×10^{5}	7×10^{5}
2	$22.3^{+10.7}_{-7.6}$	$15.8^{+6.7}_{-5.2}$	$16.9^{+5.1}_{-4.6}$	$10.3^{+3.1}_{-2.8}$	8×10^{3}	1×10^{4}
IMB						
0.5	$14.0^{+2.5}_{-2.1}$	$15.1^{+2.7}_{-2.4}$	$20.7^{+2.0}_{-2.2}$	$22.2^{+2.3}_{-2.4}$	5×10^{20}	4×10^{20}
1	$16.8^{+3.0}_{-2.8}$	$16.9^{+3.0}_{-2.7}$	$16.5^{+1.9}_{-2.0}$	$16.3^{+2.0}_{-2.0}$	6×10^{9}	6×10^{9}
1.5	$11.6^{+1.9}_{-1.6}$	$11.6^{+1.9}_{-1.6}$	$10.1^{+0.9}_{-1.0}$	$10.0^{+1.0}_{-1.0}$	2×10^{6}	2×10^{6}
2	$16.8^{+3.7}_{-2.9}$	$16.7^{+3.8}_{-3.0}$	$13.1^{+1.6}_{-1.7}$	$12.9^{+1.6}_{-1.6}$	2×10^{4}	2×10^{4}
KII						
0.5	$30.4^{+4.5}_{-4.4}$	$37.0^{+6.2}_{-5.9}$	$40.6^{+3.4}_{-3.7}$	$51.4^{+5.2}_{-5.3}$	1.6×10^{20}	9×10^{19}
1	$28.7^{+5.3}_{-4.7}$	$34.8^{+7.1}_{-6.4}$	$26.8^{+2.6}_{-2.6}$	$32.7^{+4.2}_{-3.7}$	4×10^{9}	3×10^{9}
1.5	$27.3^{+6.4}_{-5.1}$	$33.8^{+9.0}_{-7.2}$	$21.7^{+2.3}_{-2.0}$	$26.5^{+4.0}_{-3.1}$	1×10^{6}	8×10^{5}
2	$19.6^{+4.4}_{-3.1}$	$19.7^{+4.5}_{-3.1}$	$15.6^{+1.1}_{-0.8}$	$15.8^{+1.4}_{-0.9}$	2×10^{4}	2×10^{4}

Conformal neutrinos

see G. von Gersdorff and M. Quiros, Phys. Lett. B 678 (2009) 317

- A **conformally invariant** sector of the SM would have large anomalous dimension. For a fermion:

$$d_\psi = \frac{3}{2} + \gamma \qquad \text{with } \gamma > 0$$

Conformal neutrinos

see G. von Gersdorff and M. Quiros, Phys. Lett. B 678 (2009) 317

- A **conformally invariant** sector of the SM would have large anomalous dimension. For a fermion:

$$d_\psi = \frac{3}{2} + \gamma \qquad \text{with } \gamma > 0$$

- The **right-handed neutrino** has no charges under the gauge groups of the SM, therefore it can be described by an operator ψ_R belonging to a conformal sector. Its propagator is:

$$\Delta_\psi(p) = -iB_\gamma \frac{\bar{\sigma}^\mu p_\mu}{(-p^2 - i\epsilon)^{1-\gamma}} \qquad \text{with } B_\gamma = \frac{\Gamma(1-\gamma)}{(4\pi)^{2\gamma}\Gamma(1+\gamma)}$$

Conformal neutrinos

see G. von Gersdorff and M. Quiros, Phys. Lett. B 678 (2009) 317

- A **conformally invariant** sector of the SM would have large anomalous dimension. For a fermion:

$$d_\psi = \frac{3}{2} + \gamma \qquad \text{with } \gamma > 0$$

- The **right-handed neutrino** has no charges under the gauge groups of the SM, therefore it can be described by an operator ψ_R belonging to a conformal sector. Its propagator is:

$$\Delta_\psi(p) = -iB_\gamma \frac{\bar{\sigma}^\mu p_\mu}{(-p^2 - i\epsilon)^{1-\gamma}} \qquad \text{with } B_\gamma = \frac{\Gamma(1-\gamma)}{(4\pi)^{2\gamma}\Gamma(1+\gamma)}$$

- Interaction of $\psi_R = B^{1/2}\mu^\gamma \nu_R$ with SM doublet:

$$\mathcal{L} = \frac{1}{\Lambda^\gamma} y_\nu \bar{L} H \psi_R + h.c. = B_\gamma^{1/2}\left(\frac{\mu}{\Lambda}\right)^\gamma y_\nu \bar{L} H \nu_R + h.c.$$

generates a **neutrino mass**:

$$m_\nu = B_\gamma^{1/2}\left(\frac{\mu}{\Lambda}\right)^\gamma \frac{y_\nu v}{\sqrt{2}} \qquad \underset{\mu = m_\nu}{\Longrightarrow} \qquad m_\nu = B_\gamma^{\frac{1}{2(1-\gamma)}}\left(\frac{y_\nu v}{\sqrt{2}\Lambda}\right)^{\frac{\gamma}{1-\gamma}} \frac{y_\nu v}{\sqrt{2}}$$

Conformal neutrinos

Extra-dimensional reformulation

Warped space with conformal metric $ds^2 = \frac{R^2}{z^2}(dx_\mu dx^\mu - dz^2)$ and boundary $\epsilon = \frac{1}{\Lambda}$

AdS/CFT interpretation

AdS		CFT
Fields on the boundary $z = \epsilon$	$\Longleftrightarrow$	Elementary fields
Fields in the bulk		Operators

Conformal neutrino model $\longrightarrow$ SM fields localized on the boundary and ν_R propagating in the bulk

Conformal neutrinos

Extra-dimensional reformulation

Warped space with conformal metric $ds^2 = \frac{R^2}{z^2}(dx_\mu dx^\mu - dz^2)$ and boundary $\epsilon = \frac{1}{\Lambda}$

AdS/CFT interpretation

AdS		CFT
Fields on the boundary $z = \epsilon$	$\Longleftrightarrow$	Elementary fields
Fields in the bulk		Operators

Conformal neutrino model $\longrightarrow$ SM fields localized on the boundary and ν_R propagating in the bulk

Effective lagrangian for the neutrino sector leads to modified propagator:

$$\mathcal{L}_\nu = -i\bar{\nu}_L \bar{\sigma}^\mu \partial_\mu \nu_L + \frac{y_\nu v}{\sqrt{2}}(\nu_L \nu_R + h.c.) - i\Sigma(p)\nu_R \sigma^\mu \partial_\mu \bar{\nu}_R$$

$$\Downarrow$$

$$\Delta_\nu \sim \frac{1}{\Sigma(p)p^2 - \left(\frac{y_\nu v}{\sqrt{2}}\right)^2} \qquad \text{where } \Sigma(p) \underset{\epsilon p \ll 1}{\sim} N_c \left(\frac{p}{\Lambda}\right)^{1-2c}$$

Mass of the neutrino

$$m_\nu = N_c^{\frac{1}{3-2c}} \Lambda^{\frac{1-2c}{3-2c}} \left(\frac{y_\nu v}{\sqrt{2}}\right)^{\frac{2}{3-2c}} \longrightarrow$$

Conformal neutrinos for
$\gamma = c - 1/2$ and $N_c^{-1} = B_\gamma^2$

Assumption

Lorentz violation appears only in the bulk
while physics on the UV boundary is Lorentz invariant

$$\Downarrow$$

Only neutrinos can feel Lorentz violation

Assumption

Lorentz violation appears only in the bulk
while physics on the UV boundary is Lorentz invariant

$\Downarrow$

Only neutrinos can feel Lorentz violation

The expansion of $\Sigma(p)$ can contain subleading terms with a LV energy-dependence

$$\Sigma_{LV}(p) \sim N_c \left(\frac{p}{\Lambda}\right)^{-2\gamma} + \delta_{LV}\left(\frac{E}{\tilde{M}}\right)^{\beta} + \dots \qquad \text{with } \beta > -2\gamma$$

Modified dispersion relation for neutrinos

$$p^2 + \frac{2\delta_{LV}}{(1-\gamma)N_c}\frac{m_\nu^{2+2\gamma}}{\Lambda^{2\gamma}\tilde{M}^{\beta}}E^{\beta} = m_\nu^2$$

It is a power law behaviour with noninteger exponent!