Examination of Quantum Gravity Effects with Neutrino

Alexander Sakharov

John Ellis, Nicholas Harries, Nick Mavromatos, Anselmo Meregaglia, Andre Rubbia, Sarben Sarkar

Discrete ' 08, December 12, Valencia

Outlook

Lorentz violation in neutrino propagation

Manifestation of quantum gravity for «low» energy radiation probe

Limits on LV from Supernovae neutrino signals

- Neutrino emission from a SN
- Optimisation of dispersive broadened neutrino signal

CNGS and OPERA experiment

Quantum gravity decoherence in neutrino oscillations

Quantum deoherence

- MSW – like effect induced decoherence
- Stochastic fluctuations of space-time background

Sensitivity of CNGS and J-PARC beam to QG decoherence

I

Lorentz violation in neutrino propagation

Modification of dispersion relation

The existence of the lower bound at which space-time responses actively to the present of energy, may lead to violation of Lorentz invariance.

In the approximation $E << M_{QGn}$, the distortion of the standard dispersion relation may be reresnted as an expansion in E/M_{QGn}

$$E^2 = m^2 + p^2(1 + \xi_1(p/M) + \xi_2(p/M) + \ldots)$$

Linear deviation

$$\xi_1 < 0; \qquad v = c\left(1 - \frac{E}{M_{QG1}}\right); \qquad n(E) = 1 + \frac{E}{M_{QG1}}$$

Quadratic deviation

$$\xi_1 < 0; \qquad v = c\left(1 - \frac{E^2}{M_{QG2}^2}\right); \qquad n(E) = 1 + \frac{E^2}{M_{QG1}^2}$$

- Liouville strings (J. Ellis, N. Mavromatos, D. Nanopoulos, 1997, 1998, 1999)
- Effective field theory approach (R.C. Mayers, M. Pospelov 2003)
- Sace-time foam (L.J. Garay 1998)
- Loop quantum gravity (R. Gambini, J. Pullin, 1999)
- Noncomutative geometry (G. Amelino-Camelia, 2001)
- Fermions-neutrinos (J. Ellis, N. Mavromatos, D. Nanopoulos, G.Vlkov, 1999)
- Gravitationally brain localized SM particles (M.Gogberashvii, et al, 2006)

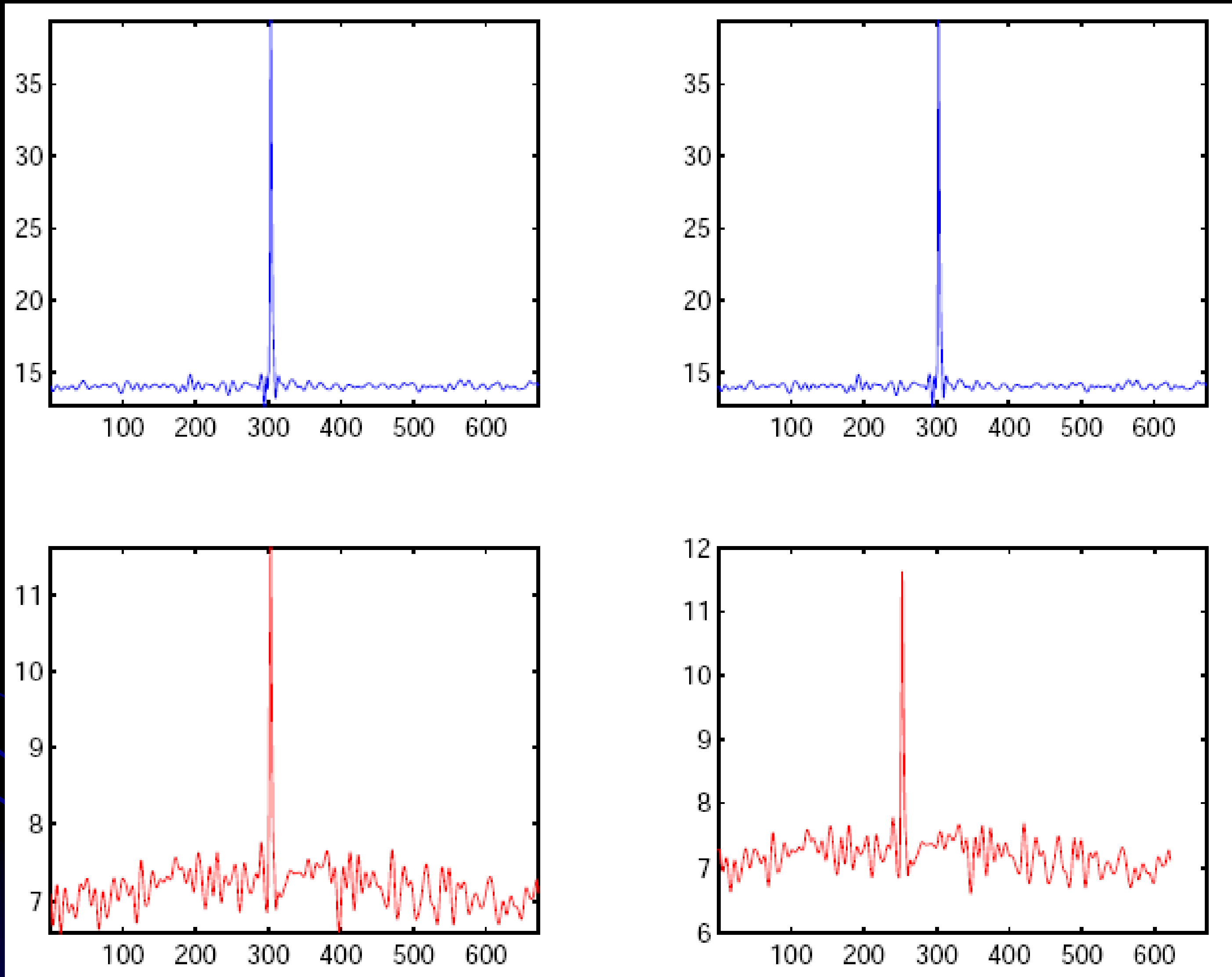
At the source

At the detector

E2

E2 < E1

E1



Photons

Pulsars: E up to 2GeV, D about 10 kpc, (Kaaret, 1999) $M_{QG1} \geq 1.5 \times 10^{15}$ GeV

GRBs: E up to MeV, D beyond 7000 Mpc (Ellis, et al, 2005,2007)

$M_{QG1} \geq 1.4 \times 10^{16}$ GeV $M_{QG2} \geq 1.2 \times 10^{6}$ GeV

AGNs: E up to 10 TeV, D about 100s Mpc (MAGIC and Ellis, et al , 2007)

$M_{QG1} \geq 0.26 \times 10^{18}$ GeV $M_{QG2} \geq 0.33 \times 10^{11}$ GeV

Neutrinos

SN: E about 10 MeV, D about 10 kpc, (Ellis, et al, 1999; Ammosov and Volkov, 2000)

GRBs neutrino-photon : $E_\nu \simeq 100$ TeV, D beyond 7000 Mpc (Piran, Jakob,2006)

MINOS: $E_\nu \approx 3$ GeV , D=734 km (MINOS, et al, 2007)

$M_{QG1} \geq 1(4) \times 10^{5}$ GeV $M_{QG2} \geq 600(250)$ GeV

Neutrino emission from Supernovae

About 20 neutrinos from SN1987a in LMC were detected by KII, IMB and BAKSAN

Energy release of 10th of MeV neutrinos is consistent with the expected $\approx 10^{53}$ erg

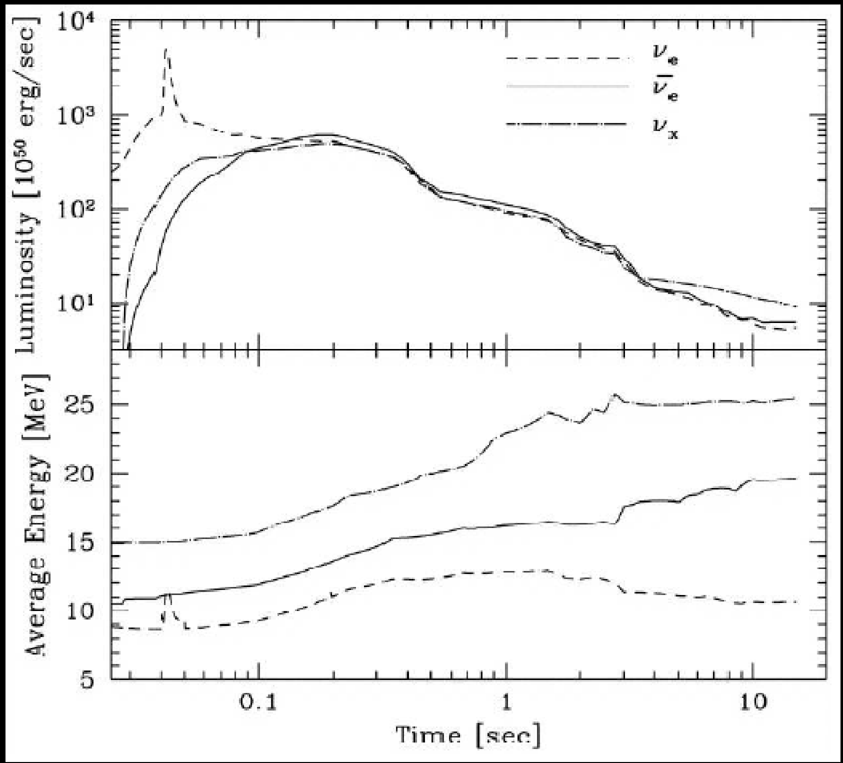
A future galactic supernova is expected to generate $\approx 10^{4}$ events in SK

During the later stage (after neutronization peak) all flavors are produced with Fermi-Dirac spectra

$\langle E_{\nu_e} \rangle = (10 - 12)$ MeV

$\langle E_{\bar{\nu}_e} \rangle = (12 - 18)$ MeV

$\langle E_{\nu_{\mu,\tau}} \rangle = (15 - 28)$ MeV



Oscillations in the core are taken into account

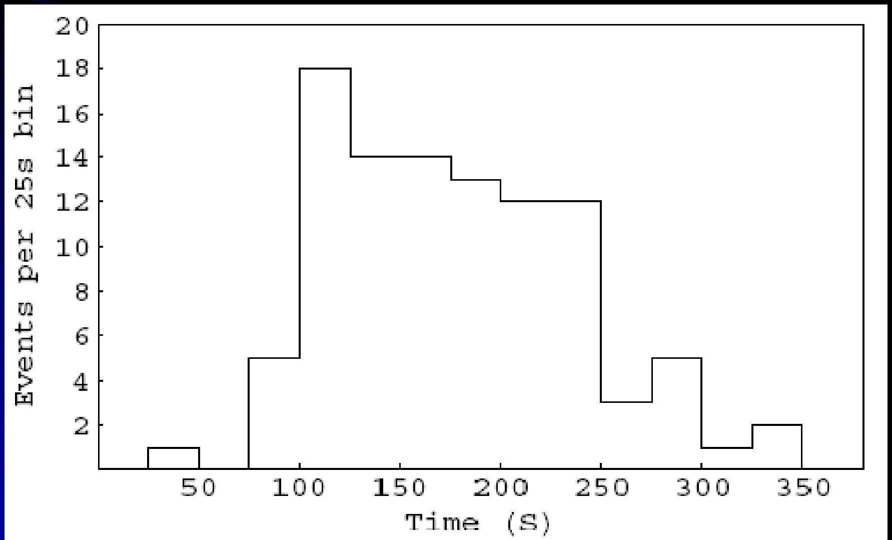
Minimal dispersion (MD)

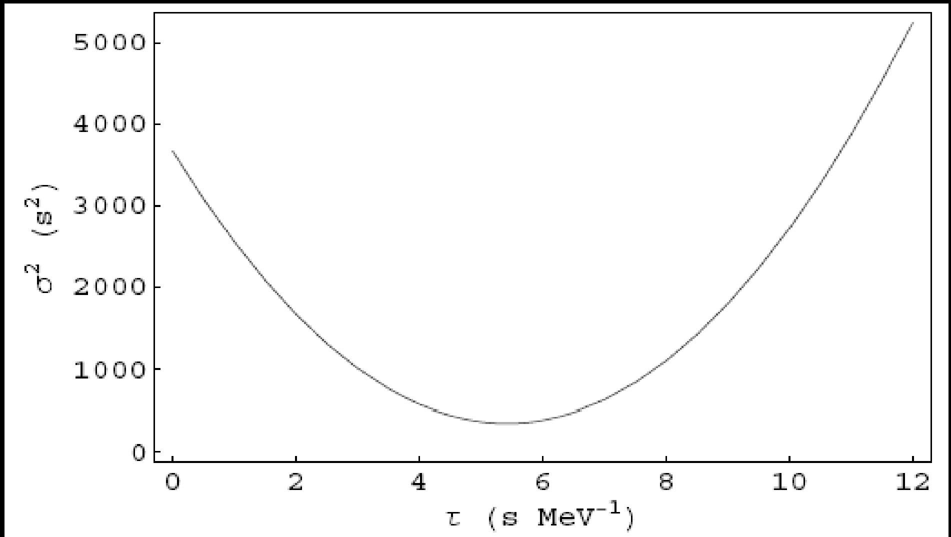
Event list with low number of events with no a reasonable time profile to be extracted

$\sigma_t^2 \equiv \langle (t - \langle t \rangle)^2 \rangle$ $\Delta t = \tau_l E^l$ $\tau_l = L/cM^l_{\nu QGl}$

The "correct" value of τ_l should always compress the neutrino signal

Any other ("incorrect") τ_l would spread in time the events $\tau_l^{min} \equiv \frac{\langle tE^l \rangle - \langle t \rangle \langle E^l \rangle}{\langle E^{2l} \rangle - \langle E^l \rangle^2}$





SN 1987a

IMB		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	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

Baksan		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	12.0	2.4
0.435	17.9	3.6
1.710	23.5	4.7
7.687	17.6	3.5
9.099	10.3	4.1

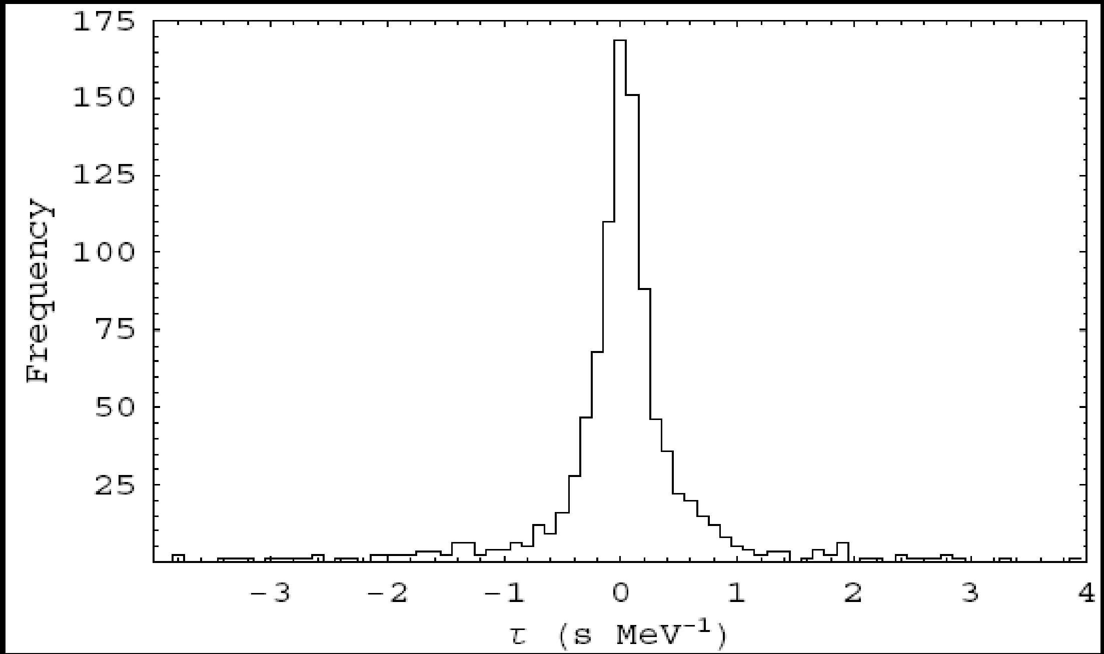
Kamiokande II		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	20.0	2.9
0.107	13.5	3.2
0.303	7.5	2.0
0.324	9.2	2.7
0.507	12.8	2.9
1.541	35.4	8.0
1.728	21.0	4.2
1.915	19.8	3.2
9.219	8.6	2.7
10.433	13.0	2.6
12.439	8.9	1.9

Minimal Dispersion

$L = (51.3 \pm 1.2)$ kpc

$M_{\nu QG1} > 2.7(2.5) \times 10^{10}$ GeV

$M_{\nu QG2} > 4.6(4.1) \times 10^{4}$ GeV

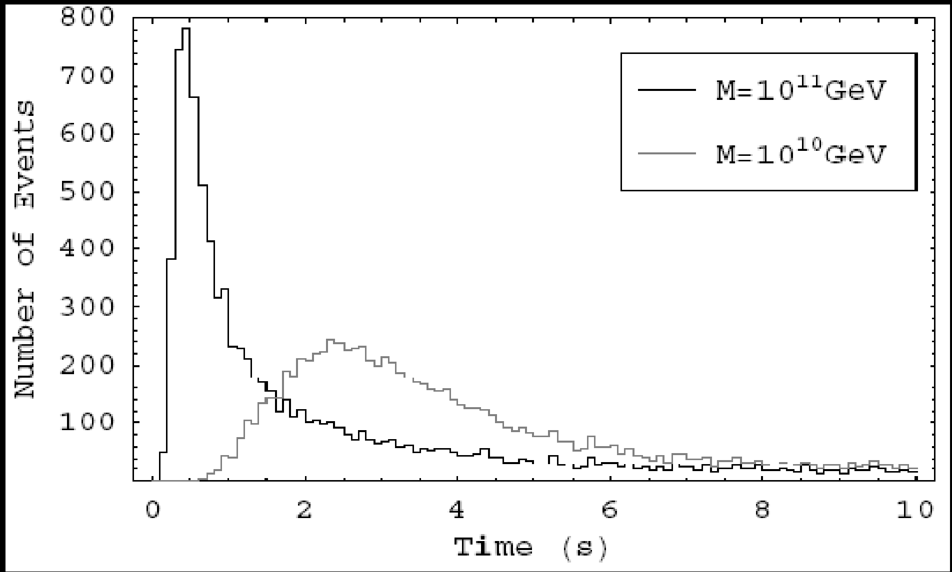


Energy cost function (ECF)

The apparent duration of a pulse is only going to be increased by dispersion.

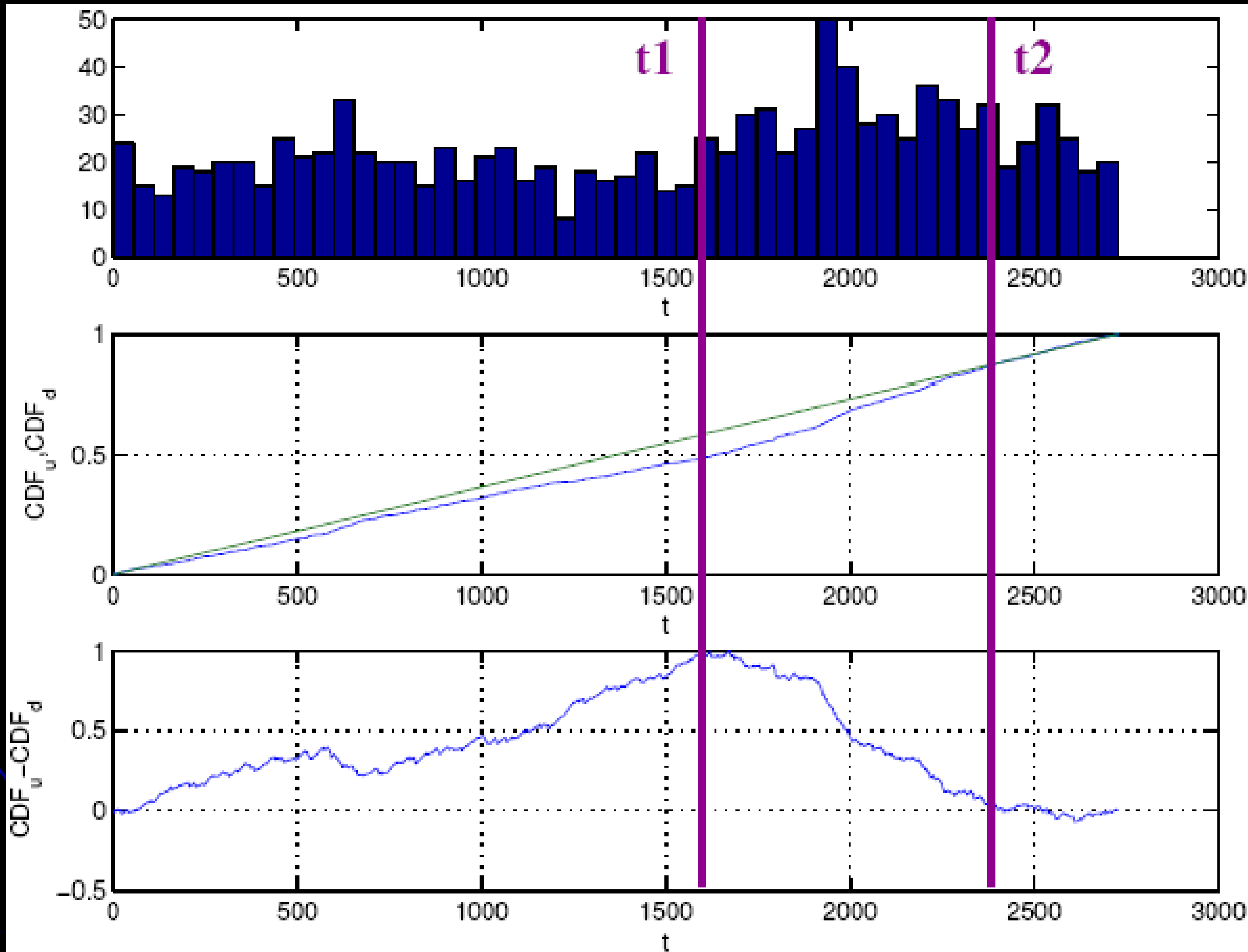
The energy per unit time decreases with the distance from the source.

The dispersion can be figured out by "undoing" the dispersion such that as much energy as possible is emitted at the source.

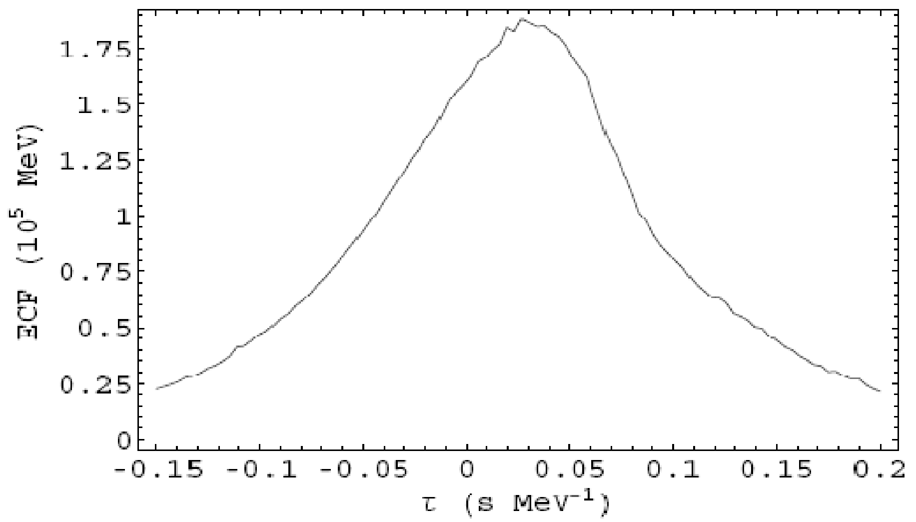


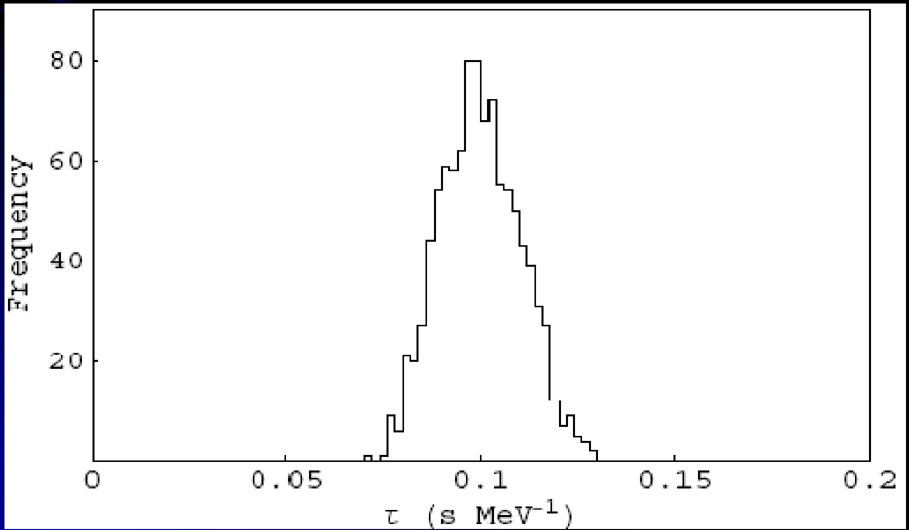
(t1,t2) contains the most active part of the flare, as determined using KS statistics

One corrects for given model of photon dispersion, linear and quadratic, by applying to each photon of energy E the time shifts.



Future Galactic Supernova





Energy Cost Function

Super-Kamiokande

$L \approx 10$ kpc

$N_\nu \approx 10000$

$M_{\nu QG1} > 2(4) \times 10^{11}$ GeV

$M_{\nu QG2} > 2(4) \times 10^{5}$ GeV

CNGS beam characteristics

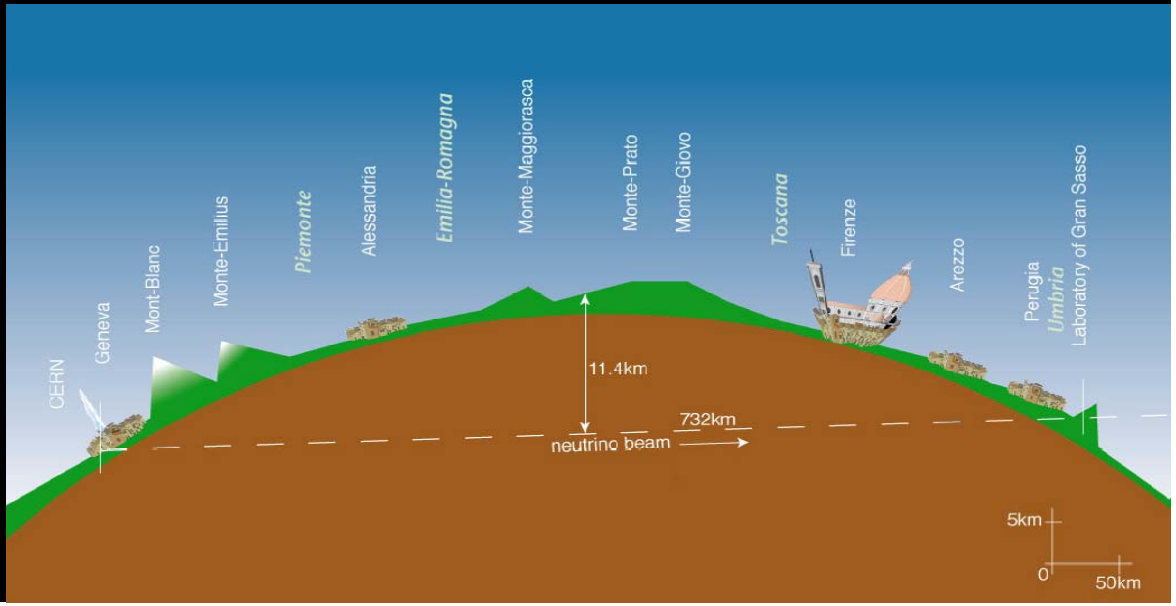
The average neutrino energy: $< E_{\nu_\mu} >= 17$ GeV

Extraction the SPS beam during spills of length $10.5\ \mu$s

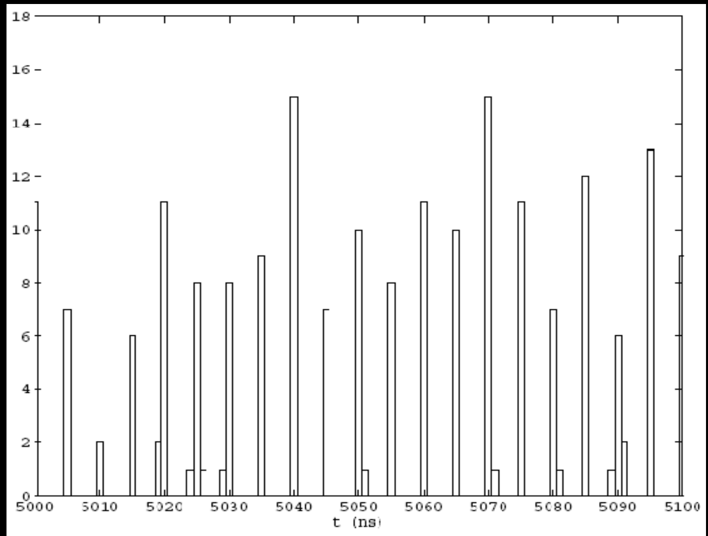
Within each spill, the beam is extracted in 2100 bunches separated by 5 ns

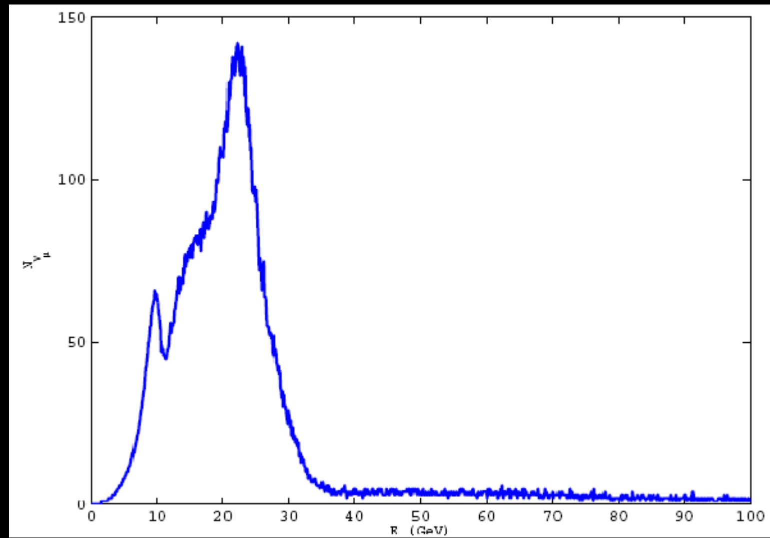
Each individual bunch has a $4-\sigma$ duration of 2 ns

$\approx 2 \times 10^4$ CC events expected to be observed in the 1.8 kton OPERA

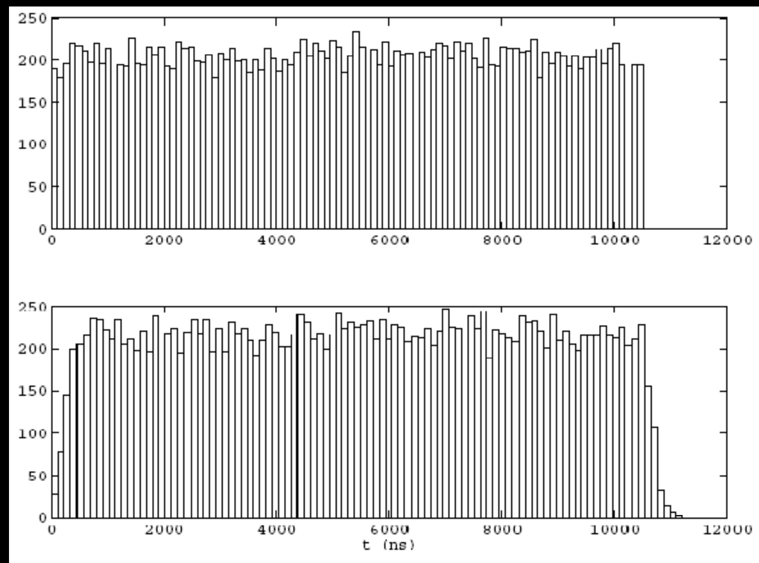


Spill analysis





100ns uncertainty in the relative timing



$$M_{\nu QG1} = 4.8 \times 10^5 \text{ GeV}$$

$$\tau_l = 5 \text{ ns/GeV}$$

Slicing estimator

Estimate the mean arrial times of 1000-event slice with increasing energies

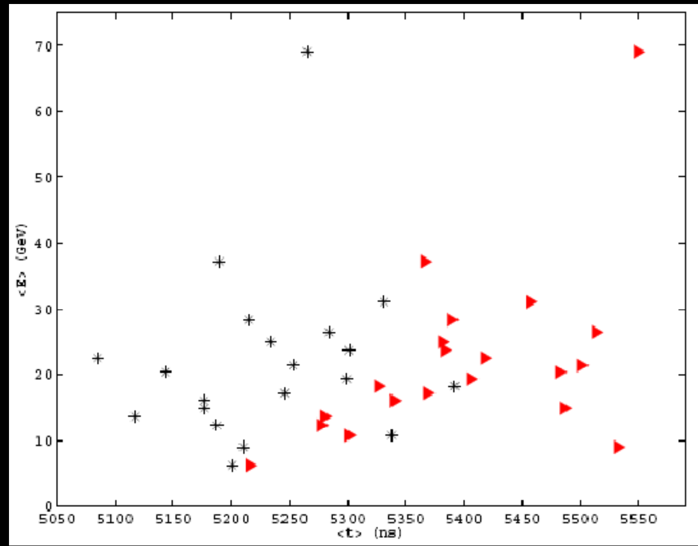
$$\tau_l = 5 \text{ ns/GeV}$$

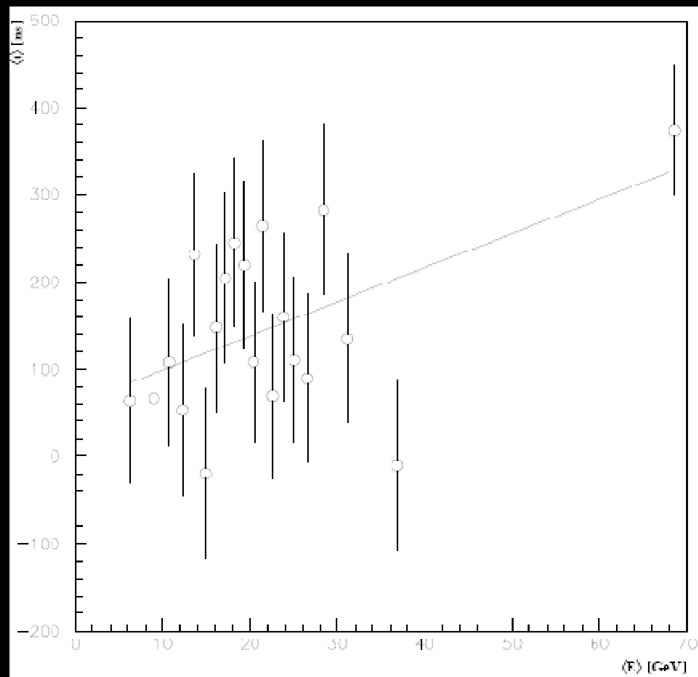
Straight line fit $\quad \Delta\langle t\rangle = \tau_l \langle E\rangle + b$

Straight line fit $\quad \Delta\langle t\rangle = \tau_q \langle E\rangle^2 + p$

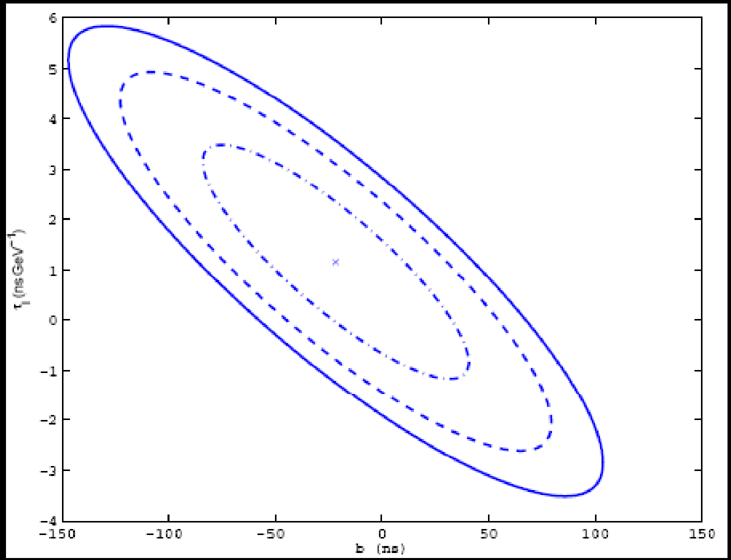
$$M_{\nu QG1} = 2.4 \times 10^6 \left(\frac{ns\ GeV^{-1}}{\tau_l}\right) \text{GeV}$$

$$M_{\nu QG2} = 1.6 \times 10^3 \sqrt{\frac{ns\ GeV^{-2}}{\tau_q}} \text{GeV}$$

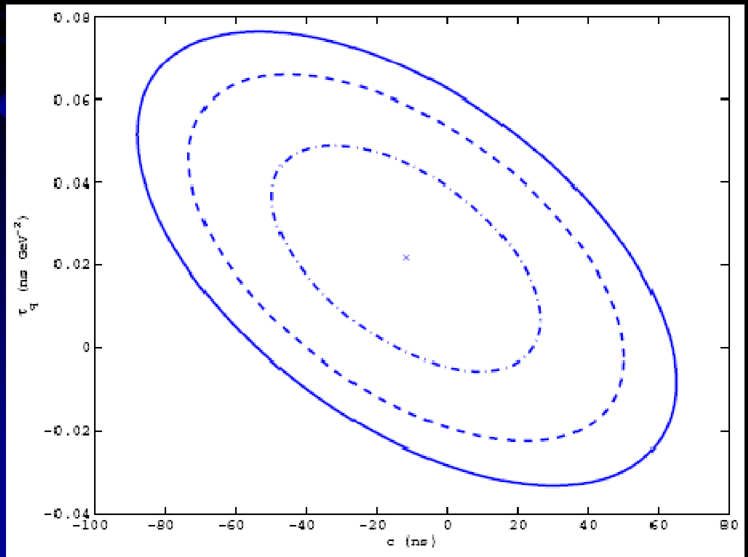




Sensitivity



$M_{\nu QG1} > 7 \times 10^5$ GeV



$M_{\nu QG2} > 8 \times 10^3$ GeV

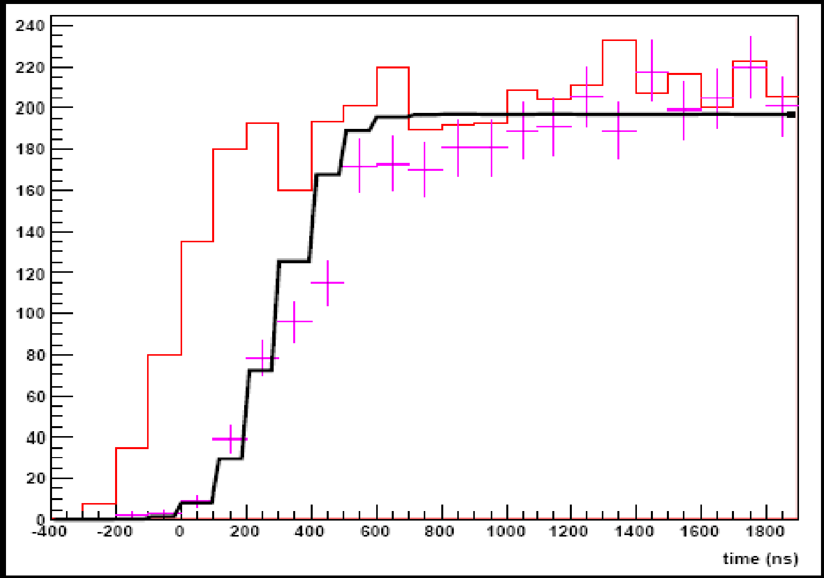
Rock Events

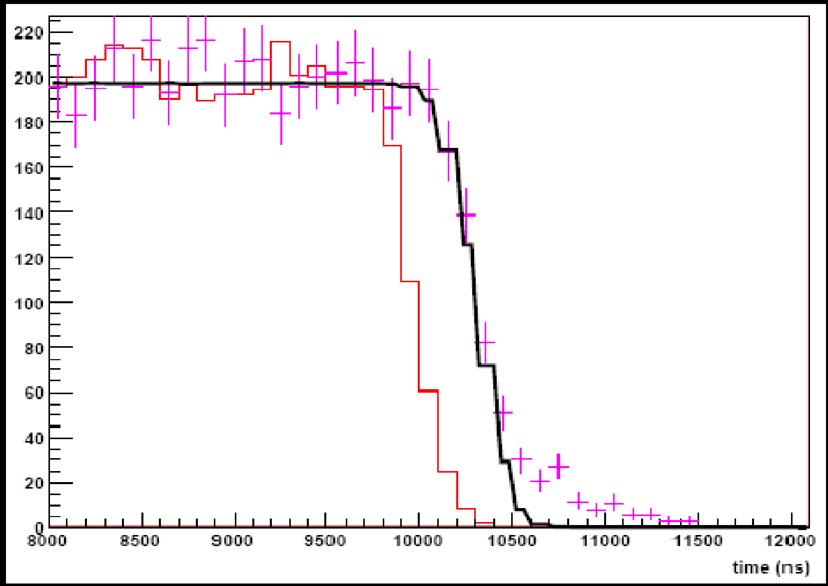
Distortion of the shape of the spill at its adges

Comparing two histograms, namly a referece one and with shifts $\tau_{l(q)}$ itroduced

OPERA may also be used to measure the timing of muons from 2×10^5 neutrino events in the rocks

$M_{\nu QG1} \approx 2.4 \times 10^5$ GeV





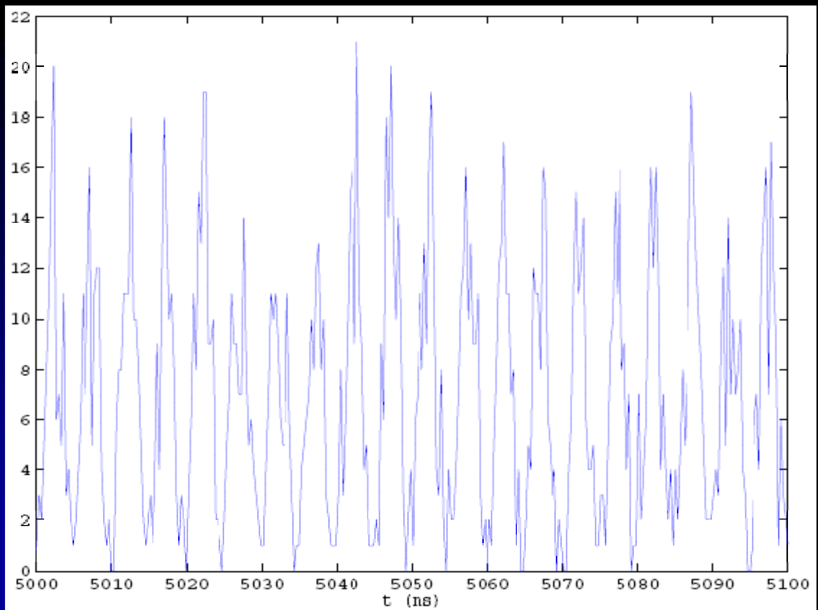
Bunch analysis

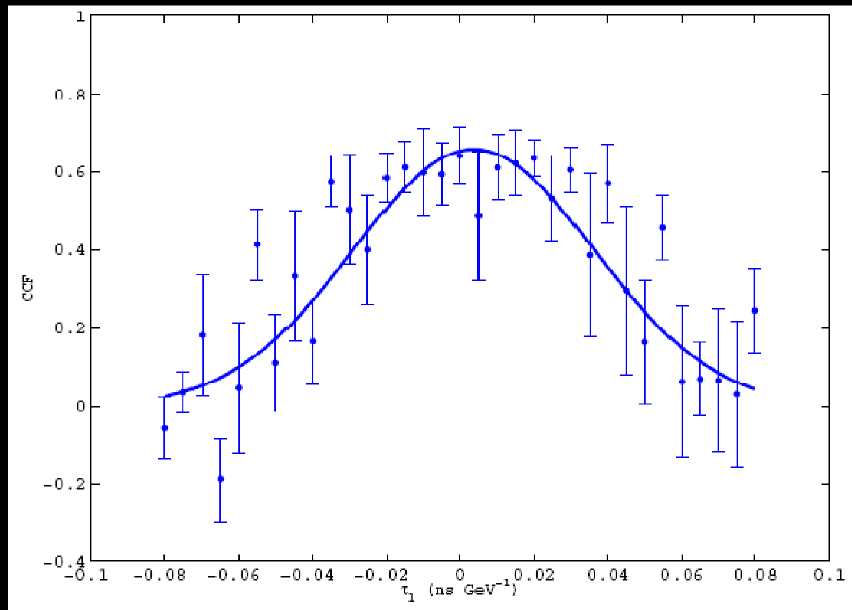
If a sub-ns resolution in OPERA coud be achived

If a synchronization of the SPS and OPERA clocks with ns precision over period 5 years could be obtained !!Challenging task!! (free electrol lasers with 10th picoseconds pulses- synchronisation over several km)

To survive the bunch periodic structure

$$\mathrm{CCF}(\tau_{l(q)}) = \frac{\langle (A(t) - \bar{A}(t))(B(t - \tau_l E^l) - \bar{B}(t - \tau_l E^l)) \rangle}{\sigma_{A(t)} \sigma_{B(t - \tau_l E^l)}}$$





Conclusions I

SN 1987a: $M_{\nu QG1} > 2.7(2.5) \times 10^{10}$ GeV $M_{\nu QG2} > 4.6(4.1) \times 10^{4}$ GeV

Future SN: $M_{\nu QG1} > 2(4) \times 10^{11}$ GeV $M_{\nu QG2} > 2(4) \times 10^{5}$ GeV

CNGS spill: $M_{\nu QG1} > 7 \times 10^{5}$ GeV $M_{\nu QG2} > 8 \times 10^{3}$ GeV

CNGS bunch structure: $M_{\nu QG1} \simeq 5 \times 10^{7}$ GeV $M_{\nu QG2} \simeq 4 \times 10^{4}$ GeV

CNGS bunch structure (rocks): $M_{\nu QG1} \simeq 4 \times 10^{8}$ GeV $M_{\nu QG2} \simeq 7 \times 10^{5}$ GeV

II

Quantum gravity decoherence in neutrino oscillations

Quantum decoherence

The time evolution of a closed quantum system

$$\frac{\partial \rho}{\partial t} = L[\rho] = -i[H,\rho] \qquad \rho > 0$$

Pure state $Tr(\rho^2) = Tr\rho = 1$

Mixed state $Tr(\rho^2) < Tr\rho = 1$

Space-time foam environment (Ellis, et al, 1984)

$$\frac{\partial \rho}{\partial t} = \Lambda_1 \rho + \Lambda_2 \rho$$

Nonunitary evolution (Lindblad mapping)

H with stochastic element in a classical metric

Generically space-time foam and the back-reaction of matter on the gravitational metric may be modeled as a randomly fluctuating environment

MSW-like effect

$$H_{\text{eff}} = H + n^{c}_{\text{bh}}(r) H_I \qquad H_I = \begin{pmatrix} a_{\nu_\mu} & 0 \\ 0 & a_{\nu_\tau} \end{pmatrix}$$

Foam medium is assumed to be to be described by Gaussian random variable

$\langle n^{c}_{\text{bh}}(t) \rangle = n_0$ The average number of foam particles

$$\langle n^{c}_{bh}(t) n^{c}_{bh}(t') \rangle \sim \Omega^2 n_0^2 \delta(t - t')$$

(Maromatos and Sarkar, 2006)

The modified time evolution (master equation)

$$\frac{\partial}{\partial t}\langle \rho \rangle = -i[H + n_0 H_I, \langle \rho \rangle] - \Omega^2 n_0^2 [H_I, [H_I, \langle \rho \rangle]]$$

$$\langle \rho \rangle^{(\nu_\mu)} = \frac{1}{2} 1_2 + \sin(2\theta) \frac{s_1}{2} + \cos(2\theta) \frac{s_3}{2}$$

$$\langle \rho \rangle^{(\nu_\tau)} = \frac{1}{2} 1_2 - \sin(2\theta) \frac{s_1}{2} - \cos(2\theta) \frac{s_3}{2}$$

$$P_{\nu_\mu \to \nu_\tau}(t) = Tr\left(\langle \rho \rangle (t) \langle \rho \rangle^{(\nu_\tau)}\right)$$

$$P_{\nu_\mu \to \nu_\tau} =$$

$$\frac{1}{2} + e^{-\Delta a_{\mu\tau}^2 \Omega^2 t \left(1 + \frac{\Delta_{12}^2}{4\Gamma}(\cos(4\theta) - 1)\right)} \sin(t\sqrt{\Gamma}) \sin^2(2\theta) \Delta a_{\mu\tau}^2 \Omega^2 \Delta_{12}^2 \left(\frac{3\sin^2(2\theta)\Delta_{12}^2}{4\Gamma^{5/2}} - \frac{1}{\Gamma^{3/2}}\right)$$

$$- e^{-\Delta a_{\mu\tau}^2 \Omega^2 t \left(1 + \frac{\Delta_{12}^2}{4\Gamma}(\cos(4\theta) - 1)\right)} \cos(t\sqrt{\Gamma}) \sin^2(2\theta) \frac{\Delta_{12}^2}{2\Gamma}$$

$$- e^{-\frac{\Delta a_{\mu\tau}^2 \Omega^2 t \Delta_{12}^2 \sin^2(2\theta)}{\Gamma}} \frac{(\Delta a_{\mu\tau} + \cos(2\theta)\Delta_{12})^2}{2\Gamma}$$

$$\Gamma = (\Delta a_{\mu\tau}\cos(2\theta) + \Delta_{12})^2 + \Delta a_{\mu\tau}^2 \sin^2(2\theta) \qquad \Delta_{12} = \frac{\Delta m_{12}^2}{2k} \qquad \Delta a_{\mu\tau} \equiv a_{\nu_\mu} - a_{\nu_\tau}$$

Damping exponent

$$\text{exponent} \sim -\Delta a_{\mu\tau}^2 \Omega^2 t f(\theta) \; ; \; f(\theta) = 1 + \frac{\Delta_{12}^2}{4\Gamma}(\cos(4\theta) - 1) \; , \; \text{or} \; \frac{\Delta_{12}^2 \sin^2(2\theta)}{\Gamma}$$

$$\Delta a_{\mu\tau} \propto G_N n_0$$

Stochastic fluctuations of Space-Time metric backgrounds

1+1, no spin

$g = \mathcal{O}\eta\mathcal{O}^T$ $\eta = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$ $\mathcal{O} = \begin{pmatrix} a_1+1 & a_2 \\ a_3 & a_4+1 \end{pmatrix}$

$\langle a_i \rangle = 0 \qquad \langle a_i a_j \rangle = \delta_{ij}\sigma_i$ - random variables

$\phi(x,t) \simeq \varphi(k,\omega)e^{-i(-\omega t+kx)}$ - plane wave solution of KG equation

$\omega = \omega(g^{\mu\nu}, k, M)$ - dispersion relation

$$\text{Prob}(1 \to 2) = \sum_{j,l} U_{1j}U^*_{2j}U^*_{1l}U_{2l}e^{i(\omega_l-\omega_j)t}$$

$$P_{\nu_\mu \to \nu_\tau}(t) = U_{12}U^*_{22}U^*_{11}U_{21}e^{i(\omega_1-\omega_2)t} + U_{11}U^*_{21}U^*_{12}U_{22}e^{i(\omega_2-\omega_1)t}$$

$$\Xi = \begin{pmatrix} \frac{1}{\sigma_1} & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma_2} & 0 & 0 \\ 0 & 0 & \frac{1}{\sigma_3} & 0 \\ 0 & 0 & 0 & \frac{1}{\sigma_4} \end{pmatrix}$$

- covariance matrix for random variables

average over the stochastic space-time fluctuations

$$\langle e^{i(\omega_1-\omega_2)t} \rangle \equiv \int d^4a \, \mathrm{exp}(-\vec{a}\cdot\Xi\cdot\vec{a}) e^{i(\omega_1-\omega_2)t} \frac{\det \Xi}{\pi^2}$$

$$\langle e^{i(\omega_1-\omega_2)t} \rangle \propto e^{-(...)t} e^{-(...)t^2}$$

- combined time evolution

Lindblad-type

(F. Benatti and R. Floreanini, 2001)

No energy dependence

$$P_{\nu_\mu \to \nu_\tau} = \frac{1}{2}\sin^2(2\theta_{23})\left[1 - \exp(-5 \cdot 10^9 \gamma_0 L)\cos\left(\frac{2.54\Delta m^2}{E}L\right)\right]$$

Inversely proportional to energy

$$P_{\nu_\mu \to \nu_\tau} = \frac{1}{2}\sin^2(2\theta_{23})\left[1 - \exp(\frac{-2.54\gamma^2_{-1}L}{E})\cos\left(\frac{2.54\Delta m^2}{E}L\right)\right]$$

Proportional to energy squired

$$P_{\nu_\mu \to \nu_\tau} = \frac{1}{2}\sin^2(2\theta_{23})\left[1 - \exp(-5 \cdot 10^{27} \gamma_2 E^2 L)\cos\left(\frac{2.54\Delta m^2}{E}L\right)\right]$$

γ_0 [eV] $\quad \gamma^2_{-1}$ [eV^2] $\quad \gamma_2$ [eV^{-1}]

Gravitational MSW

$$P_{\nu_\mu \to \nu_\tau} = \frac{1}{2} - \exp(-\kappa_1)\frac{\cos^2(2\theta_{23})}{2} - \frac{1}{2}\exp(-\kappa_2)\cos\left(\frac{2.54\Delta m^2}{E}L\right)\sin^2(2\theta_{23})$$

No energy dependence

$$\kappa_1 = 5\cdot 10^9 \alpha^2 L \sin^2(2\theta);\ \ \kappa_2 = 5\cdot 10^9 \alpha^2 L(1 + 0.25(\cos(4\theta) - 1))$$

$$\kappa_1 = 2.5\cdot 10^{19} \alpha_1^2 L^2 \sin^2(2\theta);\ \ \kappa_2 = 2.5\cdot 10^{19} \alpha_1^2 L^2(1 + 0.25(\cos(4\theta) - 1))$$

$$\kappa_1 = (5\cdot 10^9 \gamma_1^2 L + 2.5\cdot 10^{19} \gamma_2^2 L^2)\sin^2(2\theta);$$

$$\kappa_2 = (5\cdot 10^9 \gamma_1^2 L + 2.5\cdot 10^{19} \gamma_2^2 L^2)(1 + 0.25(\cos(4\theta) - 1))$$

Proportional to energy

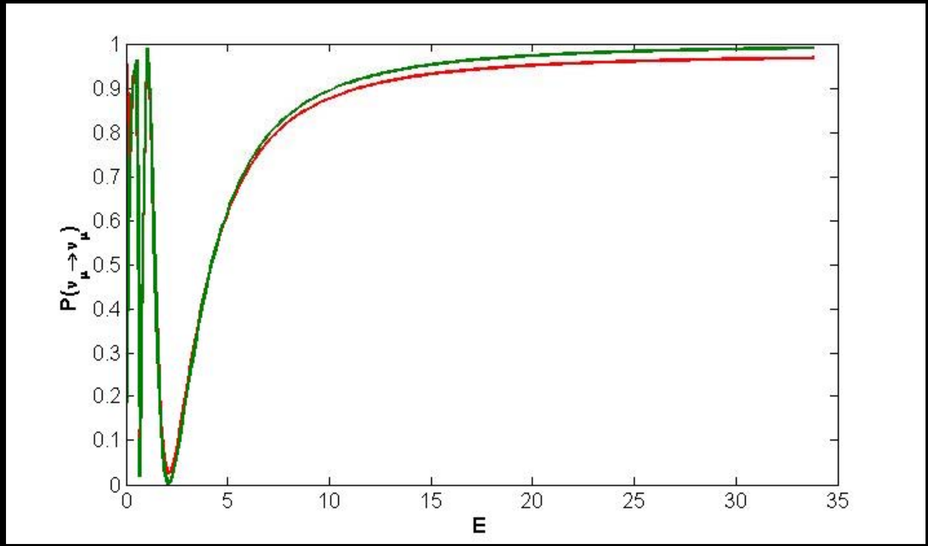
$$\kappa_1 = 5\cdot 10^{18} \beta^2 EL \sin^2(2\theta);\ \ \kappa_2 = 5\cdot 10^{18} \beta^2 EL(1 + 0.25(\cos(4\theta) - 1))$$

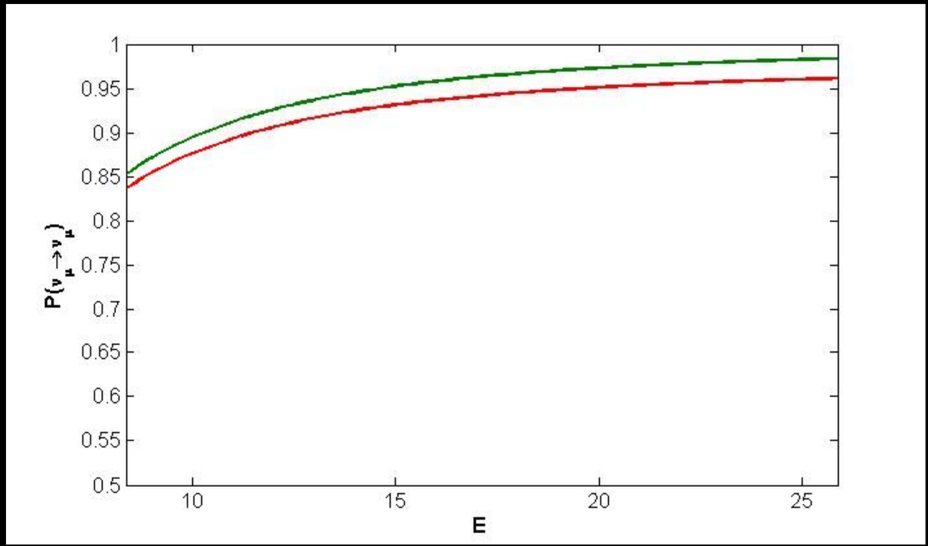
$$\kappa_1 = 2.5\cdot 10^{28} \beta_2^2 EL^2 \sin^2(2\theta);\ \ \kappa_2 = 2.5\cdot 10^{28} \beta_2^2 EL^2(1 + 0.25(\cos(4\theta) - 1))$$

$$\kappa_1 = (5\cdot 10^{18} \gamma_1'^2 EL + 2.5\cdot 10^{28} \gamma_2'^2 EL^2)\sin^2(2\theta);$$

$$\kappa_2 = (5\cdot 10^{18} \gamma_1'^2 EL + 2.5\cdot 10^{28} \gamma_2'^2 EL^2)(1 + 0.25(\cos(4\theta) - 1))$$

- *Modify the standard oscillation formula including damping factors*
- *Generate fake data with standard neutrino oscillation formula*
- *Calculate χ^2*
- *Qualitatively, we observe both the spectral distortion and suppression in the number of events, if there is decoherence, in addition to the conventional oscillations*





CNGS

CERN-SPS $\xrightarrow{\nu_\mu \qquad\qquad \nu_\mu \;\; \nu_\tau}$ ***OPERA***

L=732 km ***<E$_\nu$>=17 GeV; 4.5£ 10^{21} pot/year*** ***5 years*** ***2kT photo-emulsion***

Measure ν_μ spectrum by reconstructing μ from CC events

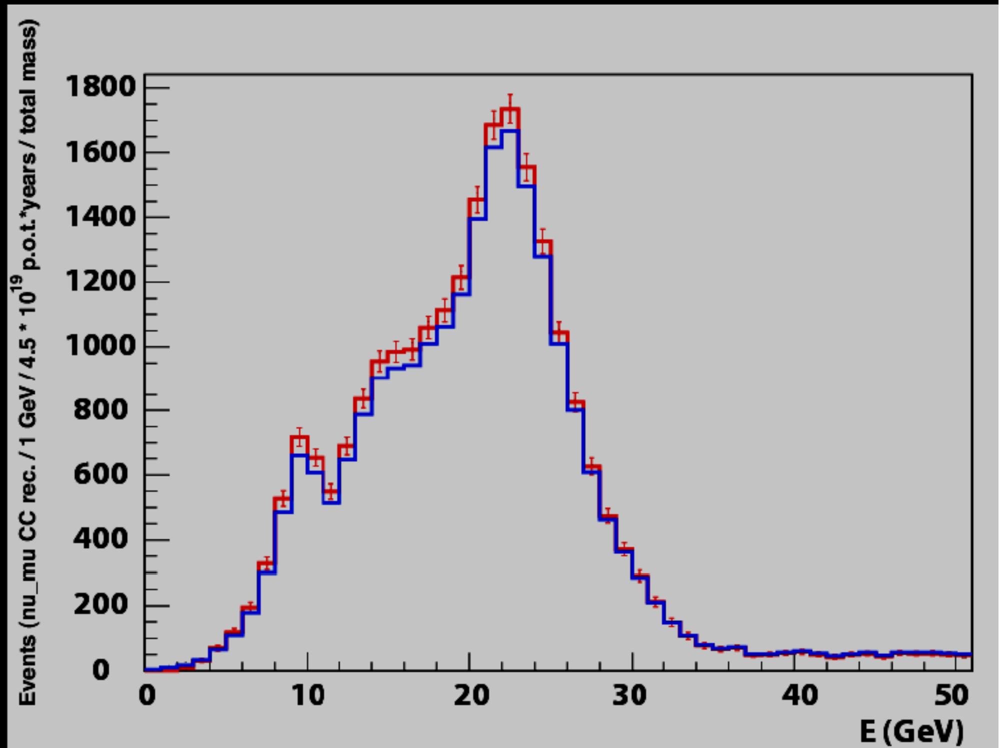
$$\frac{dN_{\mu\mu}}{dE} = A_{\mu\mu}\frac{d\phi_{\nu_\mu}}{dE}P_{\nu_\mu\to\nu_\mu}\sigma^{CC}_{\nu_\mu}(E)\epsilon_{\mu\mu}$$

$$\epsilon_{\mu\mu} = 93.5\% \quad \tilde{\sigma} = 0.2 \quad \Delta E = 20\%$$

$$\chi^2 = \sum_i [x_i - aP_i]^2/\sigma_i^2 + (1-a)^2/\tilde{\sigma}^2$$

$$\Delta m^2 = 2.5\cdot 10^{-3}\text{eV}^2$$

$$\theta_{23} = 45^\circ$$



J-PARC Tokay ν_μ → ν_μ ν_e SK

L=295 km <E$_\nu$>=600 MeV; 1.0£ 10^{21} pot/year 5 years

T2K- 22.5 kT water cherenkov

Measure ν_μ spectrum by reconstructing single- Cherenkov- ring μ QE and non-QE events

Near detector

$$\tilde{\sigma} = 0.05$$

Maximal oscillation point

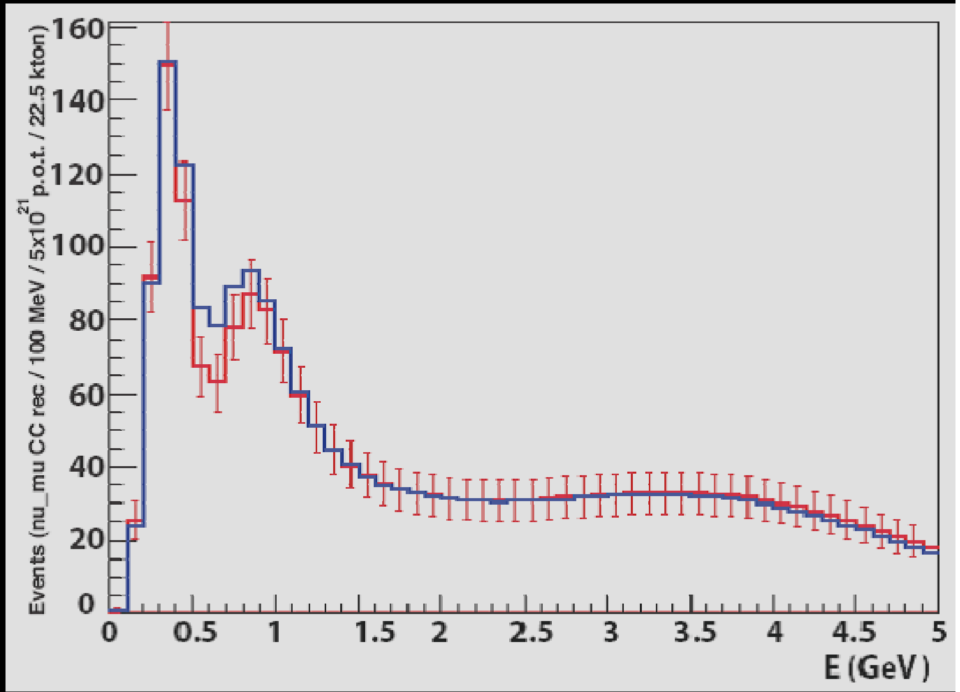
$$\tilde{\sigma}_{\text{applied}} = 0.20$$

$\epsilon_{\mu\mu} = 95\%$ $\Delta E = 20\%$

Off axis 2^0

T2KK 100 kT Argon

$\epsilon_{\mu\mu} = 95\%$ $\Delta E = 15\%$



Lindblad-type	CNGS	T2K	T2KK
γ_0 [eV] ; ([GeV])	2×10^{-13} ; (2×10^{-22})	2.4×10^{-14} ; (2.4×10^{-23})	1.7×10^{-14} ; (1.7×10^{-23})
γ_{-1}^2 [eV^2] ; ([GeV^2])	9.7×10^{-4} ; (9.7×10^{-22})	3.1×10^{-5} ; (3.1×10^{-23})	6.5×10^{-5} ; (6.5×10^{-23})
γ_2 [eV^{-1}] ; ([GeV^{-1}])	4.3×10^{-35} ; (4.3×10^{-26})	1.7×10^{-32} ; (1.7×10^{-23})	3.5×10^{-33} ; (3.5×10^{-24})
Gravitational MSW	**CNGS**	**T2K**	**T2KK**
α^2	4.3×10^{-13} eV	4.6×10^{-14} eV	3.5×10^{-14} eV
α_1^2	1.1×10^{-25} eV^2	3.2×10^{-26} eV^2	6.7×10^{-27} eV^2
β^2	3.6×10^{-24}	5.6×10^{-23}	1.7×10^{-23}
β_2^2	9.8×10^{-37} eV	4×10^{-35} eV	3.1×10^{-36} eV
β_1^2	8.8×10^{-35} eV^{-1}	3.5×10^{-32} eV^{-1}	7.2×10^{-33} eV^{-1}

Atmospheric

$$\gamma_0 < 0.4 \times 10^{-22}\ \mathrm{GeV}$$
$$\gamma_2 < 0.9 \times 10^{-27}\ \mathrm{GeV}^{-1}$$
$$\gamma_{-1}^2 < 0.7 \times 10^{-21}\ \mathrm{GeV}^2$$

Solar + KamLand

$$\gamma_0 < 0.67 \times 10^{-24}\ \mathrm{GeV}$$
$$\gamma_2 < 0.47 \times 10^{-20}\ \mathrm{GeV}^{-1}$$
$$\gamma_{-1}^2 < 0.78 \times 10^{-26}\ \mathrm{GeV}^2$$

(E. Lisi, A. Marrone and D. Montanino, 2000; Fogli, et al, 2007)

Concluding remarks

- *CNGS and J-PARC beams are very sensitive, in some particular cases, to QG induced decoherence effects*
- *In principle, the problem to distinguish between different dependences of damping exponents can be resolved it there are two baselines*
- *Damping signatures could be mimicked by uncertainties in determination of neutrino energy and propagation length*
- *Long baseline experiments are less affected by the risk of erroneous misinterpretations of conventional effects as a signature of decoherence*

Spare slides

Synchronization

GPS discipline oscillations (GPSDO)

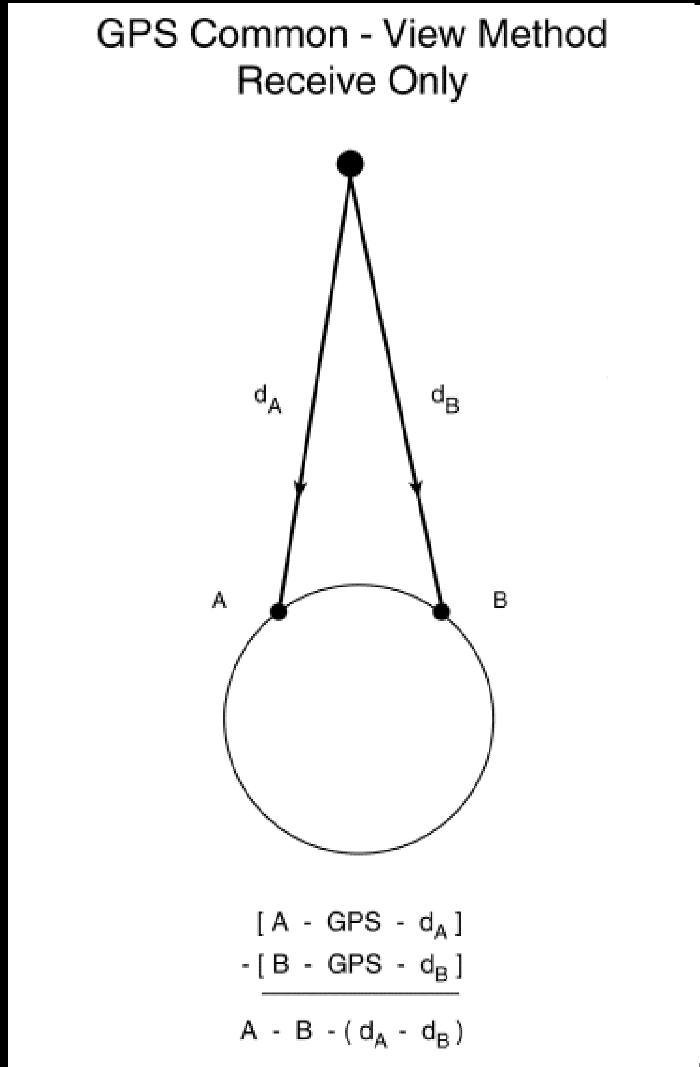
“Common-view” GPS, the same GPS satellite for CERN and LNGS clock

“Carrier-Phase” GPS, carrier frequency instead of the codes transmitted by the satellite

Optical timing synchronization

Common View GPS Time Transfer

Two stations, A and B, receive a one-way signal simultaneously from a single transmitter and measure the time difference between this received signal and their own local clock



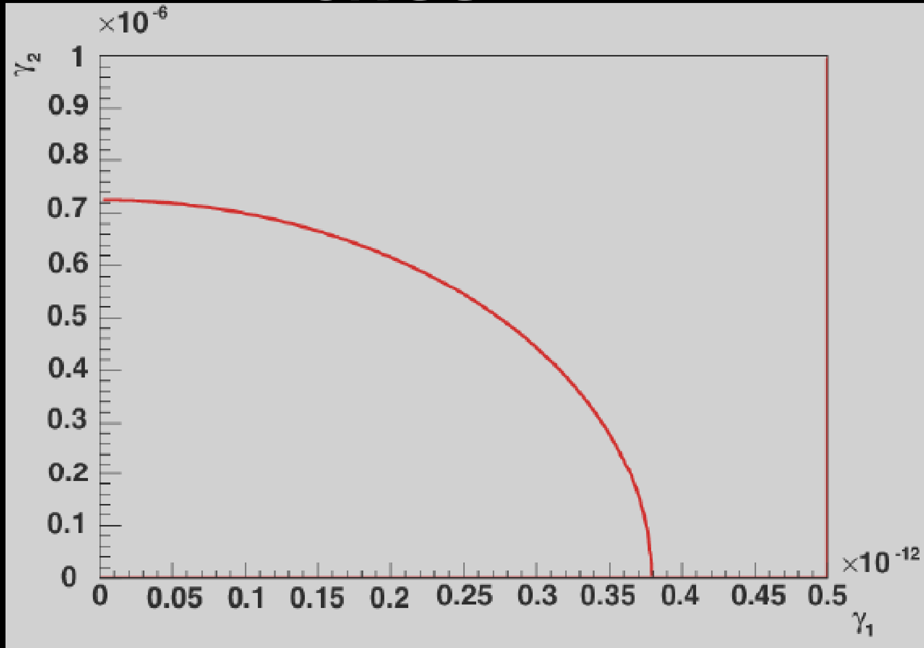
Each station observes the time difference between its clock and GPS time plus a propagation delay, which can be largely removed by using the one-way GPS time transfer procedures.

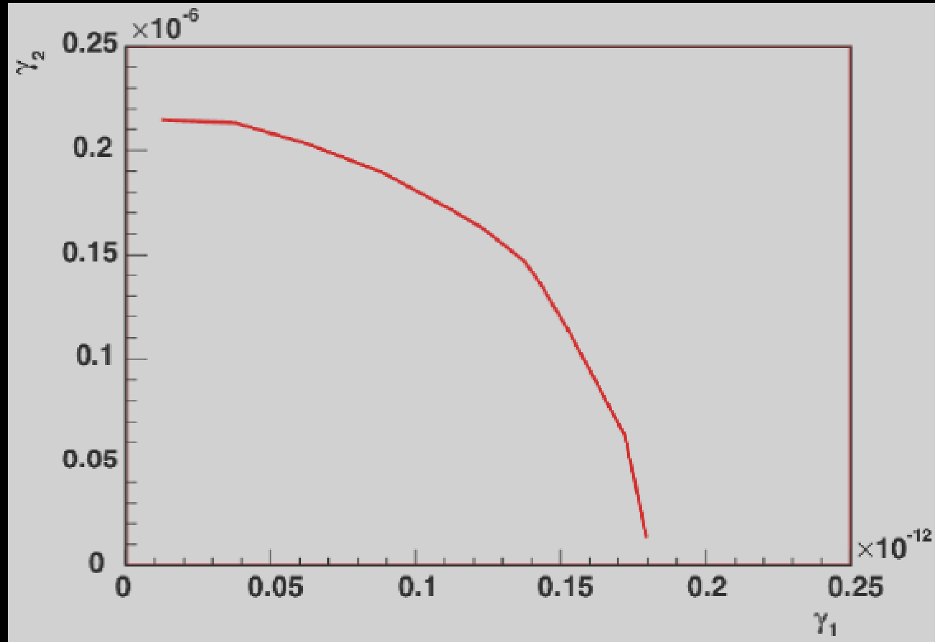
By exchanging data files and performing a subtraction, the time difference between the two receiving stations is obtained and the GPS clock drops out

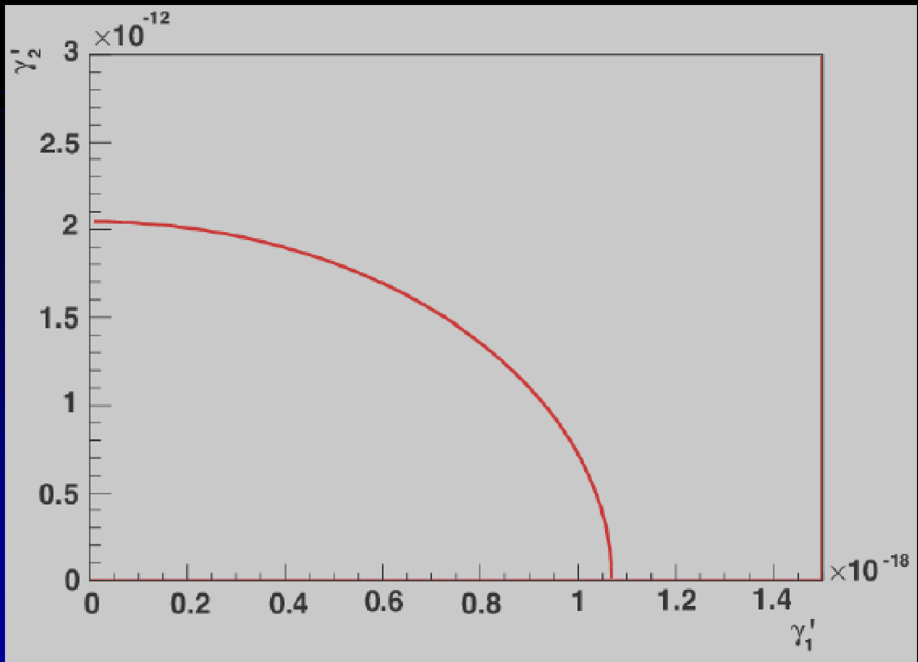
The accuracy of common-view time transfers is typically in the 1 to 10 ns range

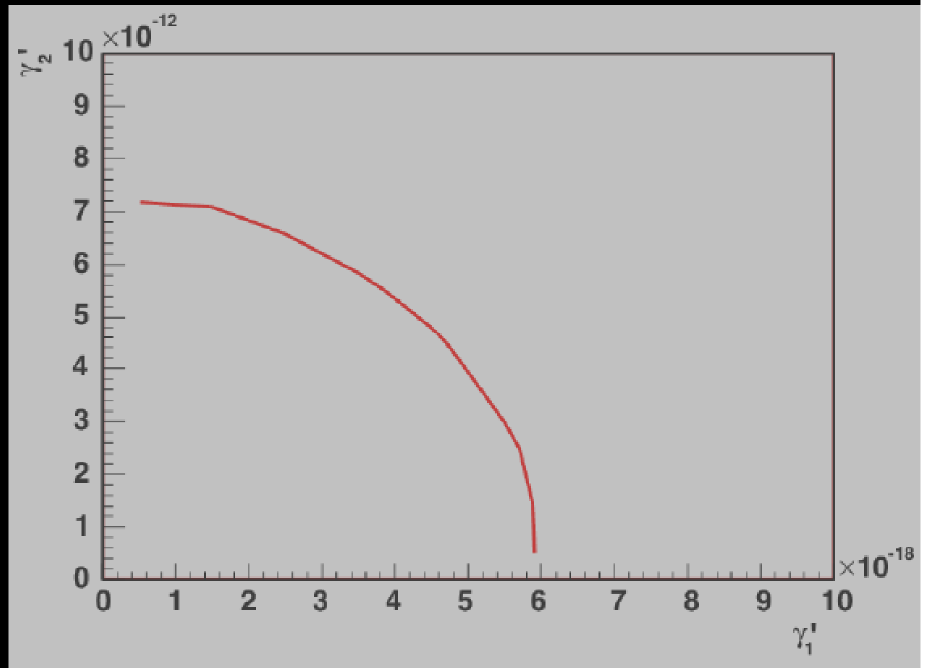
CNGS

J-PARC T2K









Since in practice neutrino wave is neither detected nor produced with sharp energy of well-defined propagation length, we have to average over the L/E dependence etc

$$\langle P \rangle = \int_{-\infty}^{\infty} dx P(x) \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-l)^2}{2\sigma^2}}$$

$$l = \langle x \rangle$$

$$\sigma = \sqrt{\langle (x - \langle x \rangle)^2 \rangle}$$

$$x = \frac{L}{4E} \longrightarrow \langle x \rangle = \frac{\langle L \rangle}{4\langle E \rangle}$$

$$\langle 2 \sin^2(\Delta m^2_{ab} x) \rangle$$

$$\langle P_{\alpha\beta} \rangle = \delta_{\alpha\beta} -$$

$$2 \sum_{a=1}^{n} \sum_{b=1, a<b}^{n} \text{Re}\left(U^*_{\alpha a} U_{\beta a} U_{\alpha b} U^*_{\beta b}\right)\left(1 - \cos(2\ell \Delta m^2_{ab}) e^{-2\sigma^2(\Delta m^2_{ab})^2}\right) -$$

$$2 \sum_{a=1}^{n} \sum_{b=1, a<b}^{n} \text{Im}\left(U^*_{\alpha a} U_{\beta a} U_{\alpha b} U^*_{\beta b}\right) \sin(2\ell \Delta m^2_{ab}) e^{-2\sigma^2(\Delta m^2_{ab})^2}$$

$$\langle \sin(2\Delta m^2_{ab} x) \rangle$$

$$\langle P_{\mu\tau}\rangle(\langle L\rangle,\langle E\rangle) = \frac{1}{2}\sin^2 2\theta \left(1 - e^{-2\sigma^2(\Delta m^2_{\mu\tau})^2}\cos\frac{\Delta m^2_{\mu\tau}\langle L\rangle}{2\langle E\rangle}\right)$$

$$\sigma = \frac{L}{4E}r$$

pessimistic $$r = \frac{\Delta L}{L} + \frac{\Delta E}{E}$$

optimistic $$r = \sqrt{\left(\frac{\Delta L}{L}\right) + \left(\frac{\Delta E}{E}\right)}$$

$$\gamma_0 L = 2\sigma^2(\Delta m^2_{\mu\tau})^2$$

$$\gamma_0 = \frac{2\sigma^2(\Delta m^2_{\mu\tau})^2}{L}$$

$$\gamma_0 = \frac{(\Delta m^2_{\mu\tau})^2 L}{8E^2}r^2$$

Atmospheric

$R \simeq 6400$ km

$d \simeq 10$ km

$$\frac{\Delta L}{L} = \frac{R}{\sqrt{R^2 \cos^2\vartheta + 2Rd + d^2}} \Delta \cos\vartheta$$

$L(\cos\vartheta = -0.95) \simeq 12000$ km $\quad \Delta L/L \simeq 0.11 \quad \Delta E/E \sim 1$

$$\sigma_{\rm atm} \approx 3 \times 10^{-4}\ m/eV$$

$$\gamma_0^{\rm atm} = 2 \frac{(\Delta m^2_{\mu\tau})^2}{L(\cos\vartheta = -0.95)} \sigma^2_{\rm atm} \sim 10^{-24}\ \text{GeV}$$

GNGS

$L \simeq 1000$ km $\quad \Delta L/L \simeq 0.001 \quad \Delta E/E \simeq 0.2$

$\sigma_{\rm cngs} \approx 2 \times 10^{-6}\ m/eV \qquad \gamma_0^{\rm CNGS} \sim 10^{-28}$ GeV