GRK1147 Introductory talk

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A bit about me:

- undergraduate and master's at Pontificia Universidad Católica del Perú, in Lima
- mainly worked on tests of new physics in the astrophysical UHE neutrino flux
  - ▷ *CPT* violation

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  - ▷ comparison of two AGN neutrino production models

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  - ▷ a low-energy β-beam to explore the Earth's crust

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– why study new physics with UHE ν's?

The standard, mass-driven, neutrino flavour-oscillation mechanism predicts

$$P_{\alpha\beta} \equiv P_{\nu_\alpha \to \nu_\beta} \propto \sin^2\left(E^{-1}\right) .$$

Super-Kamiokande found, in the range $10\text{ MeV} \lesssim E \lesssim 100\text{'s TeV}$,

$$P_{\alpha\beta} \propto \sin^2\left(E^n\right), \quad n = -0.9 \pm 0.4 \text{ (90\% C.L.)} .$$

$\therefore$ At these energies, other mechanisms, if present, are *subdominant*.

At higher energies, $P_{\alpha\beta}$ could be affected by new physics such as

- ▶ Modifications to the energy-momentum relation ◀
- ▶ Violation of *CPT* symmetry ◀
- ▶ Supersymmetry ◀
- ▶ Extra dimensions
- ▶ . . .

The most energetic ν's (up to $\sim 10^{10}$ GeV) are expected from cosmological sources:

- ▷ active galactic nuclei (AGN)
- ▷ gamma ray bursts (GRBs)

We have tried to answer:

To what extent are new physics contributions to high-energy neutrino oscillations currently allowed/detectable?

– general scheme for introducing new physics in UHE ν's

$$\left(\phi_e^0 : \phi_\mu^0 : \phi_\tau^0\right) = (1:2:0)\,,(1:0:0)\,,(0:1:0), \text{etc.}$$

$$P_{\alpha\beta}$$

New physics affects the transition probability

$$\langle P_{\alpha\beta}\rangle = \sum_{i=1}^{3} \left|U_{\alpha i}\right|^2 \left|U_{\beta i}\right|^2$$

and so the flavour composition at Earth,

$$\left(\phi_e : \phi_\mu : \phi_\tau\right)$$

$$\phi_\alpha = \sum_{\beta=e,\mu,\tau} \langle P_{\beta\alpha}\rangle \phi_\beta^0$$

are affected, too ⇢ we study these deviations

CPT is (apparently) a fundamental symmetry of Nature

More precisely . . .

at the explored energies (> TeV), all known interactions are *CPT*-invariant.

interaction	*C*	*P*	*T*	*CP*	*CPT*
gravitational	✓	✓	✓	✓	✓
electromagnetic	✓	✓	✓	✓	✓
strong	✓	✓	✓	✓	✓
weak	×	×	×	×	✓

$\therefore$ The SM has been designed to be invariant under this symmetry.

But, at higher, unexplored, energies, *CPT* could no longer be conserved.

CPT violation through a modified dispersion relation

From

$$E^2 = |\mathbf{p}_i|^2 + m_i^2 + b_i|\mathbf{p}_i|^2 E^{-1}$$

we can derive

$$P_{\alpha\beta}(E,L) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin^2\left(\frac{\Delta m_{ij}^2}{4E} + \frac{b_{ij}}{4}L\right) ,$$

with b_{ij} independent of E.

At high energies, $\Delta m_{ij}^2/(4E) \to 0$, oscillations are too rapid, and we use an average probability instead, i.e.,

$$P_{\alpha\beta}(E \gg 1) \to \langle P_{\alpha\beta}(b_{ij})\rangle \text{ (const.)}$$

Flavour composition at Earth, assuming $\left(\phi_e^0 : \phi_\mu^0 : \phi_\tau^0\right) = (1/3 : 2/3 : 0)$:

$$\langle \phi_\alpha(b_{ij})\rangle = \sum_\beta \langle P_{\beta\alpha}(b_{ij})\rangle \phi_\beta^0 = \begin{cases} 1/3 & , \text{ for standard oscillations } (b_{ij} = 0) \\ \text{not } 1/3 & , \text{ if CPTV is allowed } (b_{ij} \neq 0) \end{cases}$$

Is it possible to obtain $\langle \phi_\alpha(b_{ij})\rangle \neq 1/3$ given the current bounds on b_{ij}?

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Current bounds from atm., solar, SK and K2K ν's, at low energies ($\lesssim$ 1 TeV):

$$b_{21} \leq 1.6 \times 10^{-21} \text{ GeV} \quad , \quad b_{32} \leq 5.0 \times 10^{-23} \text{ GeV}$$

In our analysis we

- use AGN neutrinos: $E \lesssim 10^{12}$ GeV, $L \sim 100$ Mpc
- take into account cosmological expansion
- assume limited detector resolution ⇒ use energy-averaged flavour ratios

Best-case scenario (b_{ij} = upper bounds):

$\langle \phi_\mu \rangle \neq 1/3$ only for $E_o \gtrsim 10^{16.5}$ GeV

$> 10^4$ times higher than the maximum energy of AGN ν's

$\therefore$ *CPT* violation is **not** detectable in the UHE ν flux *if* it only modifies the osc. phase.

So we will now modify both phase and amplitude ▶

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CPT violation in the Standard Model Extension

We use the Standard Model Extension (SME):

- D. Colladay and V. A. Kostelecky, 1998
- Augments the SM to include spontaneous breaking of *CPT*
- Generic couplings that violate Lorentz and *CPT*
- Does not affect the gauge structure or renormalisability of the SM

D. COLLADAY, V.A. KOSTELECKY, *Phys. Rev.* **D 55**, 6760 (1997) [HEP-PH/9703464]
D. COLLADAY, V.A. KOSTELECKY, *Phys. Rev.* **D 58**, 116002 (1998) [HEP-PH/9809521]

$$\mathcal{L}^{\text{SME}}_{\text{leptons}} \supset \mathcal{L}^{\nu}_{\text{CPTV}} = b_{\mu\alpha\beta}\overline{\nu}_{\alpha}\gamma^{\mu}\nu_{\beta}$$

- *CPT*-odd Lorentz violation ($b_{\mu\alpha\beta} \in \mathbf{R}$ and $\overline{\nu}_{\alpha}\gamma^{\mu}\nu_{\beta}$ is *CPT*-odd)
- model-independent vector coupling
- introduces *E*-independent contributions $\propto b_{ij} \equiv b_i - b_j$

$$H_{\text{tot}} = H_{\text{vac}}\left(\{\theta_{ij}\}, \left\{\Delta m^2_{ij}\right\}, \delta_{\text{CP}}\right) + H_{\text{CPTV}}\left(\{\theta_{bij}\}, \{b_{ij}\}, \delta_b, \phi_{b2}, \phi_{b3}, \lambda\right)$$

(i) Std. mixing parameters fixed by experiments.

(ii) All phases set to zero.

(iii) λ controls the intensity of the CPTV:
  - ▷ $\lambda = 0$: no CPTV
  - ▷ $\lambda = 100$: dominant CPTV

$\Rightarrow$ Free (unknown) parameters: λ, θ_{b12}, θ_{b13}, θ_{b23}

New (average) probability

$$\langle P_{\alpha\beta}\rangle = \sum_i \left|[U_{\text{tot}}]_{\alpha i}\right|^2 \left|[U_{\text{tot}}]_{\beta i}\right|^2 \Rightarrow \langle \phi_\alpha(\theta_{bij}, \lambda)\rangle = \sum_\beta \langle P_{\beta\alpha}(\theta_{bij}, \lambda)\rangle \phi^0_\beta ,$$

with $U_{\text{tot}} = U_{\text{tot}}$ (std. parameters & CPTV parameters).

We examine the flavour ratios

$$R \equiv \langle\phi_\mu\rangle/\langle\phi_e\rangle \quad , \qquad S \equiv \langle\phi_\tau\rangle/\langle\phi_\mu\rangle \ ,$$

let the std. θ_{ij}, Δm^2_{ij} vary within their 3σ bounds, and $0 \leq \theta_{bij} \leq \pi$:

We also found that it might be possible to identify the presence of CPTV after 15 years of IceCube (not shown)

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Auger reported a correlation between UHECRs (> 55 EeV) and known AGN:

- 29 of them correlated to positions of AGN
- 2 correlated to Centaurus A

Two models of AGN ν production, based on the UHECR-UHEν connection:

- Koers-Tinyakov model – KT (based on MPR model):
  - normalisation assumes all sources behave like Cen A
  - diffuse flux at Earth (GeV^{-1} cm^{-2} s^{-1} sr^{-1}):

$$\phi_{\text{KT}}(E_\nu) \equiv \phi_{\text{KT}}(E_\nu; \alpha)$$

- Becker-Biermann model – BB:
  - normalisation uses all 29 events
  - diffuse flux at Earth:

α, $\Gamma_\nu/\Gamma_{\text{CR}}$, $z_{\text{CR}}^{\text{max}}$ taken as free parameters

$$\phi_{\text{BB}}(E_\nu) \equiv \phi_{\text{BB}}\left(E_\nu; \alpha, \Gamma_\nu/\Gamma_{\text{CR}}, z_{\text{CR}}^{\text{max}}\right)$$

To constrain the models, we let α, $\Gamma_\nu/\Gamma_{\text{CR}}$, $z_{\text{CR}}^{\text{max}}$ vary and compared the resulting $\phi_{\text{KT/BB}}$ with existing bounds on UHEν

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Limit on diffuse flux	$E_\nu^2 \phi_{\nu_\mu}$ [GeV cm^{-2} s^{-1} sr^{-1}]	Energy range [GeV]	Exp. time	Upgoing ν_μ
IceCube-86 prel. 5σ sensitivity (IC86)	$\geq 7 \times 10^{-9}$	$10^{4.5} - 10^7$	5 years	50.28
IceCube-40 prel. upper bound (IC40)	$\leq 8 \times 10^{-9}$	$10^{4.5} - 10^7$	375 days	5.90
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We vary

$$2 \leq \alpha \leq 3 \quad , \quad 1 \leq \Gamma_\nu/\Gamma_{\text{CR}} \leq 20 \quad , \quad 10^{-3} \leq z_{\text{CR}}^{\text{max}} \leq 0.03$$

For each point $\left(\alpha, \Gamma_\nu/\Gamma_{\text{CR}}, z_{\text{CR}}^{\text{max}}\right)$, we calculate the number of ν_μ at IceCube-86, in the range $10^5 \leq E_\nu/\text{GeV} \leq 10^8$, after 5 years:

$$N_{\text{KT}}\left(\alpha\right) \quad , \quad N_{\text{BB}}\left(\alpha, \Gamma_\nu/\Gamma_{\text{CR}}, z_{\text{CR}}^{\text{max}}\right)$$

The KT rates, however, are visible or valid only if, for that value of α,

$$N_{\text{KT}}\left(\alpha; \text{@IC86}\right) \geq \text{IC86 sensitivity} = 50.28$$
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– KT event-rate expectations in IceCube-86: $N_{\mathrm{KT}} = N_{\mathrm{KT}}(\alpha)$

$T = 5$ years
$10^5 \leq E_\nu/\mathrm{GeV} \leq 10^8$
upgoing ν_μ's

upper limit set by
◀ **IC40** upper bound

lower limit set by
IC86 sensitivity ▶

set by **AMANDA**
◀ upper bound

e.g., for "strong" redshift evolution of the sources:

$$85 \leq N_{\mathrm{KT}} \leq 95\,(2709) \quad , \quad 2.25 \leq \alpha \leq 2.27\,(2.81)$$

- We repeated this for BB (not shown), $N_{\mathrm{BB}} = N_{\mathrm{BB}}\left(\alpha, \Gamma_\nu/\Gamma_{\mathrm{CR}}, z_{\mathrm{CR}}^{\mathrm{max}}\right)$, and bounded α, $\Gamma_\nu/\Gamma_{\mathrm{CR}}$, $z_{\mathrm{CR}}^{\mathrm{max}}$
- Also, we found (very small) regions of parameter space where the predictions of the two models can be distinguished at the $5\sigma - 10\sigma$ level

Contents

Current and future work

Currently focused on the neutrino flux from gamma ray bursts (GRBs):

- cosmic-ray propagation from source to Earth including energy losses
- decay and decoherence in the flux of neutrinos from GRBs
- GRB neutrino signals at KM3NeT

A bit down the road:

- GRB neutrino bounds from ANTARES
- cosmogenic neutrinos (detection with JEM/EUSO?)

Thanks!

Backup slides

Contents

Two allowed models of AGN ν flux: $\Phi_{\nu_{\text{all}}} \sim E_\nu^{-\alpha}$

Experimental analogue of R:

$R_{\text{exp}} \equiv N_{\nu_\mu} / \left(N_{\text{sh}}^{\text{CC}} + N_{\text{sh}}^{\text{NC}} \right)$

downgoing ν's, 15 years

$E_\nu \in \left[10^6, 10^{12} \right]$ GeV

1σ away from
solid region ►
boundary

θ_{ij}, Δm^2_{ij} varied within 3σ

all phases set to zero

hatched: std. oscillations

solid: std. oscillations
+ dominant CPTV

MB, A.M. GAGO, C. PEÑA-GARAY, *JHEP* **04**, 066 (2010) [ARXIV:1001.4878] - LIMITS UPDATED TO DECEMBER 2010

Contents

– BB event-rate expectations in IceCube-86: $N_{\mathrm{BB}}\left(\alpha, \Gamma_\nu/\Gamma_{\mathrm{CR}}, z_{\mathrm{CR}}^{\mathrm{max}}\right)$

e.g., for no source evolution:

– comparison between the models

Isocontours of $\Delta \equiv |N_{\mathrm{BB}} - N_{\mathrm{KT}}|$ (in units of $\sigma \equiv \sqrt{N_{\mathrm{KT}}}$) for no source evolution:

comparison valid only within
regions of **simultaneous visibility** ▶

Contents

SUSY RGE effects on UHE neutrinos

Dimension-five operator:

$$\mathcal{L}_\nu = \frac{1}{4}(\overline{L_i^c} H)\frac{m_{ij}^\nu}{\Lambda_\nu}(L_j H)$$

RGE of the mass operator:

$$16\pi^2 \frac{dm_{ij}^\nu}{dx} = C_{\mathrm{SM/MSSM}} \left((Y_e^\dagger Y_e)_{ik}^T m_{kj}^\nu + m_{ik}^\nu (Y_e^\dagger Y_e)_{kj} \right) + \alpha_{\mathrm{SM/MSSM}}\, m_{ij}^\nu \quad (x \equiv \ln(\mu/\mu_0))$$

RGE running of mixing angles θ_{12}, θ_{23}, θ_{13} performed with the `REAP` package

We used:

- $\tan\beta = 50$
- normal mass hierarchy
- $m_1 = 0.43$ eV (from WMAP7-only)
- $\Lambda_{\mathrm{SUSY}} = 1$ TeV
- we set $\mu^2 = Q^2$ to avoid large logarithmic corrections $\Rightarrow \theta_{ij} = \theta_{ij}\left(Q^2\right)$

S. Antusch, J. Kersten, M. Lindner, M. Ratz, M.A. Schmidt, *JHEP* **0503**, 024 (2005) [hep-ph/0501272]
S. Antusch, J. Kersten, M. Lindner, M. Ratz *Nucl. Phys.* **B 674**, 401 (2003) [hep-ph/0305273]

$\phi_e^0 : \phi_\mu^0 : \phi_\tau^0$

$\mu = 10^4$ GeV?

$U'_\nu \neq U_{\text{PMNS}}$

$P_{\alpha\beta}$

$\mu = m_\pi$

$U_\nu = U_{\text{PMNS}}$

$\phi_e : \phi_\mu : \phi_\tau$

$$P_{\alpha\beta}(Q) = \sum_{i=1}^{3} \left|(U_\nu)_{\alpha i}\right|^2 \left|\left(U'_\nu(Q)\right)_{\beta i}\right|^2$$

MB, A.M. GAGO, J. JONES, *JHEP* 1105, 133 (2011) [ARXIV:1012.2728]

$$T \equiv \frac{\phi_{\nu_\mu+\bar{\nu}_\mu}}{\phi_{\nu_e+\bar{\nu}_e} + \phi_{\nu_\mu+\bar{\nu}_\mu} + \phi_{\nu_\tau+\bar{\nu}_\tau}} \qquad R \equiv \frac{\phi_{\nu_e+\bar{\nu}_e}}{\phi_{\nu_\tau+\bar{\nu}_\tau}}$$

Good separation between SM and MSSM for composition at production $\left(\phi^0_{\nu_e+\bar{\nu}_e} : \phi^0_{\nu_\mu+\bar{\nu}_\mu} : \phi^0_{\nu_\tau+\bar{\nu}_\tau}\right) = (1:0:0)$ –

$Q^2 = 10^{11}$ GeV^2

var. only θ_{13}
and phases

full 3σ variation
and phases

Worse for (0 : 1 : 0), (1 : 1 : 0) and (1 : 2 : 0) (not shown).

After applying required cuts on Q^2, we expect $10^{-6} - 10^{-7}$ downgoing ν's at IceCube in 15 yrs $\Rightarrow$ IceCube has no sensitivity to MSSM running through the flavour ratios

Contents

A low-energy β–beam to explore the Earth's crust

C.A. ARGÜELLES, MB, A.M. GAGO, CURRENTLY UNDER EVALUATION [1201.6080]

- ^{6}He ions accelerated to $\gamma = 25$
- decay into low-energy ($5 - 150$ MeV) $\bar{\nu}_e$'s
- sensitive to matter effects
- long baseline: $L_0 = 1500$ km
- carbon target: $\bar{\nu}_e + ^{12}\mathrm{C} \rightarrow e^+ + X$

goal:
try to detect the presence of
deep (> 10 km) underground cavities

Measure sensitivity to the presence of a cavity with

$$\chi^2\left(w, d, \rho\right) = \sum_i^{\text{bins}} \frac{\left[N_i^{\text{cav}}\left(w, d, \rho\right) - N_i^{\text{no-cav}}\right]^2}{N_i^{\text{no-cav}}} \quad \blacktriangleright$$

Cavity identification at 5σ to 10σ is possible

Caveat: luminosity boost ×5000 is required