Leptonic CP violation at neutrino telescopes

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Main motivation of this work

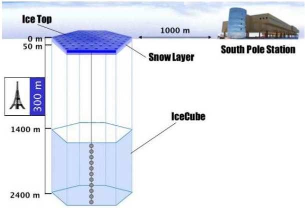
study the sensitivity of neutrino telescopes to leptonic δ_{CP}

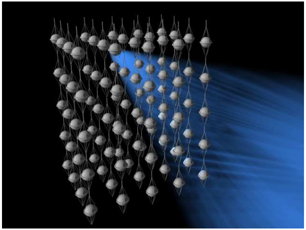
- flavour ratios dependence on the neutrino mixing angles
  - which mixing angle uncertainty affects them the most
  - the dependence on δ_{CP}
- required precision to get useful information on δ_{CP}
  - a χ^2 analysis to distinguish at least among CP-conserving and CP-violating values
- possibility to check flavour models?
  - models with NLO corrections to TBM and BM patterns

D. Meloni and T. Ohlsson, arXiv:1206.6886 [hep-ph]

ICECUBE

It is a large scale (km^3) neutrino telescope currently operating in the Antarctic ice





Neutrino flavors can be identified via their characteristic interaction topology

J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, Phys. Rev. D **68**, 093005 (2003)]

- IceCube has an energy threshold of $\sim$ 100 GeV for detecting muon tracks, and $\sim$ 1 TeV for detecting electron- and tau-related showers
- Above an energy threshold of $\sim$ 1 PeV , it is possible to distinguish between the electron-related electromagnetic showers and the tau-related hadronic showers

L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler, Phys. Lett. B **621**, 18 (2005)

Neutrino flux ratios

- The observable fluxes of astrophysical neutrinos will be a linear combination of the fluxes at source

$$\phi_{\nu_\alpha} = \sum_{\nu_\beta} P(\nu_\alpha \to \nu_\beta)\, \phi^0_{\nu_\beta}$$

- For propagation over astronomical distance scales, the oscillation lengths $\lambda_{ij} = 4\pi E_\nu/|\Delta m^2_{ij}| \ll L$, $P(\nu_\alpha \to \nu_\beta)$ is independent from E_ν and L so that

$$\langle P(\nu_\alpha \to \nu_\beta)\rangle \;=\; \sum_j |U_{\alpha j}|^2\, |U_{\beta j}|^2 \simeq \begin{pmatrix} 0.55 & 0.28 & 0.17 \\ 0.28 & 0.35 & 0.38 \\ 0.17 & 0.38 & 0.46 \end{pmatrix}$$

$(\theta_{23} = 41^\circ,\ \theta_{13} = 9^\circ$ and $\theta_{12} = 33^\circ)$

Neutrino fluxes at the source: ϕ_ν^0

- the dominant source of astrophysical neutrinos is the decay of charged pions into muons and consecutive μ decay (πS)

$$\begin{aligned}\pi &\to \mu\,\nu \\ &\hookrightarrow \mu \to \nu\,\nu\,e\end{aligned}$$

then at the source one expects:

$$\{\nu_e + \overline{\nu}_e, \nu_\mu + \overline{\nu}_\mu, \nu_\tau + \overline{\nu}_\tau\} \sim \{1, 2, 0\}$$

- for sources dominated by pions where muons lose all their energy before decay (μD) we have :

$$\{\nu_e + \overline{\nu}_e, \nu_\mu + \overline{\nu}_\mu, \nu_\tau + \overline{\nu}_\tau\} = \{0, 1, 0\}$$

- on the Earth, ν fluxes depend on the transition probabilities

neutrino fluxes at the detector: ϕ_ν

- better to work with the flavour ratios

$$R_{\alpha\beta} = \frac{\phi_{\nu_\alpha}}{\phi_{\nu_\beta}}$$

- a more experimentally useful variable:

$$R = \frac{\phi_{\nu_\mu}}{\phi_{\nu_e} + \phi_{\nu_\tau}} = R_{\mu e}\frac{1}{1+R_{\tau e}} = (R_{e\mu})^{-1}\frac{1}{1+(R_{e\tau})^{-1}}$$

- expansion in the small parameters:

$$\theta_{13}$$
$$\delta_{23} = \theta_{23} - \pi/4$$
$$\delta_{12} = \theta_{12} - \bar{\theta}_{12}$$

($\bar{\theta}_{12}$ being the best-fit value for θ_{12})

Estimate of the uncertainties for pion-beam sources

up to second order in the small δ_{ij} and θ_{13}

$$R_{e\mu} = 1 + \frac{3}{4}\cos(\delta)\sin(4\theta_{12})\,\theta_{13} - \frac{3}{2}\sin^2(2\theta_{12})\,\delta_{23}$$

$$\sim 1 + 0.5\cos(\delta)\,\theta_{13} - 1.3\,\delta_{23} + \mathcal{O}(\delta_{ij}^2)$$

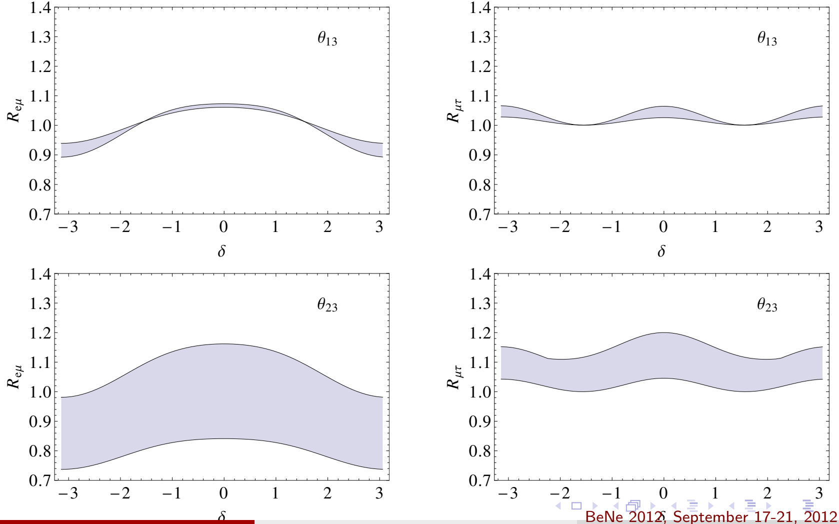
$$R_{\mu\tau} = 1 + 2\cos^2(\delta)\sin^2(2\theta_{12})\,\theta_{13}^2 + 2\cos(\delta)\sin(4\theta_{12})\,\theta_{13}\,\delta_{23} + [\cos(4\theta_{12}) + 7]\;\delta_{23}^2$$

$$\sim 1 + 1.7\cos^2(\delta)\,\theta_{13}^2 + 1.3\cos(\delta)\,\theta_{13}\,\delta_{23} + 6.3\,\delta_{23}^2$$

- numerically, $\delta_{12} \sim 0.05$, $\theta_{13} \sim 0.2$ and $|\delta_{23}| \sim 0.15$
- main uncertainty from the current error on θ_{23}
- the contribution of θ_{13} is modulated by $\delta \longrightarrow$ no impact for $\cos(\delta) \sim 0$
- no dependence on δ_{12} at this order

Estimate of the uncertainties for pion-beam sources

exact results



Estimate of the uncertainties for muon-damped sources

up to second order in the small δ_{ij} and θ_{13}

$$R_{e\mu} = 0.6 + 1.1\,\delta_{12} + 0.7\cos(\delta)\,\theta_{13} - 1.7\,\delta_{23} + \mathcal{O}(\delta_{ij}^2)$$

$$R_{\mu\tau} = 1.0 - 0.4\cos(\delta)\,\theta_{13} + 0.9\,\delta_{23} + \mathcal{O}(\delta_{ij}^2)$$

important differences against πS:

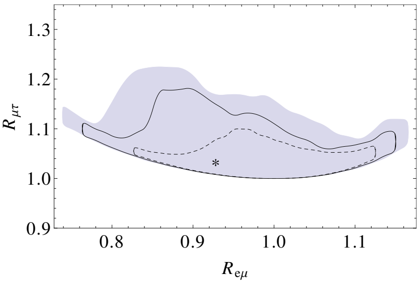
- $R_{e\mu}$ has a leading dependence on δ_{12}
- $R_{\mu\tau}$ is corrected by the standard unit value by linear terms in θ_{13} and δ_{23}

similarities:

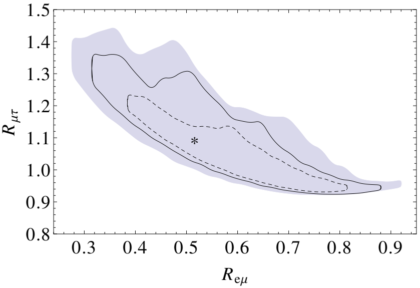
- the uncertainty on θ_{23} is the dominant source of error
- the qualitative behavior of the neutrino flux ratios as functions of δ is similar to the πS's ones

Correlations among flavour ratios

πS



μDS



1,2 and 3 σ bounds

- $R_{e\mu} \in [0.85, 1.18]\,,\ R_{\mu\tau} \in [1.00, 1.21]$
- moderate correlation

- $R_{e\mu} \in [0.27, 0.92]\,,\ R_{\mu\tau} \in [0.92, 1.42]$
- stronger correlation

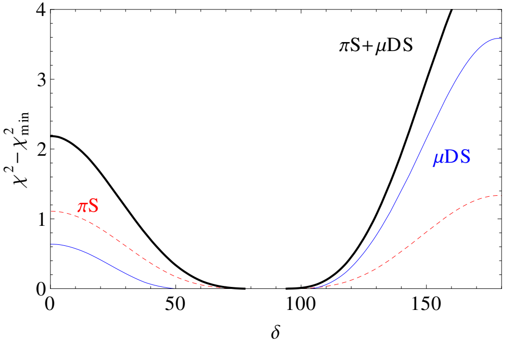
Potential to measure a non-vanishing δ_{CP}

To evaluate how a given true δ_{CP} can be distinguished from other non-vanishing values, we build a simple χ^2 function

$$\chi^2 = \Sigma_{\rm sources} \left\{ \left[\frac{R^{\rm exp} - R(\theta_{ij}, \delta_{CP})}{\sigma_R}\right]^2 + \left[\frac{R_{e\tau}^{\rm exp} - R_{e\tau}(\theta_{ij}, \delta_{CP})}{\sigma_{R_{e\tau}}}\right]^2 \right\}$$

- $R^{\rm exp}$ are ratios evaluated at the best fit points for θ_{ij} and true δ_{CP}
- we consider the possibility of having the sum of both contributions from πS and μDS sources
- we marginalize over all mixing parameters θ_{ij} but δ_{CP}
- the uncertainties (σ) are "experimental" errors on flavour ratios: here we assume an optimistic 5% error

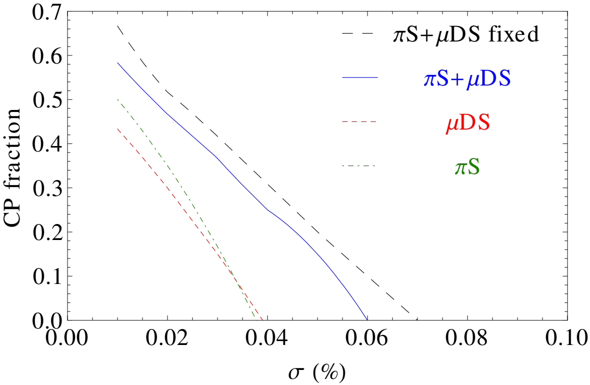
Potential to measure a non-vanishing δ_{CP}



- single sources cannot distinguish a maximally violating phase from 0 or π at 2σ
- only the combination of πS and μDS is useful for $\delta_{CP} = \pi/2$

Potential to measure a non-vanishing δ_{CP}

- same exercise for every input value of δ_{CP} as a function of σ
- at a given confidence level, there exist a range of phases for which $[\chi^2 - \chi^2_{min}](0, \pi) > $ CL: *CP fraction*

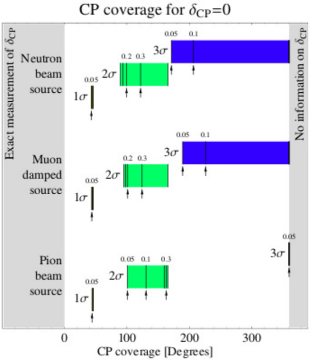


- as expected, large precision in the R's is required

What about combining with long-baseline experiments?

in an earlier study by W. Winter [Phys. Rev. D **74**, 033015 (2006)]:
inclusion of MINOS+Double CHOOZ + T2K and NOνA

- physics potential in term of CP coverage: range of fit values of δ_{CP} which fit the chosen true value, and can be between 0 (precise determination of δ_{CP}) and $360°$ (no information on δ_{CP})



even a 30% measurement of a muon damped flux can have a substantial impact (2σ, $\delta_{CP} = 0$)

Checking flavour models ??

The correlations among the flavour ratios can be used to check flavour models?

- clearly every successful model should overlap to some portion in the $(R_{e\mu}, R_{\mu\tau})$-plane, since they have to reproduce the experimental values of the various mixing angles
- it could happen that a specific model predicts a well-defined correlation between the two neutrino flux ratios that can be checked at neutrino telescopes to favor or disfavor the presumed neutrino mass texture
- as an example, we consider the Bi-Maximal mixing at LO
  $(\sin^2\theta_{23})_{\rm BM} = \frac{1}{2} \qquad (\sin^2\theta_{12})_{\rm BM} = \frac{1}{2} \qquad (\sin\theta_{13})_{\rm BM} = 0$
  with suitable NLO corrections

G. Altarelli, F. Feruglio and L. Merlo, JHEP **0905**, 020 (2009)

D. Meloni, JHEP **1110**, 010 (2011)

Checking flavour models ??

expansion around BM

- for pion-beam sources, we find that

$$(R_{e\mu}^{\pi S})_{\rm BM} = 1 - \frac{3}{2}\,\delta_{23} + \mathcal{O}(\delta_{ij}^2)$$
$$(R_{\mu\tau}^{\pi S})_{\rm BM} = 1 + 2\cos^2(\delta)\,\theta_{13}^2 + 6\,\delta_{23}^2$$

- for muon-damped sources, we obtain

$$(R_{e\mu}^{\mu DS})_{\rm BM} = \frac{2}{3} - \frac{20}{9}\,\delta_{23}\,,$$
$$(R_{\mu\tau}^{\mu DS})_{\rm BM} = 1 + \frac{4}{3}\,\delta_{23}$$

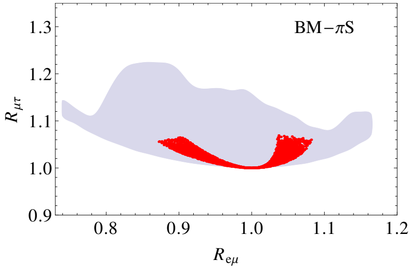
in both cases, no leading dependence on δ_{12} (which should be of $\mathcal{O}(\lambda_{\mathcal{C}})$)

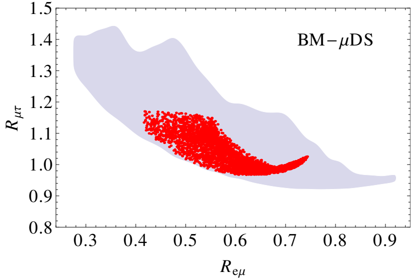
Checking flavour models ??

model-dependent NLO corrections G. Altarelli, F. Feruglio, L. Merlo and E. Stamou, JHEP **1208**, 021 (2012)

$$(s_{23}^2)_{\rm BM} = \frac{1}{2} \quad (s_{12}^2)_{\rm BM} = \frac{1}{2} - \frac{1}{\sqrt{2}}\,{\rm Re}(c_{12}^e + c_{13}^e)\,\xi \quad (s_{13})_{\rm BM} = \frac{1}{\sqrt{2}}\,|c_{12}^e - c_{13}^e|\,\xi$$

- $|c_{ij}^{e,\nu}| \sim \mathcal{O}(1)$ and are entries of unitary matrices diagonalizing the charged lepton and neutrino mass matrices at the next-to-leading order
- $\xi \simeq 0.163$ to maximize the success rate to reproduce all mixing angles inside their corresponding 3σ ranges





large deviations from $R_{\mu\tau} \sim 1$ kill the model

Summary

- We studied the possibility to obtain information from δ_{CP} from flavour ratios at neutrino telescopes
  - this is a difficult task, mainly due to the still large errors on θ_{23} and the experimental difficulty in measuring the flavour ratios
  - notice that no astrophysical high energy sources have not been observed so far, so a more promising possibility would be to use future neutrino telescopes data in synergy with other laboratory experiments
- combining information from astrophysical sources and long-baseline experiments helps
- with enough statistics, flux ratios could be used for an independent check of flavour models