Non-unitarity bounds

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1. Non-oscillation bounds

2. NuFact prospects

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Non-oscillation bounds in general

- We assume the Minimal Unitarity Violation (MUV) Lagrangian (see talk by S. Antusch)

  Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP10(2006)084, hep-ph/0607020

- We will parametrize the non-unitary mixing matrix as

$$N = (1 + \varepsilon)U, \quad \varepsilon = \varepsilon^\dagger$$

- A very usual combination will be $NN^\dagger \simeq 1 + 2\varepsilon$, also note that $(NN^\dagger)^2 \simeq 1 + 4\varepsilon$
- Bounds are taken from:

  Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP10(2006)084, hep-ph/0607020

  Antusch, Baumann, Fernandez-Martinez, NPB810(2009)369, 0807.1003

  See also: Nardi, Roulet, Tommasini, PLB327(1994)319, hep-ph/9402224

  Tommasini, Barenboim, Bernabeu, Jarlskog, NPB(1995)444, hep-ph/9503228

W decays

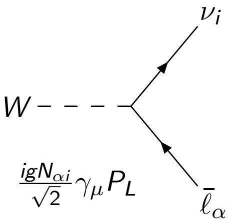
- For the $W \to \ell_\alpha \nu_i$ decay, ν_i is not measured
- Decay rate is

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon,

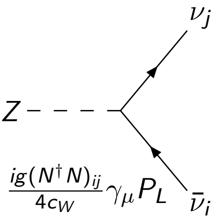
JHEP10(2006)084, hep-ph/0607020

$$\Gamma(W \to \ell_\alpha \nu) = \Gamma_{SM}(W \to \ell_\alpha \nu)(NN^\dagger)_{\alpha\alpha}$$

- Note that the NU effect on the G_F measurement in $\mu \to e\nu\bar{\nu}$ must be considered in bound



Invisible **Z** decay width



- Invisible decay width is

  Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon,

  JHEP10(2006)084, hep-ph/0607020

$$\Gamma(Z \to \mathrm{inv}) = \Gamma_{SM}(Z \to \mathrm{inv})\frac{\mathrm{tr}[(NN^\dagger)^2]}{3}$$

- Must again compensate for NU effect on G_F measurement

Universality tests

- Comparisons between decays with same types of couplings
- Generally constraints combinations such as

$$\frac{(NN^\dagger)_{\alpha\alpha}}{(NN^\dagger)_{\beta\beta}}$$

- Examples include:

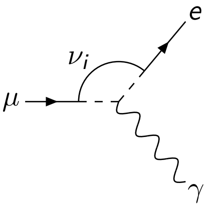
$$\begin{aligned} W \rightarrow e\nu \quad &\text{vs.} \quad W \rightarrow \tau\nu \\ \tau \rightarrow \mu\nu \quad &\text{vs.} \quad \tau \rightarrow e\nu \\ \tau \rightarrow \pi\nu \quad &\text{vs.} \quad \pi \rightarrow \mu\nu \\ &\text{etc.} \end{aligned}$$

Rare lepton decays

- Loop induced processes such as $\ell_\alpha \to \ell_\beta \gamma$
- GIM suppressed in the SM
- Bounds are given by

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP10(2006)084, hep-ph/0607020

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} \simeq \frac{100\alpha}{96\pi} \frac{|(NN^\dagger)_{\alpha\beta}|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}}$$



Off-diagonals from mixing with heavy states

- If NU is due to some mixing with heavy states, then ε is negative semi-definite
- In particular this implies

Antusch, Baumann, Fernandez-Martinez, NPB810(2009)369, 0807.1003

$$|\varepsilon_{\alpha\beta}|^2 \leq |\varepsilon_{\alpha\alpha}\varepsilon_{\beta\beta}|$$

as well as

$$\varepsilon_{\alpha\alpha} < 0$$

Summarized bounds

- Without considering mixing bounds (90 % CL)

$$|\varepsilon_{\alpha\beta}| < \begin{pmatrix} 2.0\times10^{-3} & 0.6\times10^{-4} & 0.8\times10^{-2} \\ 0.6\times10^{-4} & 0.8\times10^{-3} & 0.5\times10^{-2} \\ 0.8\times10^{-2} & 0.5\times10^{-2} & 2.7\times10^{-3} \end{pmatrix}$$

- Including mixing bounds (90 % CL)

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Non-unitarity @ NuFact

- 130 km baseline NuFact,

  see Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda, PLB649(2007)427

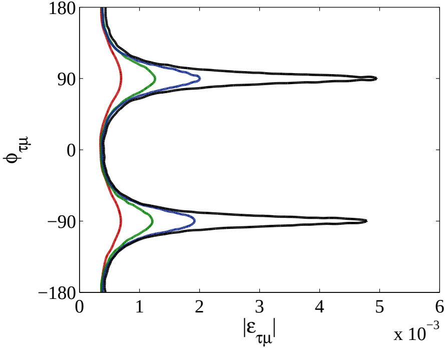
- Thoroughly explored in IDS setup

  Antusch, MB, Fernandez-Martinez, Lopez-Pavon, PRD80(2009)033002, 0903.3986

- All 15 MUV parameters free in MCMC analysis

  MB, Fernandez-Martinez, CPC181(2010)227, 0903.3985

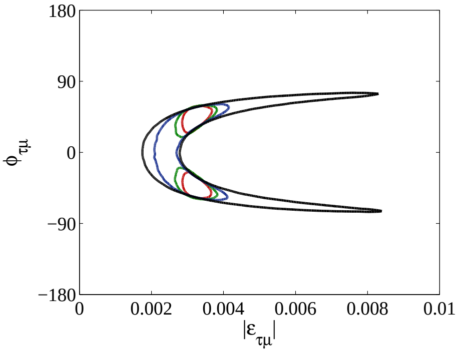
$\varepsilon_{\mu\tau}$ sensitivity



PRD80(2009)033002, 0903.3986

- W/o near detector, good sensitivity to Re($\varepsilon_{\mu\tau}$)
- Near τ-detector bounds absolute value
- Leads to CP-sensitivity

$\varepsilon_{\mu\tau}$ sensitivity



PRD80(2009)033002, 0903.3986

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ν_μ disappearance effect

- The sensitivity to $\text{Re}(\varepsilon_{\mu\tau})$ comes from matter effects in ν_μ disappearance
- To leading order in $\varepsilon_{\alpha\beta}$:

$$P_{\mu\mu} \simeq P_{\mu\mu}^{\text{std}} - 2\,\text{Re}(\varepsilon_{\mu\tau}) AL \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right)$$

$A = \sqrt{2} G_F n_e$

- Similar to effects in, *e.g.*, sterile neutrinos

Donini, Fuki, Lopez-Pavon, Meloni, Yasuda, JHEP08(2009)041, 0812.3703

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Non-unitarity @ MINOS/NOνA

- $\nu_\mu \to \nu_\mu$ channel:
  - Recall the leading NU contribution

$$P_{\mu\mu} \simeq P_{\mu\mu}^{\rm std} - 2\,\mathrm{Re}(\varepsilon_{\mu\tau}) AL \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right)$$

  - Needs large baseline$\times$density
- $\nu_\mu \to \nu_e$ channel:
  - Leading NU effects proportional to $\varepsilon_{e\mu}$
  - Very constrained by $\mu \to e\gamma$

MINSIS near τ detector

- The zero distance effect is

$$P_{\mu\tau}(L=0) = |N^\dagger N|^2_{\mu\tau} = 4|\varepsilon_{\mu\tau}|^2$$

- Only sensitive to absolute value (no CP-violation information)
- Sensitivity to $|\varepsilon_{\mu\tau}|$ is $0.5 \times \sqrt{P_{\mu\tau} \text{ sensitivity}}$
- $P_{\mu\tau} < 10^{-6} \Rightarrow |\varepsilon_{\mu\tau}| < 5 \times 10^{-4}$ – very competitive with NuFact near detector

MINUS near τ detector

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MINUS "near" τ detector

- The MINOS near detector is *not* at $L = 0$
- Standard $\nu_\mu \to \nu_\tau$ term is (@ $L = 1.03$ km)

$$P_{\mu\tau}^{\rm std} \simeq \sin^2(2\theta_{23}) \left(\frac{\Delta m_{31}^2 L}{4E}\right)^2 \simeq 1.16 \times 10^{-5} \left(\frac{1 \text{ GeV}}{E}\right)^2$$

- Interference terms will become important

Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda, PLB649(2007)427, hep-ph/0703098

- Expanded in ε and L, the oscillation probability is

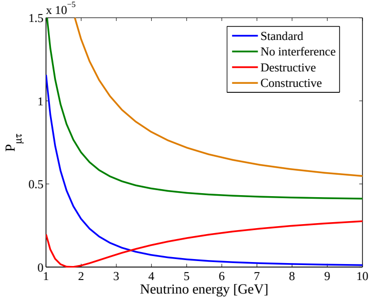
$$P_{\mu\tau} \simeq |2\varepsilon_{\mu\tau} - iH_{\mu\tau}L| = 4|\varepsilon_{\mu\tau}|^2 + |H_{\mu\tau}L|^2 + 4\,\text{Im}(\varepsilon_{\mu\tau}^* H_{\mu\tau})L$$

with $H_{\mu\tau} \simeq \frac{\Delta m_{31}^2}{4E}\sin(2\theta_{23})$

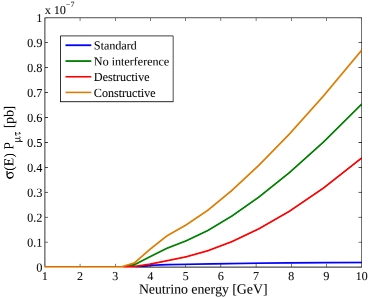
MINUS and CP-violation

As an example, with $\varepsilon_{\mu\tau} = 10^{-3}$ ($\sim$ upper bound)

Oscillation probability



Probability $\times$ X-section



CP-violation could be observable through interference term

Features of MINUS "near" detection

- The standard term CP-violation is severely suppressed by θ_{13}
- A CP-violation signal would therefore indicate CP-violation in the non-standard sector
- If θ_{13} is too small for Double Chooz, could be first short-baseline neutrino oscillation signal
- Interference term is *not* unique to non-unitarity

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Summary

- Non-oscillation bounds are relatively strong
- A NuFact has prospects to see CP-violating signals through matter effects
- MINSIS would not benefit from current far detectors
- MINSIS would be competetive with NuFact near detector
- MINSIS could instead measure non-standard CP-violation through interference
- MINSIS on the verge of detecting standard oscillation terms