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FASERv: a non-unitary of the leptonic mixing matrix

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CONAHCYT

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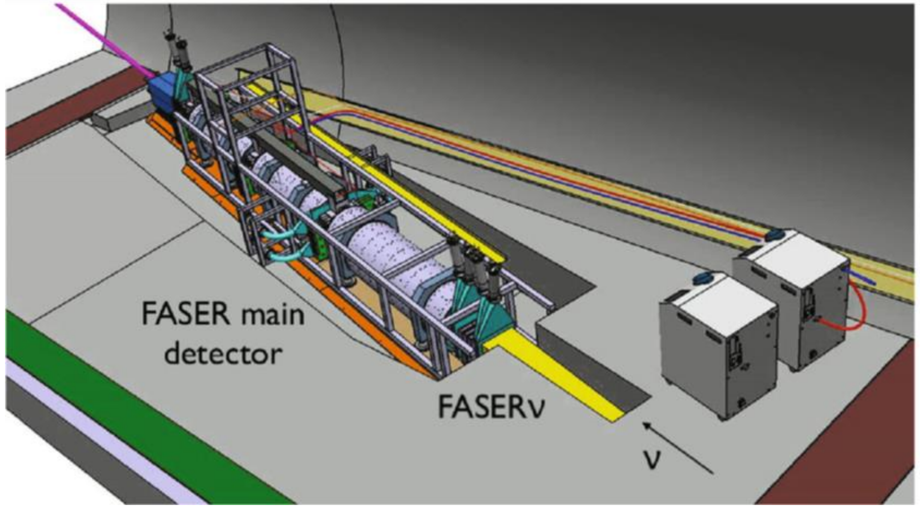
FASER experiment and FASERν (FASERν2) detector

FASERν features[1]:

- has a total Tungsten target mass of 1.2 tons.
- A baseline of 480 m.
- Works from 100 GeV to 1 TeV.
- Expects, approximately, 1000 ν_e, 3000 ν_μ and 20 ν_τ

FASER:
Forw**A**rd **S**earch **E**xpe**R**iment at the LHC



[1]Henso Abreu et al. Eur. Phys. J. C,80(1):61, 2020.
Henso Abreu et al. First Direct Observation of Collider Neutrinos with FASER at the LHC. 3 2023.

The PDG parametrization

$$U = R_{23}(\theta_{23};0)R_{13}(\theta_{13};\delta)R_{12}(\theta_{12};0)P$$

$$R_{13}(\theta_{13};\delta) = \begin{pmatrix} cos\ \theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & cos\ \theta_{13} \end{pmatrix}$$

Dirac phase

$$P = diag(1, e^{i\alpha}, e^{i\beta})$$

Majorana phase

Neutrino oscillation probability

$$P(\nu_\alpha \to \nu_\beta) = \left|\sum_j U^*_{\alpha j}U_{\beta j}e^{\frac{-i\,m_j^2}{2E}L}\right|^2 = \delta_{\alpha\beta} - 4\sum_{i>j}\Re\{U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\}\sin^2\left(\frac{\Delta m^2_{ij}}{4E}L\right) - 2\sum_{i>j}\Im\{U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\}\sin\left(\frac{\Delta m^2_{ij}}{2E}L\right)$$

The symmetric Parametrization and the non-unitary effects

K= $\omega_{23}(\theta_{23};\phi_{23})\omega_{13}(\theta_{13};\phi_{13})\omega_{12}(\theta_{12};\phi_{12})$[2,3]

$$\omega_{23}(\theta_{23};\phi_{23}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & e^{-i\phi_{23}}s_{23} \\ 0 & -e^{i\phi_{23}}s_{23} & c_{23} \end{pmatrix}$$

We can extend this formalism to an arbitrary number of neutral heavy leptons :

$$U_{n\times n} = \omega_{n-1,n} \times \omega_{n-2,n} \times \cdots \omega_{1,n} \times \omega_{n-2,n-1} \times \cdots \omega_{23} \times \omega_{13} \times \omega_{12}$$

$$U_{n\times n} = \begin{pmatrix} N_{3\times 3} & S_{3\times m} \\ T_{m\times 3} & V_{m\times m} \end{pmatrix},\ n = m+3$$

The light neutrino sector is no longer unitary.

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{SM}$$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{ij}^{3} N^*_{\alpha i}N_{\alpha j}N_{\beta i}N^*_{\beta j} - 4\sum_{i>j} \Re\{N^*_{\alpha i}N_{\alpha j}N_{\beta i}N^*_{\beta j}\}\sin^2\left(\frac{\Delta m^2_{ij}}{4E_\nu}L\right) - 2\sum_{i>j} \Im\{N^*_{\alpha i}N_{\alpha j}N_{\beta i}N^*_{\beta j}\}\sin\left(\frac{\Delta m^2_{ij}}{2E_\nu}L\right)$$

[2]J. Schechter and J. W. F. Valle. Phys. Rev. D, 25:2951, 1982.
[3]W. Rodejohann , J.W.F. Valle. Phys.Rev.D 84 (2011), 073011

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The features and approximations of symmetric parametrization

$$P(\nu_\alpha \to \nu_\beta) \approx \sum_{ij}^{3} N^*_{\alpha i} N_{\alpha j} N_{\beta i} N^*_{\beta j}$$

$$P_{ee} = \alpha_{11}^4$$

$$P_{\mu e} = \alpha_{11}^2 |\alpha_{21}|^2$$

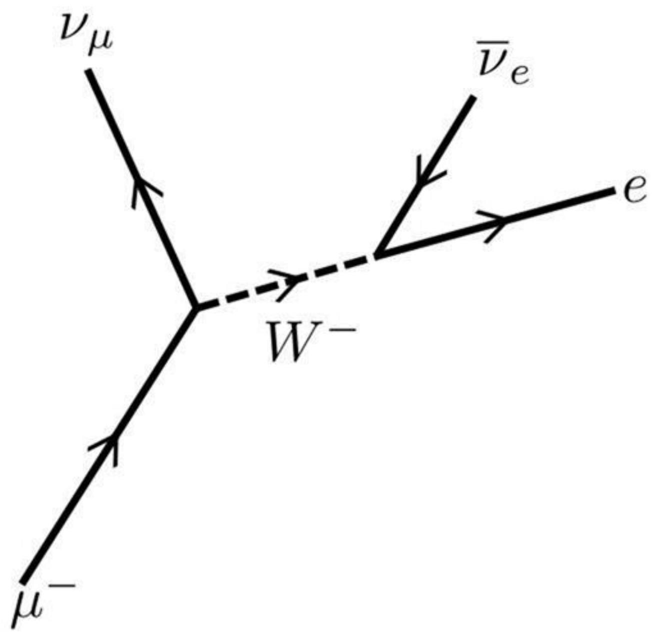
$$P_{\mu\mu} = (|\alpha_{21}|^2 + \alpha_{22}^2)^2$$

$$P_{e\tau} = \alpha_{11}^2 |\alpha_{31}|^2$$

$$P_{\mu\tau} \approx \alpha_{22}^2 |\alpha_{32}|^2$$

$$P_{\tau\tau} = (|\alpha_{32}|^2 + |\alpha_{31}|^2 + \alpha_{33}^2)^2$$

$$|\alpha_{ij}| \leq \sqrt{(1-\alpha_{ii}^2)(1-\alpha_{jj}^2)}$$



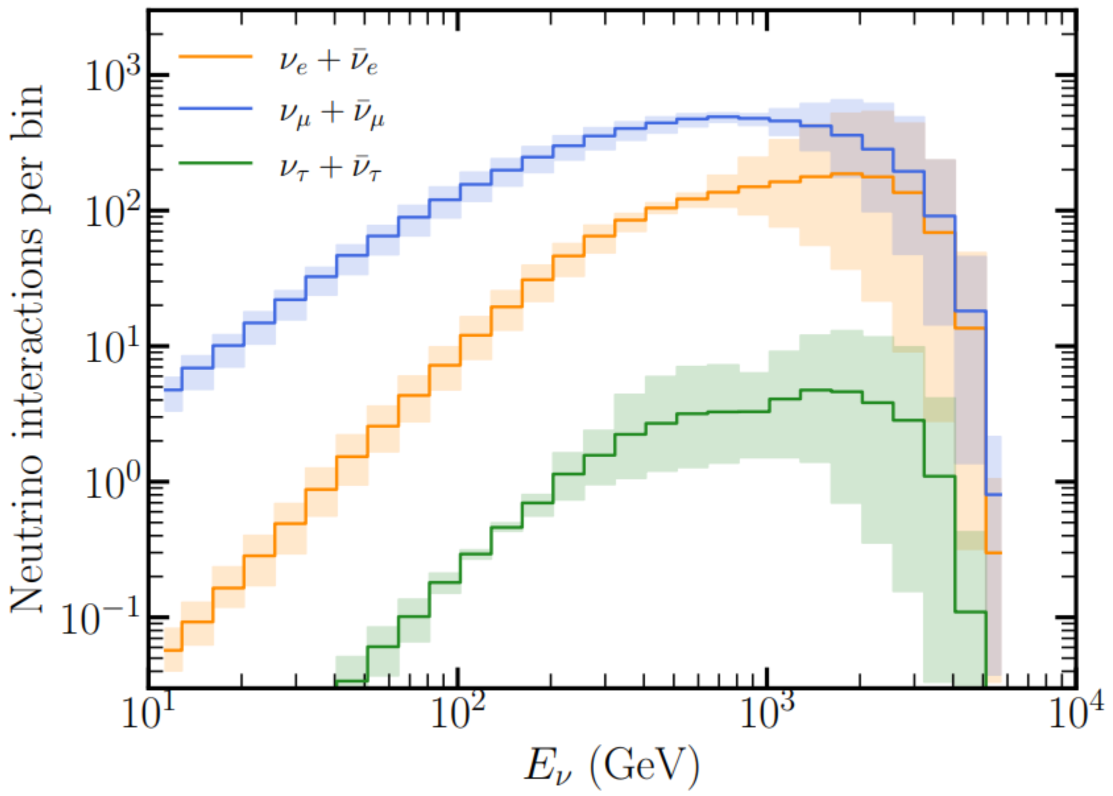
$$^6G_\mu = G_F\sqrt{(NN^\dagger)_{11}(NN^\dagger)_{22}} = G_F\sqrt{\alpha_{11}^2(\alpha_{22}^2 + |\alpha_{21}|^2)}$$

[4]Enrico Nardi, Esteban Roulet, and Daniele Tommasini.Phys.Lett.B, 327:319–326, 1994.

Neutrinos events computation

$$N_\alpha^{SM} = \epsilon_\alpha N_T \int f(E_{reco}) R(E_{reco}, E_\nu) \sigma_\alpha(E_\nu) \phi_\alpha dE_\nu dE_{reco}$$

	FASERν		FASERν2	
Lepton flavor	10^2-10^4GeV	100-600 GeV	10^2-10^4GeV	100-600 GeV
e	1095±937	307±101	44230	20775
μ	2807±909	1163±190	193630	85044
τ	19±19	6±4	767	314



Felix Kling and Laurence. Phys. Rev. D, 104(11):113008, 2021.

χ^2 analysis

We take into account each disappearance and appearance channel for each flavor.

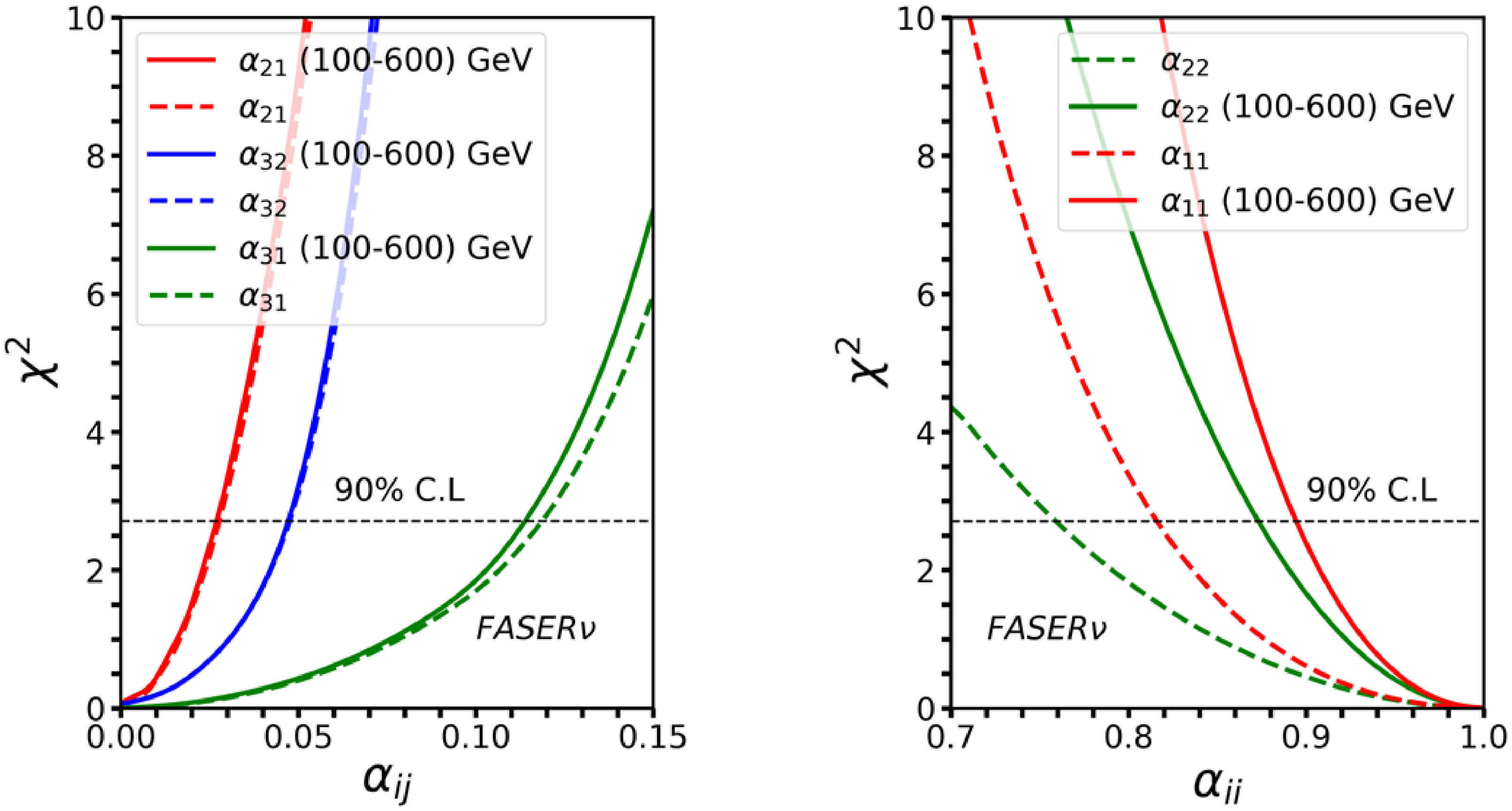
$$\chi^2 = \sum_{\alpha=1}^{3} \frac{\left(N_\alpha^{NU} - N_\alpha^{exp}\right)^2}{\sigma^2} + \sum_{ij} \frac{\left(\alpha_{ij} - \delta_{ij}\right)^2}{\sigma_{ij}^2}$$

We have included priors to the values of α_{ij} that will be marginalized in our fit, using as errors, σ_{ij}, the current constraints[6].

$$N_\alpha^{NU} = \frac{1}{\alpha_{11}^2(\alpha_{22}^2 + |\alpha_{21}|^2)} (N_\alpha P_{\alpha\alpha} + \sum_{\beta \neq \alpha} P_{\alpha\beta} N_\beta)$$

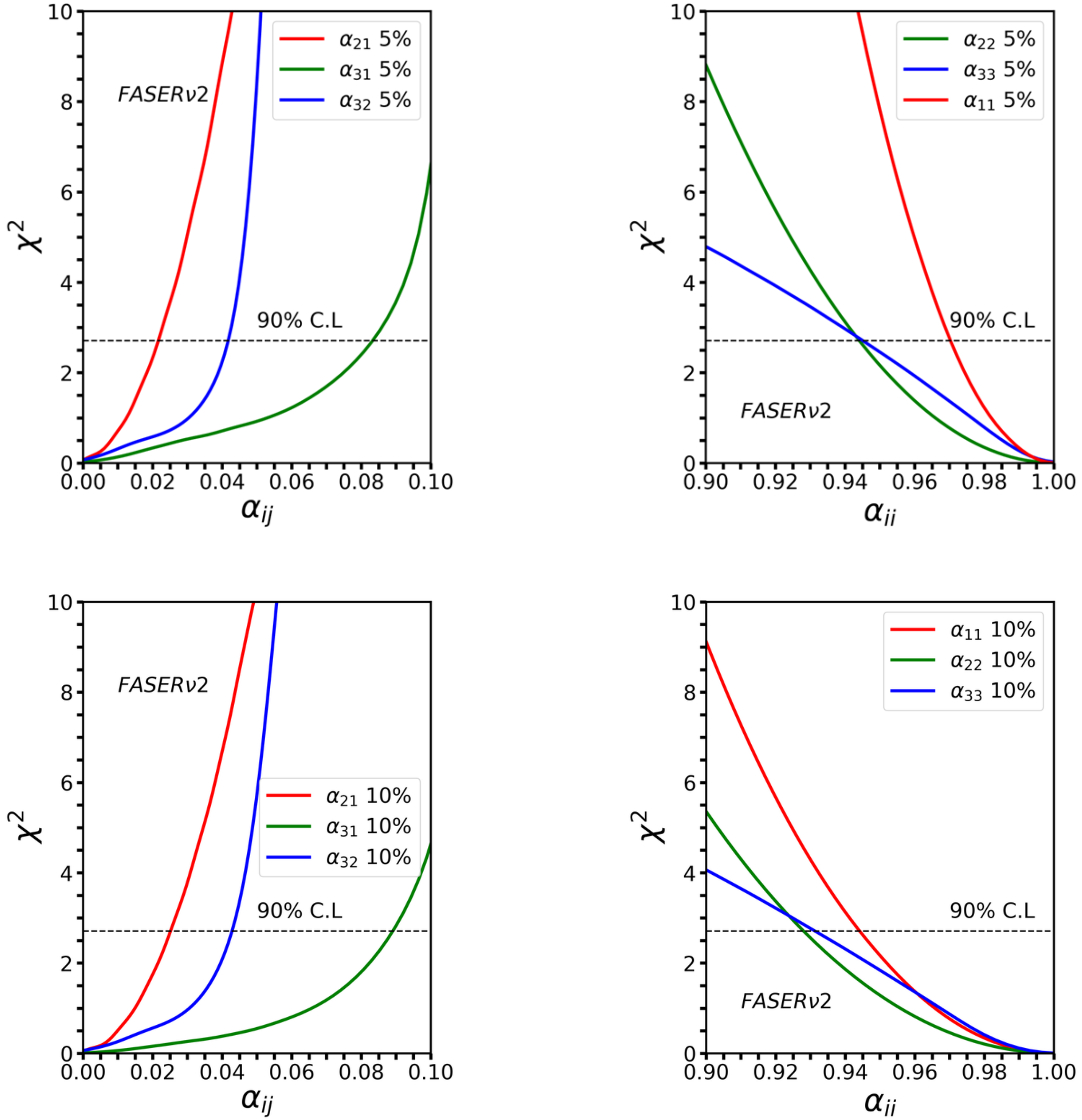
[6]D. V. Forero, C. Giunti, C. A. Ternes, and M. Tortola. Phys.Rev.D, 104(7):075030, 2021.

FASERν Results



J. M. Celestino-Ramírez, F. J. Escrihuela , L. J. Flores, O. G. Miranda.Phys. Rev. D, 109(1):L011705, 2024.

FASERν2 Results



J. M. Celestino-Ramírez, F. J. Escrihuela , L. J. Flores, O. G. Miranda.Phys. Rev. D, 109(1):L011705, 2024.

	FASERν		FASERν2		
Parameters	10^2-10^4GeV	100-600 GeV	100-600 GeV (5%)	100-600 GeV (10%)	Current limit
$\alpha_{11} \geq$	0.818	0.894	0.97	0.944	0.969
$\alpha_{22} \geq$	0.760	0.873	0.944	0.928	0.995
$\alpha_{33} \geq$	-	-	0.945	0.932	0.890
$\alpha_{21} \leq$	0.028	0.027	0.022	0.025	0.013
$\alpha_{31} \leq$	0.118	0.114	0.083	0.089	0.033
$\alpha_{32} \leq$	0.048	0.048	0.042	0.043	0.009

J. M. Celestino-Ramírez, F. J. Escrihuela , L. J. Flores, O. G. Miranda.Phys. Rev. D, 109(1):L011705, 2024.
D. V. Forero, C. Giunti, C. A. Ternes, and M. Tortola. Phys.Rev.D, 104(7):075030, 2021

Conclusions

- We find that the expected FASERν sensitivity to non-unitarity parameters might give complementary information, useful perhaps in a global analysis.
- On the other hand, for the FASERν2 case, the perspectives are much better and the sensitivity to the α_{11} (related with the electron neutrino disappearance channel) and α_{33} (related with the tau neutrino disappearance channel) parameters could be quite competitive with current restrictions.

Thank you!

Back up

The charged current (CC) lagrangian

$$L = \frac{-g}{\sqrt{2}} W_{\mu}^{-} \sum_{i=1}^{3} \sum_{j=1}^{n} K_{ij}\, \bar{l}\gamma^{\mu} P_L \nu_j$$

The CC interaction does not concern the Neutral heavy leptons because they are singlets under the electro-weak symmetry. Just the new massive state is taking account in the CC interaction.

$$U_{n\times n} = \begin{pmatrix} N_{3\times 3} & S_{3\times m} \\ T_{m\times 3} & V_{m\times m} \end{pmatrix}$$

$$K = \begin{pmatrix} N_{3\times 3} & S_{3\times m} \end{pmatrix}$$

The process of marginalizing the α parameters

As we said, all the Alpha parameters are involved in the analysis. We did a scan of all the Alpha parameters and the marginalized part is to find the combination of the other 5 Alpha parameters (that you are not interested in) that minimize the chi-squared value for each value of the Alpha parameter that we are interested in analysis.