Constraining New Physics with neutrino oscillations

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Motivation

Neutrino masses and mixing → evidence of Physics Beyond the SM

High energy NP

Deviations from unitarity of the PMNS mixing matrix at low energies

↓

constraining
3x3 unitarity
Is relevant

New CP violation sources

Low energy NP

Light Sterile neutrinos

↓

Very relevant in short baseline neutrino oscillation experiments

New CP violation sources

NSI: model independent way of parameterizing the whole possible New Physics effects in neutrino oscillations.

New Physics from High Energies

NP coming from high energies

Smallness of neutrino masses calls for a New Physics explanation probably coming from Higher Energies.

↓

- Consider SM as a low energy effective theory of a higher energy one able to explain this fact.

- New Physics manifest in the low energy effective theory via higher dimension operators:

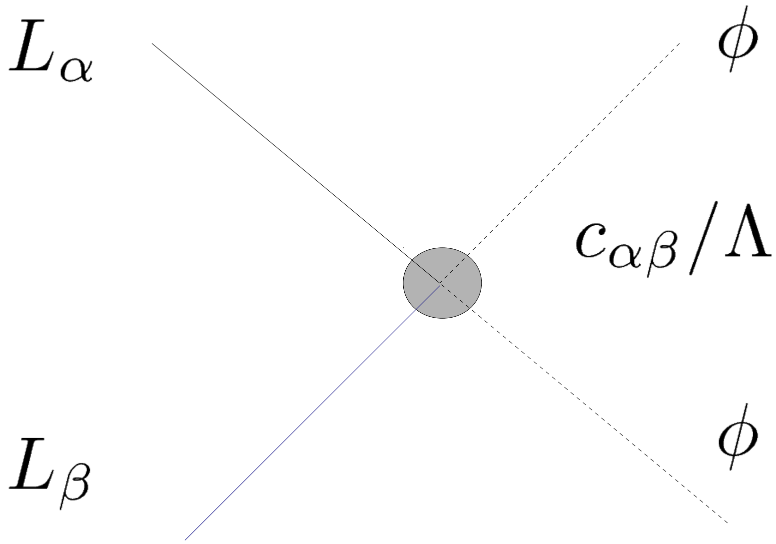
$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \dots \text{ with } \delta\mathcal{L}^{d} \propto \frac{1}{\Lambda^{d-4}}$$

NP coming from high energies

- With the SM field content, the lowest dimension effective operator is the following (d=5):

$$\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{L^c}_{\alpha}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) \xrightarrow{\text{SSB}} \frac{cv^2}{\Lambda}\overline{\nu^c_\alpha}\nu_\alpha$$

Weinberg 76



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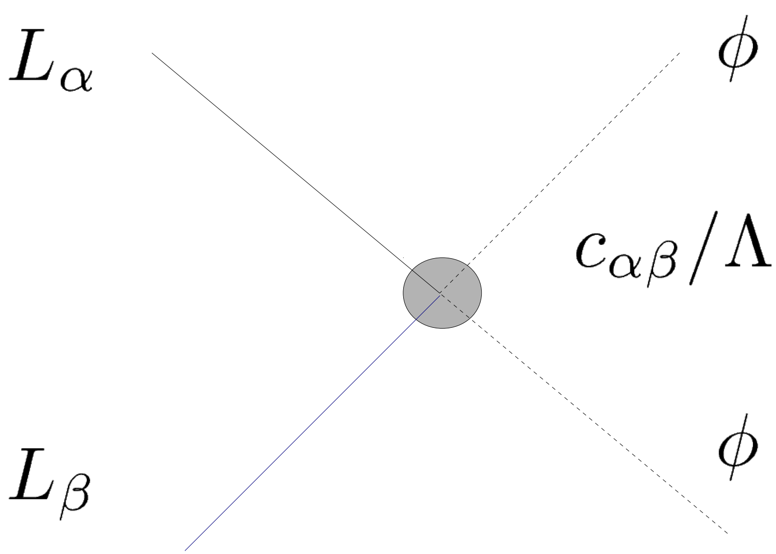

Smallness of neutrino masses can be explained

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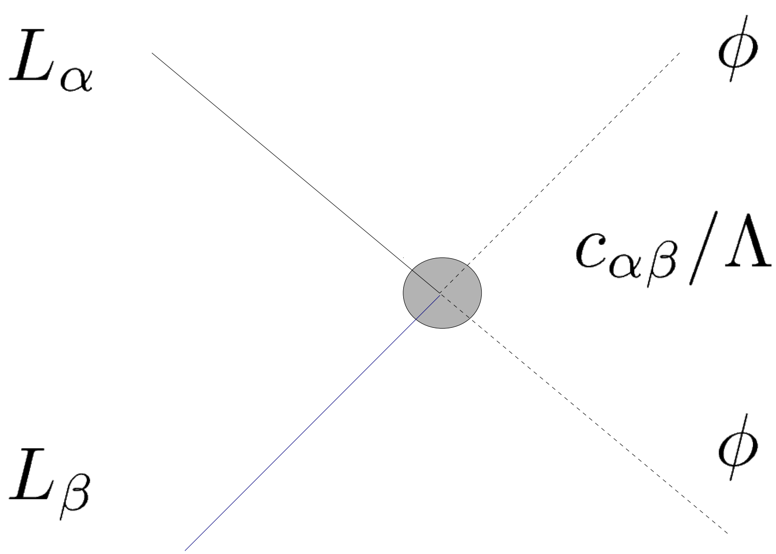
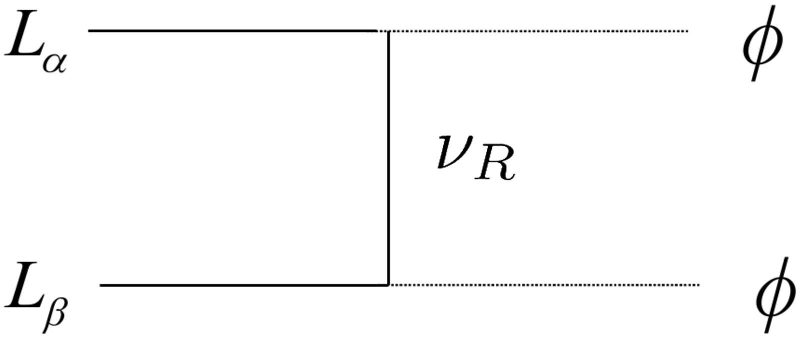


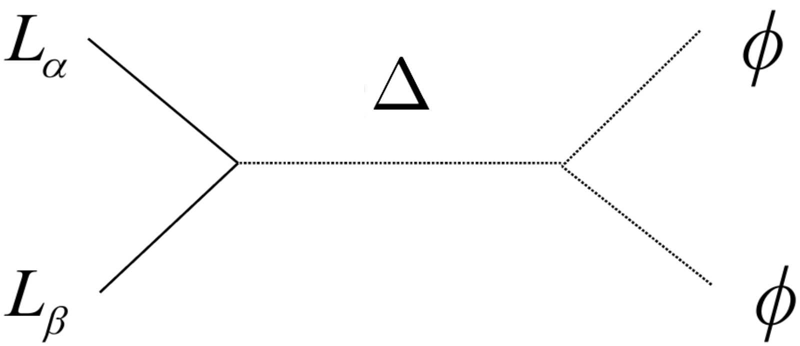
Smallness of neutrino masses can be explained

Models behind?

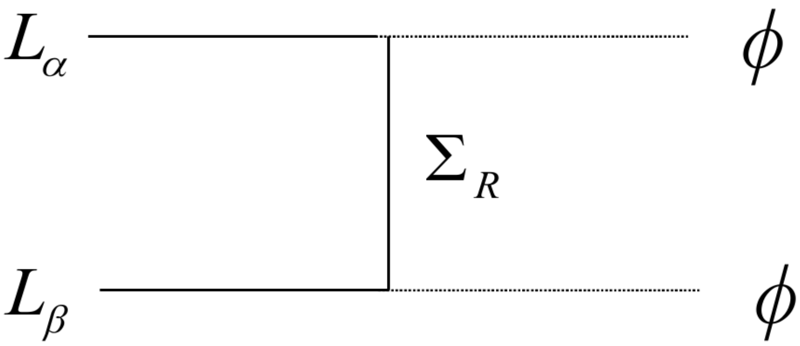
NP coming from high energies



Heavy fermion singlet: ν_R. Type I *seesaw.* Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.



Heavy scalar triplet: Δ. Type II *seesaw.* Magg, Wetterich 80; Schecter, Valle 80; Lazarides, Shafi, Wetterich 81; Mohapatra, Senjanovic 81.



Heavy fermion triplet: Σ

Type III *seesaw.* Foot, Lew, Joshi 89

NP coming from high energies

- This NP can produce deviations from the unitarity of the PMNS matrix at low energy. For instance, in the Type I *seesaw*, through the d=6 operator:

$$\frac{1}{\Lambda^2}\left(\overline{L}_\alpha\tilde{\phi}\right) i\partial\!\!\!/\left(\tilde{\phi}^\dagger L_\beta\right) \xrightarrow{\text{SSB}} i\overline{\nu}_\alpha k_{\alpha\beta}\partial\!\!\!/\nu_\beta$$

Broncano, Gavela, Jenkins 02

Correction to the kinetic term lead to
deviations from 3x3 unitarity
at low energies

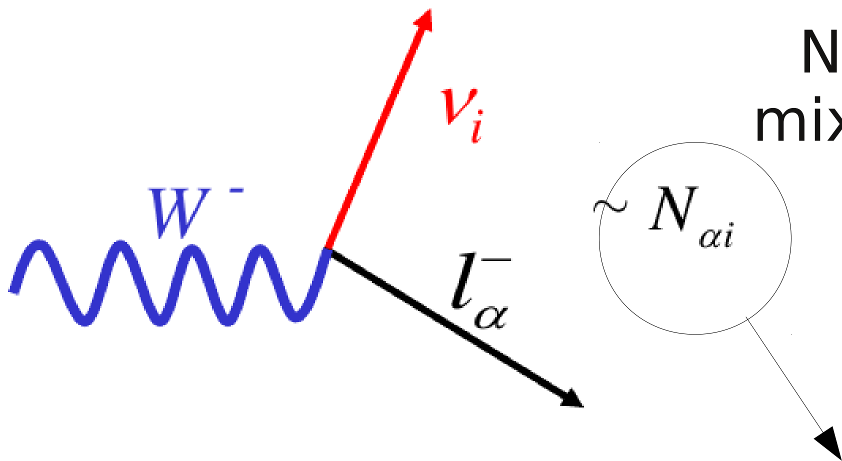
- Generically this unitarity violation arises as long as heavy fermions are involved (type-I and type-III seesaws, extra dimensions...)

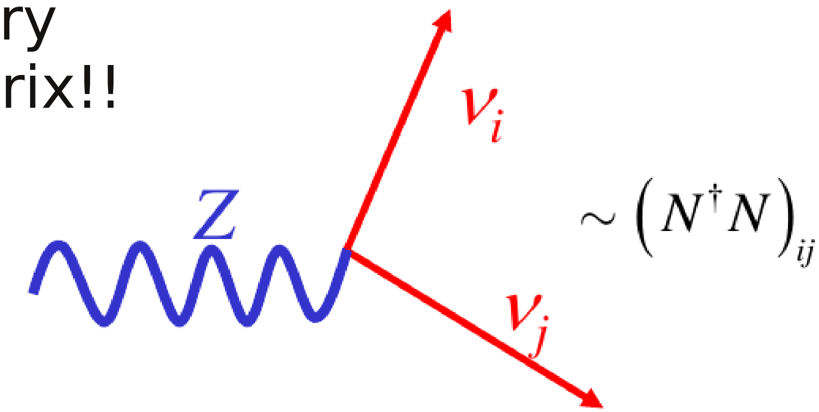
Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 06

Abada, Antusch, Biggio, Bonnet, Gavela, Hambye 07

Deviations from unitarity

Non unitary
mixing matrix!!





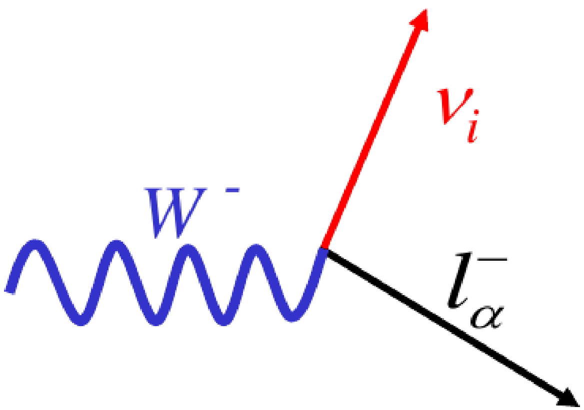
$$(1+\eta)_{\alpha\beta}\, U_{\beta i}$$

They affect neutrino oscillations. In particular:

$$P_{\alpha\beta}\left(L=0\right) \propto |\left(NN^\dagger\right)_{\alpha\beta}|^2 \approx 4|\eta_{\alpha\beta}|^2$$

Zero
Distance
Effect

Deviations from unitarity

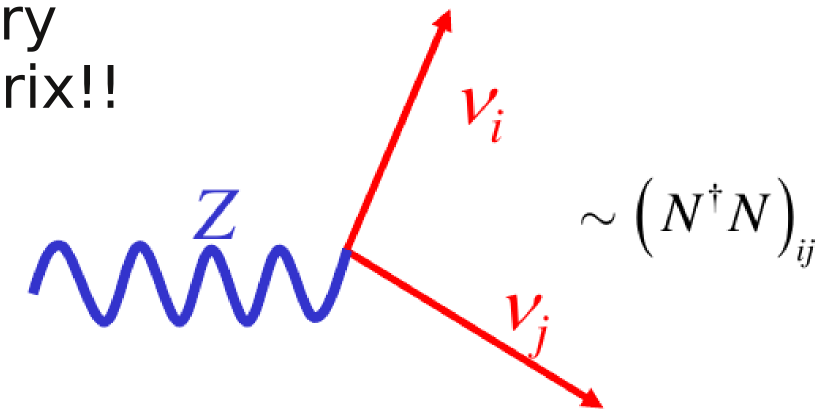


Non unitary mixing matrix!!

$\sim N_{\alpha i}$

$$(1+\eta)_{\alpha\beta}\, U_{\beta i}$$

PMNS



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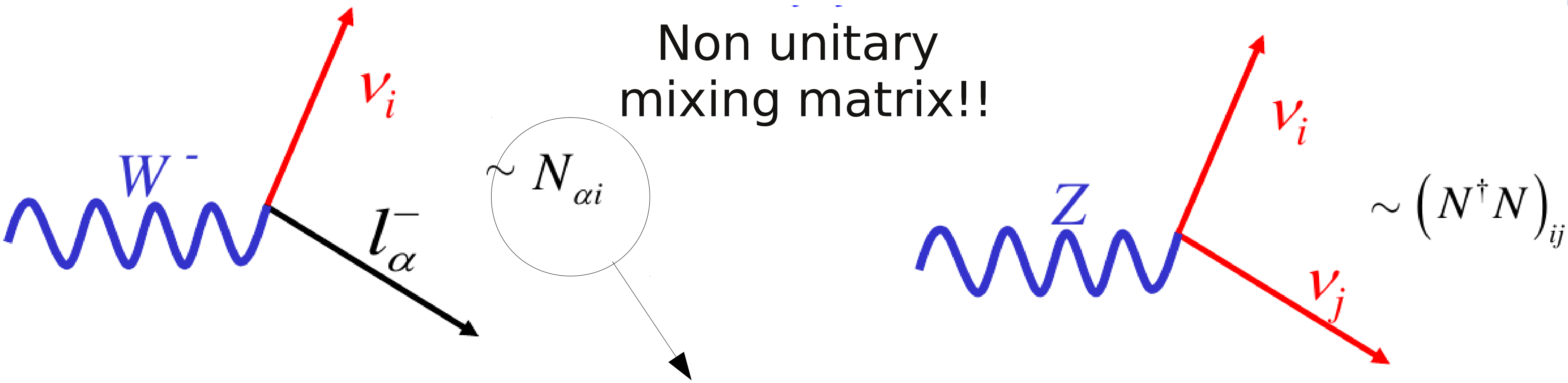
Zero Distance Effect

Deviations from unitarity



$$(1+\eta)_{\alpha\beta}\, U_{\beta i}$$

deviations PMNS

They affect neutrino oscillations. In particular:

$$P_{\alpha\beta}\left(L=0\right) \propto \left| \left(N N^\dagger\right)_{\alpha\beta} \right|^2 \approx 4 |\eta_{\alpha\beta}|^2$$

Zero Distance Effect

Deviations from unitarity

- Present neutrino oscillations and EW decay data confirm unitarity at % level

RARE LEPTON DECAYS

- $\mu \to e\gamma \quad \left(NN^\dagger\right)_{e\mu} < 8\cdot 10^{-6}$ (MEG)
- $\tau \to e\gamma \quad \left(NN^\dagger\right)_{e\tau} < 8.4\cdot 10^{-3}$ (BABAR)
- $\tau \to \mu\gamma \quad \left(NN^\dagger\right)_{\mu\tau} < 1.0\cdot 10^{-2}$ (Belle)

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ZERO-DISTANCE EFFECT @ NF

- $\nu_e \to \nu_\mu$ $\quad \left(NN^{\dagger}\right)_{e\mu} < 2.3 \cdot 10^{-4}$
- $\nu_e \to \nu_\tau$ $\quad \left(NN^{\dagger}\right)_{e\tau} < 2.9 \cdot 10^{-3}$
- $\nu_\mu \to \nu_\tau$ $\quad \left(NN^{\dagger}\right)_{\mu\tau} < 2.6 \cdot 10^{-3}$

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- No information about CP-phases. Extra CP-phases from non-unitarity!

Can we measure the new CP-phases in the future?

New CP violation effects

- Interference with standard neutrino oscillations at longer L gives

sensitivity to new CP-violation effects

$$P_{\mu\tau} = \sin^2 2\theta_{23} \sin^2 \frac{\Delta_{31} L}{2} - 2|\eta_{\mu\tau}| \sin\delta_{\mu\tau} \sin 2\theta_{23} \sin \Delta_{31} L + 4|\eta_{\mu\tau}|^2$$

SM

CP-violating iterference

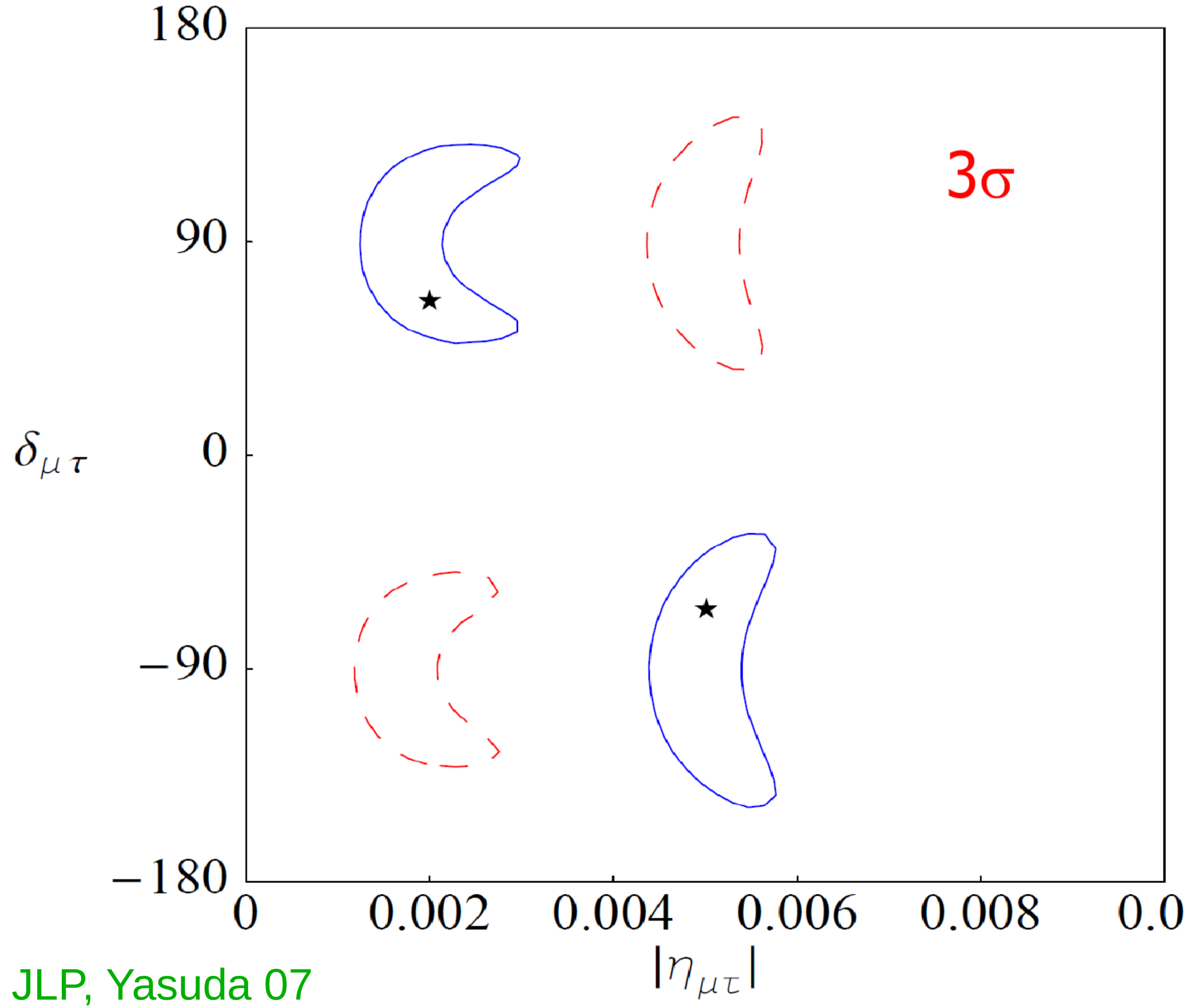
Zero distance effect

Clean new CP-asymmetry in $\nu_\mu \to \nu_\tau$ channel !

Gavela, Fernandez-Martinez, JLP, Yasuda 07

$\nu_\mu \to \nu_\tau$: New CP-asymmetry!

$$N_{\mu\tau} - N_{\bar{\mu}\bar{\tau}} \propto 8|\eta_{\mu\tau}|\sin\delta_{\mu\tau}\sin(2\theta_{23})\sin(\Delta_{13})$$



@ a 50 GeV NuFact
with L = 130 Km

Gavela, Fernandez-Martinez, JLP, Yasuda 07

$\nu_\mu \rightarrow \nu_\tau$: New CP-asymmetry!

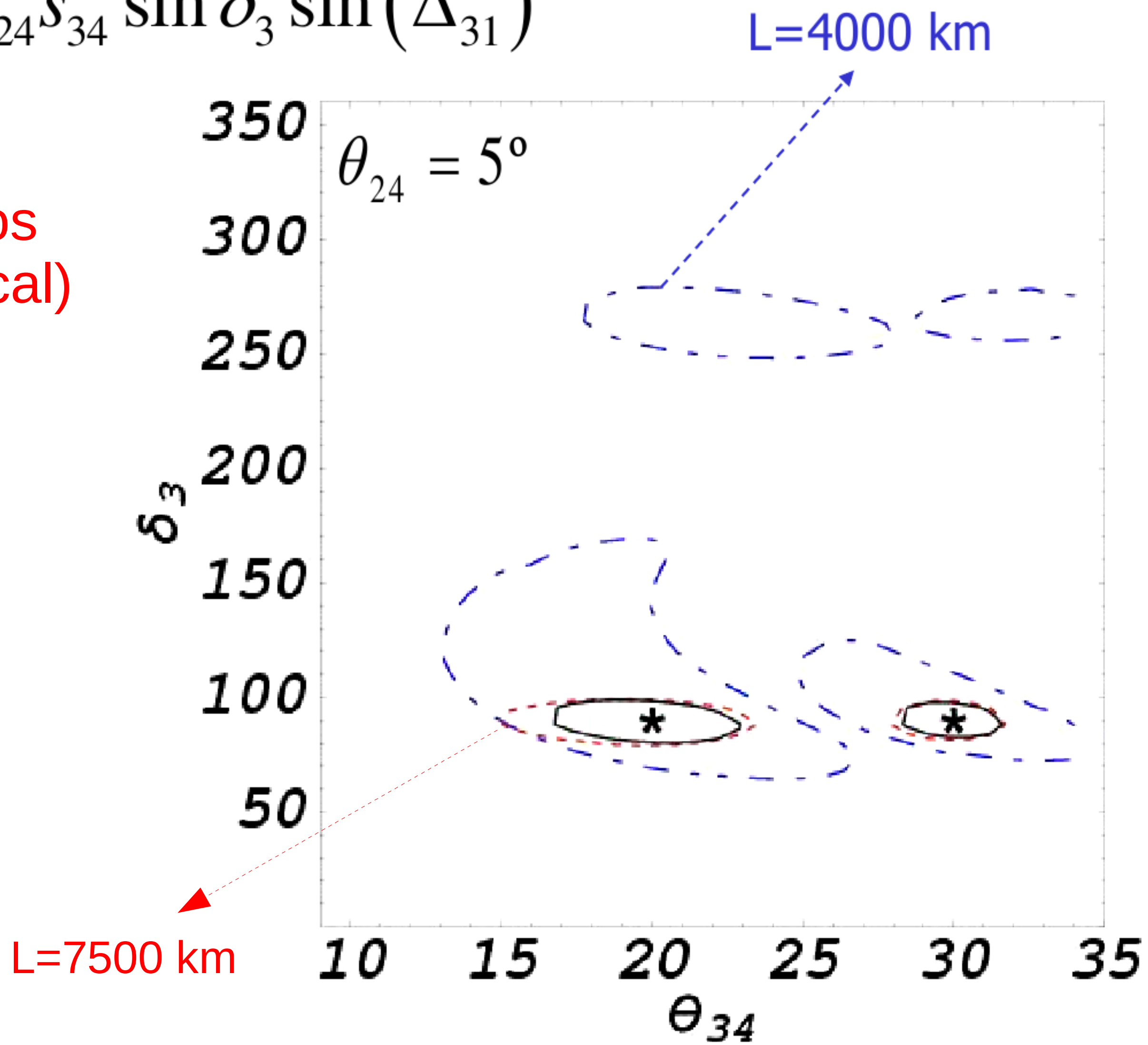
$$N_{\mu\tau} - N_{\bar{\mu}\bar{\tau}} \propto 2 s_{24} s_{34} \sin\delta_3 \sin(\Delta_{31})$$

- Light sterile neutrinos (3+1 phenomenological)

- Same interference Effect !!

NuFact 50 GeV

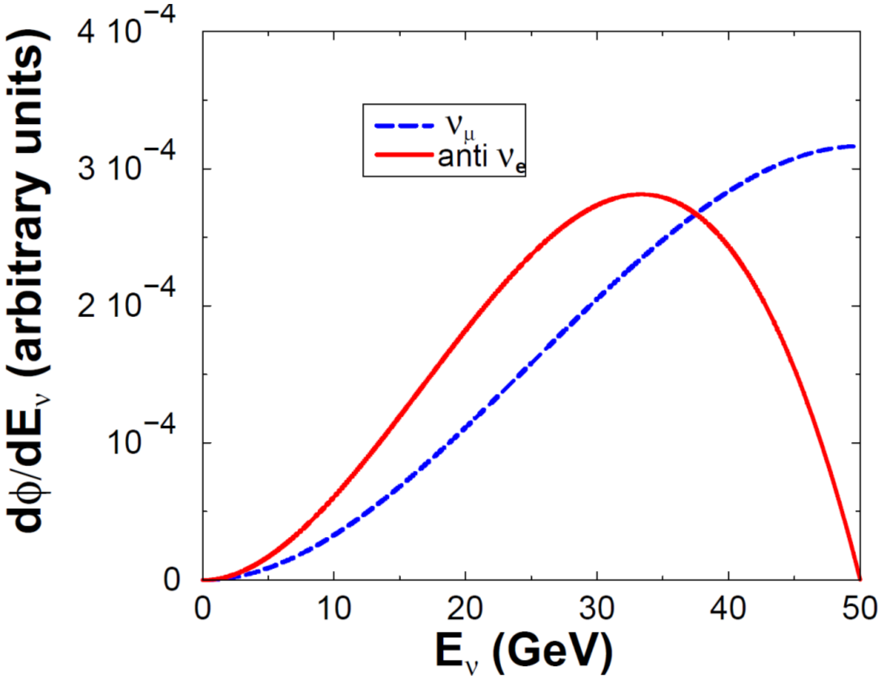
99% CL



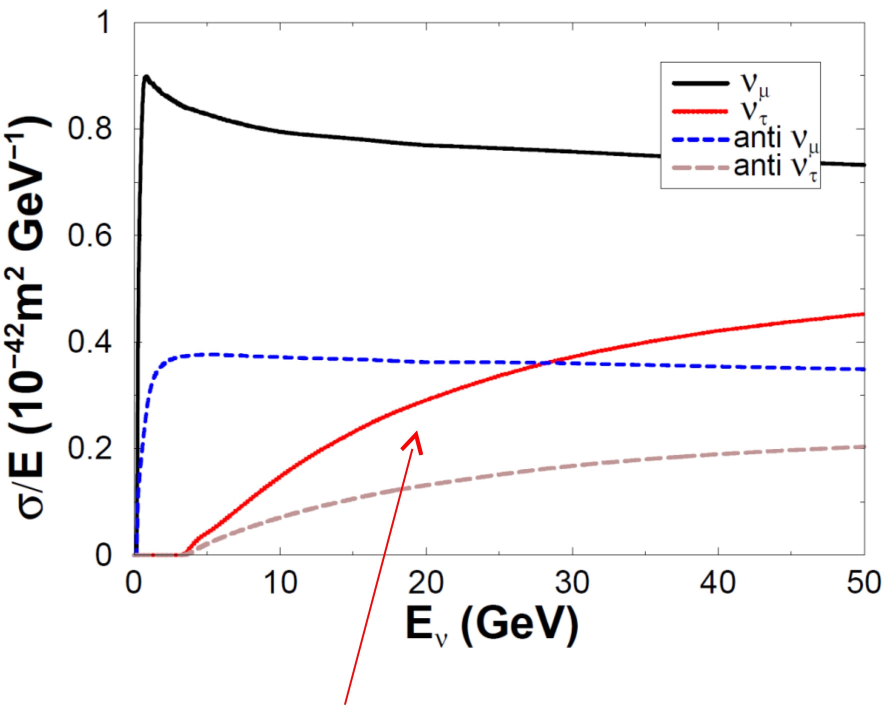
A. Donini, K. Fuki, J.L.P., D. Meloni and O. Yasuda; arXiv:0812.3703

$\nu_\mu \to \nu_\tau$: New CP-asymmetry!

- Very high energy machine required to probe this new CP-asymmetry



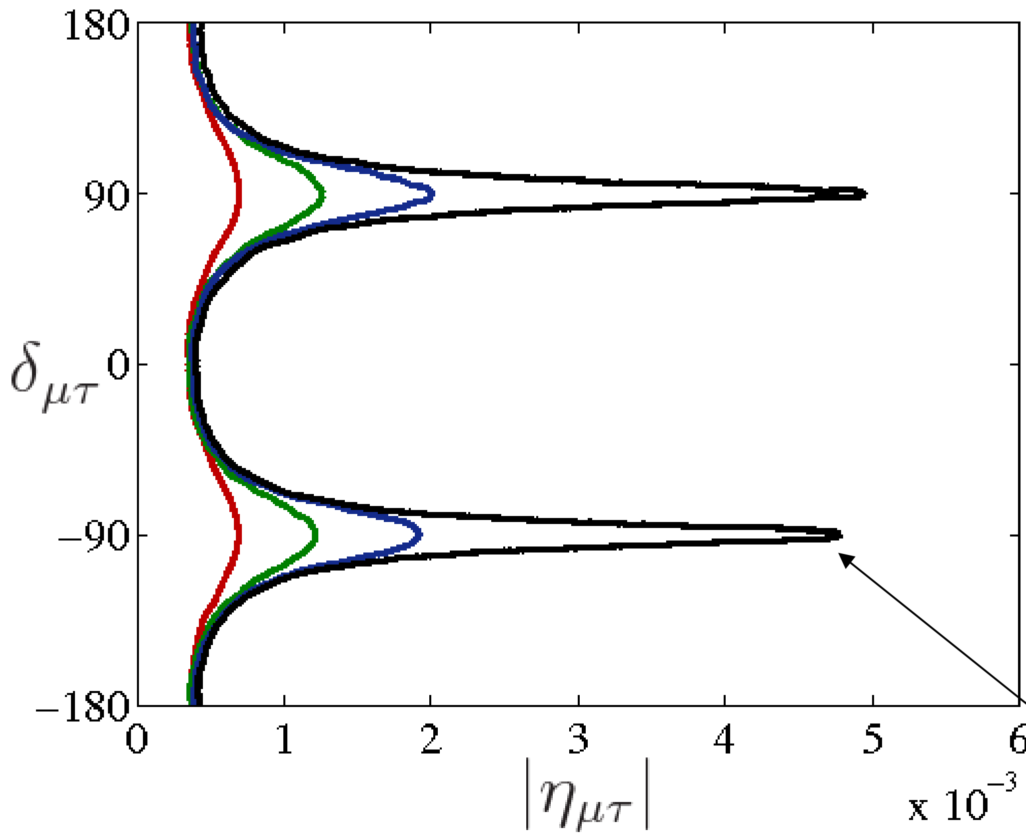
50 GeV NuFact fluxes @ 3000 km



ν_τ cross-section

New CP violation effects

90%C.L.



Non-unitarity from high energy NP

@ 25 GeV Nufact without tau detectors

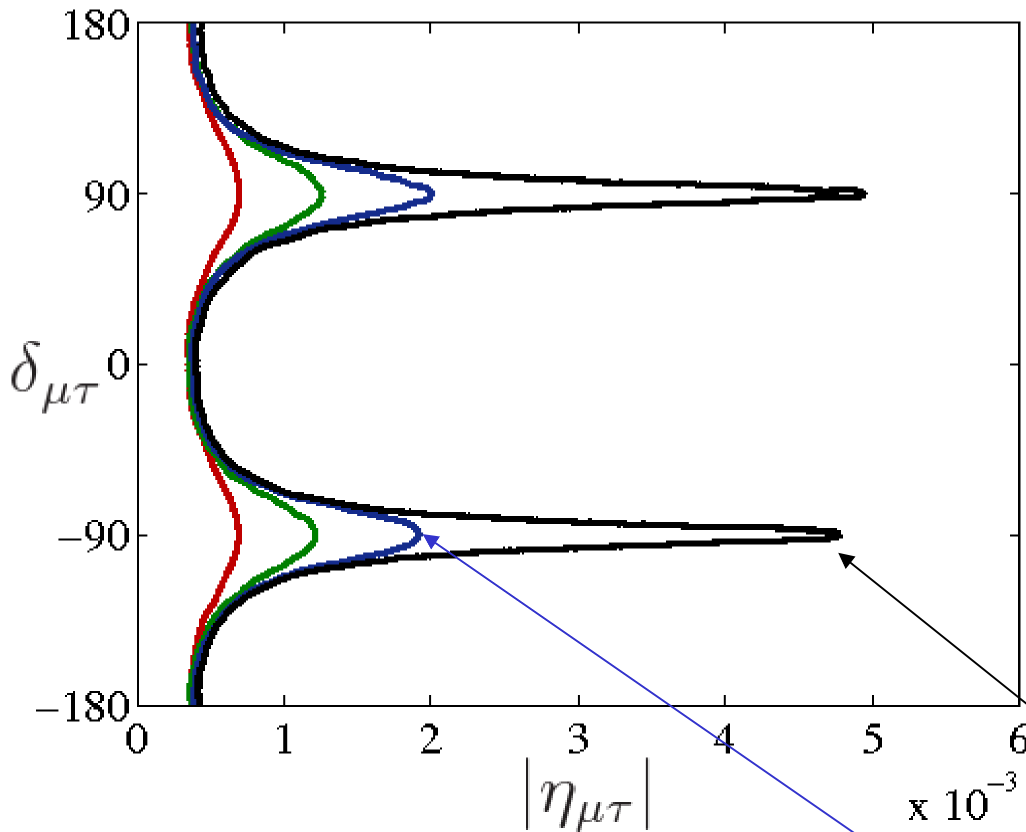
(previous) IDS NuFact (without near detectors)

$$P_{\mu\mu} = P_{\mu\mu}^{SM} + 2\,\mathrm{Re}\left(\eta_{\mu\tau}\right)\left(AL\right)\sin\left(\Delta_{31}L\right) + \ldots$$

Antusch, Blennow, Fernández-Martinez, JLP 09

New CP violation effects

90%C.L.



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+100 ton Near detector

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+

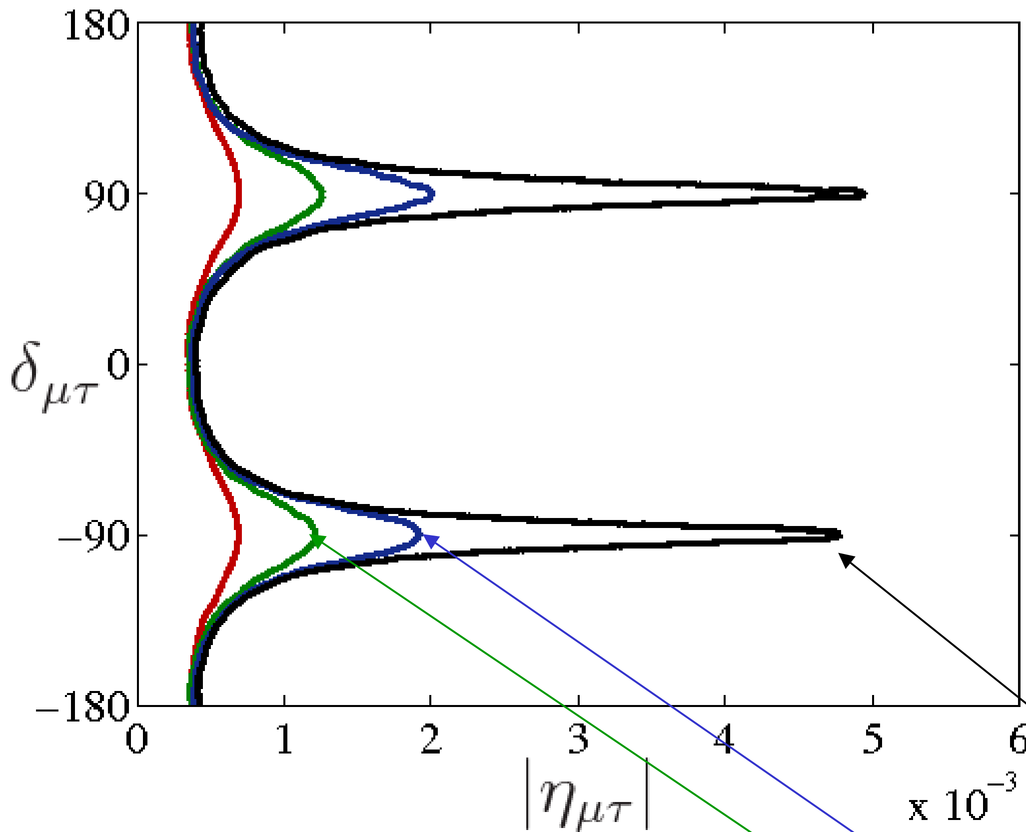
$$P_{\mu\tau}(L=0) \propto \left|\eta_{\mu\tau}\right|^2$$

Sensitivity to the imaginary part!!

Antusch, Blennow, Fernández-Martinez, JLP 09

New CP violation effects

90%C.L.



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+100 ton Near detector

+1 kton Near detector

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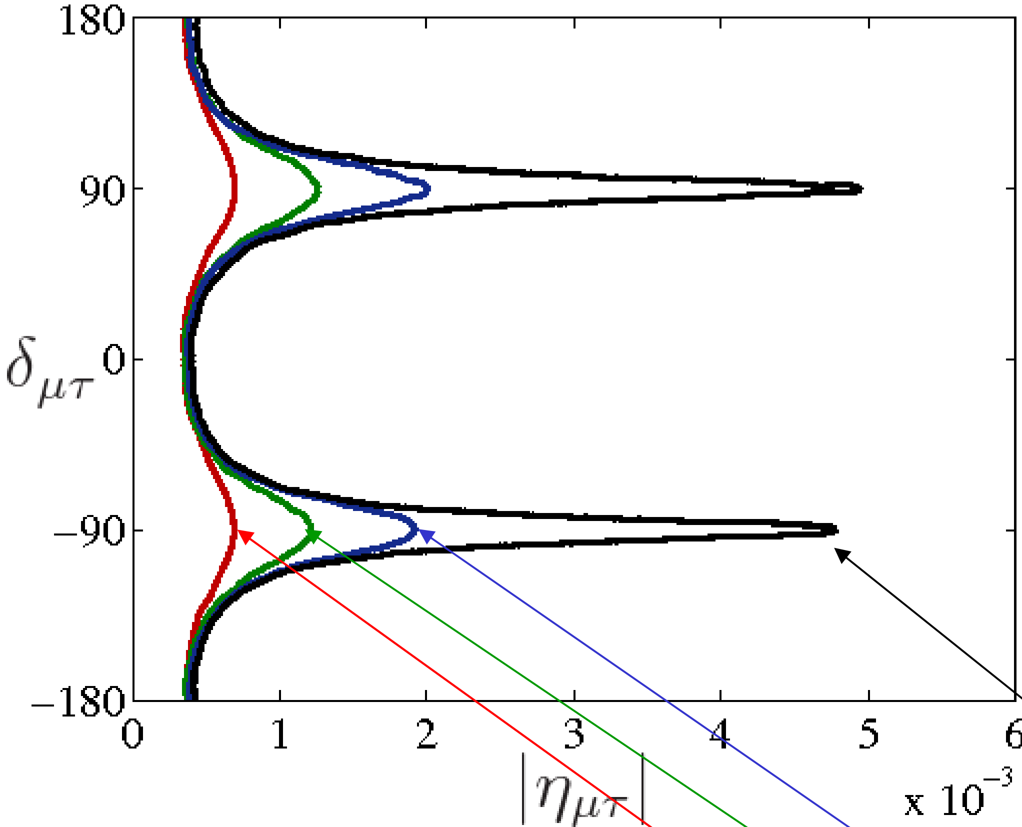


Non-unitarity from high energy NP
@ 25 GeV
Nufact without tau detectors

(previous) IDS NuFact (without near detectors)

+100 ton Near detector

+1 kton Near detector

+10 kton Near detector

$$P_{\mu\mu} = P_{\mu\mu}^{SM} + 2\mathrm{Re}(\eta_{\mu\tau})(AL)\sin(\Delta_{31}L) + \ldots$$

+

$$P_{\mu\tau}(L=0) \propto |\eta_{\mu\tau}|^2$$

Sensitivity to the imaginary part!!

Antusch, Blennow, Fernández-Martinez, JLP 09

Non-Standard neutrino Interactions (NSI)

Biggio, Blennow, Coloma, Davidson, Fernandez-Martinez, Grossman, Gonzalez-Garcia, Huber, kopp, Minakata, Ohlsson, Ota, Schwetz, Valle, Winter, Wolfenstein, Yasuda, etc, etc, etc...

NSI: what is that?

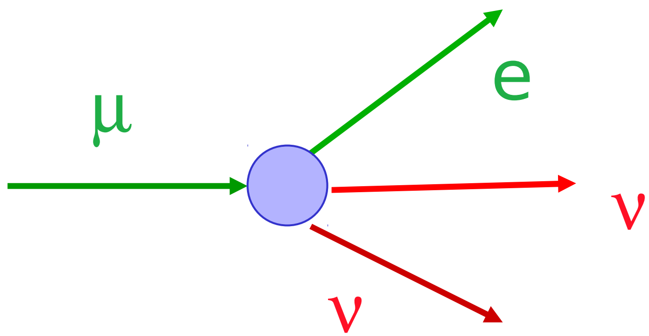
$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum \delta\mathcal{L}_i^{p,d,m}$$

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum \delta\mathcal{L}_i^{p,d,m}$$

NSI@production

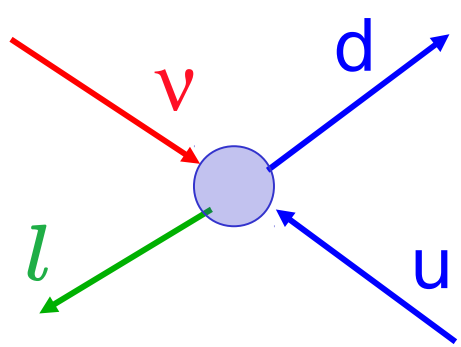
$$\mu^- \to e^- \nu_\mu \bar{\nu}_\alpha$$



$$\delta\mathcal{L}^p : \epsilon^p_{e\alpha}(\bar{\mu}\gamma^\mu_L \nu_\mu)(\bar{\nu}_\alpha \gamma_{\mu L} e)$$

NSI@detection

$$\nu_\alpha N \to l_\alpha^- N'$$



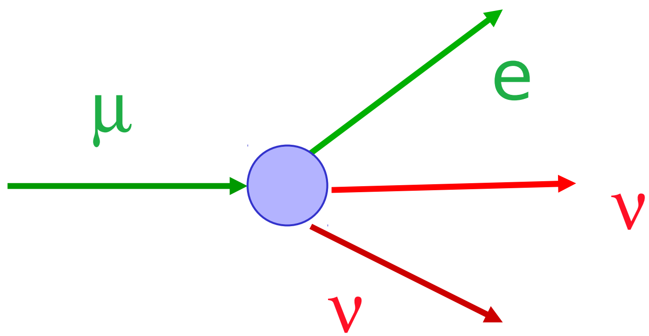
$$\delta\mathcal{L}^d : \epsilon^d_{\mu\alpha}(\bar{\nu}_\alpha \gamma^\mu_L \mu)(\bar{d}\gamma_{\mu L} u)$$

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum \delta\mathcal{L}_i^{p,d,m}$$

NSI@production

$\mu^- \to e^- \nu_\mu \bar{\nu}_\alpha$



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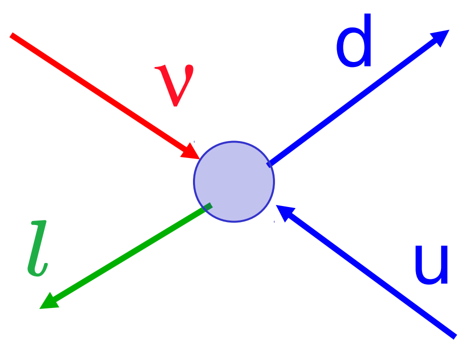
NSI@detection

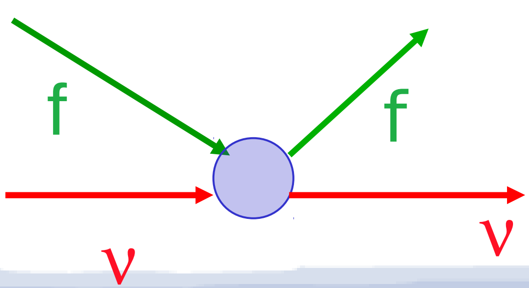
$\nu_\alpha N \to l_\alpha^- N'$



$$\delta\mathcal{L}^d : \epsilon_{\mu\alpha}^d (\bar{\nu}_\alpha \gamma_L^\mu \mu)(\bar{d}\gamma_{\mu L} u)$$

NSI@propagation

$\nu_\alpha f \to \nu_\beta f$



$$\delta\mathcal{L}^m : \epsilon_{\alpha\beta}^m (\bar{\nu}_\alpha \gamma_L^\mu \nu_\beta)(\bar{f}\gamma_\mu f)$$

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum \delta\mathcal{L}_i^{p,d,m}$$

NSI@production

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_\alpha$$

NSI@detection

$$\nu_\alpha N \rightarrow l_\alpha^- N'$$

Near Detectors

MINSIS workshop report,
arXiv:1009.0476 [hep-ph]
etc

NSI@propagation

$$\nu_\alpha f \rightarrow \nu_\beta f$$

Effective matter Potential:
Far Detectors

NSI: what is that?

- Model independent approach. Very mild experimental constraints:

NSI in propagation

$$|\varepsilon_{\alpha\beta}^{\oplus}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

neutral Earth-like matter

$$|\varepsilon_{\alpha\beta}^{\odot}| < \begin{pmatrix} 2.5 & 0.21 & 1.7 \\ 0.21 & 0.046 & 0.21 \\ 1.7 & 0.21 & 9.0 \end{pmatrix}$$

neutral Solar-like matter

Biggio, Blennow, Fernandez-Martinez;09

- However, from a theoretical point of view, NSI parameters are not expected to be so huge at all!

Gavela, Hernandez, Ota, Winter 08

Antusch, Baumann, Fernandez-Martinez 08

NSI: feasible models behind?

- Of course, it makes sense to keep constraining the NSI effects and NP in general but...

- ..is there any feasible model predicting large NP effects in neutrino oscillations close to these bounds? Challenging...

1. The NSI effective operators should come from gauge invariant ones. NP may not affect only to the neutrino sector being more constrained.

2. If the NSI come from higher energy NP, they will be suppressed by the NP scale.

NSI: feasible models behind?

- Interesting possibility: inverse seesaw models and similar realizations based on minimal violation of lepton number.

- They can be implemented at the TeV or below affecting only to the neutrino sector. Rich phenomenology.

Mohapatra, Valle 86

$$M_\nu = \begin{pmatrix} 0 & Y_1^T v/\sqrt{2} & 0 \\ Y_1 v/\sqrt{2} & \mu' & \Lambda \\ 0 & \Lambda^T & \mu \end{pmatrix}.$$

small Lepton number violation parameters

NSI: feasible models behind?

- Neutrino masses explained with $\Lambda \lesssim TeV$ thanks to *extra suppression with lepton number violation parameter*:

$$\delta\mathcal{L}^{d=5} = c_5 \left(\overline{L^c}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L\right) \xrightarrow{\text{EWSB}} \mu\frac{v^2}{\Lambda^2}\overline{\nu^c_\alpha}\nu_\alpha$$

$c_5 \to \mathcal{O}\left(\mu/\Lambda^2\right)$

neutrino masses explained

- *d=6 operator does not violate L, no extra suppression* relatively large non-unitarity effects, close to present non-unitarity bounds.

$$\delta\mathcal{L}^{d=6} = c_6 \left(\overline{L}\tilde{\phi}\right) i\partial\!\!\!/ \left(\tilde{\phi}^\dagger L\right) \xrightarrow{\text{EWSB}} \mathcal{O}\left(v^2/\Lambda^2\right)$$

$c_6 \to \mathcal{O}\left(1/\Lambda^2\right)$

Large Non-unitarity effects!

Very Low Energy New Physics

Sterile Neutrinos

- Sterile neutrinos strongly affect oscillation physics.
- LSND/reactors anomaly requires an extra $\Delta m^2_{LSND} \sim eV$
- Tension between appearance and disappearance experiments. Difficult to accommodate all data (3+1 can not make it)
- CP-violation and at least two extra sterile neutrinos needed.

See talks in WG1 session of Wednesday: B. Fleming, P. Huber, G. Karagiorgi

Light Sterile Neutrinos White Paper, Abazajian et al arXiv: 1204.5379 and refs. therein

Sterile Neutrinos

- Tension between appearance and disappearance experiments

$$P_{\mu e} \sim |U_{ej}|^2 |U_{\mu j}|^2$$ ☺ LSND/MB signal

$$P_{ee} \sim |U_{ej}|^2$$ ☺ reactor anomaly

$$P_{\mu\mu} \sim |U_{\mu j}|^2$$ ✗ no signal...

- Difficult to accommodate all data. Convincing signal should appear in all these channels.

Sterile Neutrinos

- Best fits in the 3+2 phenomenological model (PM). Number of free parameters: 9 angles + 5 phases + 4 neutrino mass differences.

$3+2$ PM	$\lvert\Delta m^2_{41}\rvert(\text{eV}^2)$	$\lvert\Delta m^2_{51}\rvert(\text{eV}^2)$	$\lvert U_{e4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\mu 5}\rvert$	ϕ_{45}
KMS[13]	0.47	0.87	0.128	0.138	0.165	0.148	$1.64\ \pi$
GL[14]	0.9	1.61	0.13	0.13	0.14	0.078	$1.51\ \pi$

Kopp, Maltoni, Schwetz (KMS) arXiv:1103.4570
Giunti, Laveder, (GL) arXiv:1107.1452

See also recent analysis by Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz; arXiv:1207.4765

- Phenomenological models are model independent. In general, models are more constrained.

- What happens in a realistic model with sterile neutrinos?

Minimal Sterile Neutrino Model

- Mini-seesaw model (very low scale Majorana mass) De Gouvea et al 05

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} - \frac{1}{2}\overline{\nu_{si}} M_{ij} \nu^c_{sj} - (Y)_{i\alpha}\overline{\nu_{si}}\widetilde{\phi}^\dagger L_\alpha + {\rm h.c.}$$

- Minimal extension of the SM that accounts for neutrino masses and naturally includes sterile neutrinos (MM).

Minimal Sterile Neutrino Model

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- Minimal extension of the SM that accounts for neutrino masses and naturally includes sterile neutrinos (MM).

- More predictive than the phenomenological models (PM). In 3+2 models:

Model	# Δm^2	# Angles	# Phases
3 ν	2	3	1
3+2 MM	4	4	3
3+2 PM	4	9	5

Minimal Sterile Neutrino Model

- Mini-seesaw model (very low scale Majorana mass) De Gouvea et al 05

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin}} - \frac{1}{2}\overline{\nu_{si}} M_{ij} \nu^c_{sj} - (Y)_{i\alpha}\overline{\nu_{si}}\widetilde{\phi}^\dagger L_\alpha + \text{h.c.}$$

- Minimal extension of the SM that accounts for neutrino masses and naturally includes sterile neutrinos (MM).

- More predictive than the phenomenological models (PM). In 3+2 models:

Model	# Δm^2	# Angles	# Phases
3 ν	2	3	1
3+2 MM	4	4	3
3+2 PM	4	9	5

Minimal Sterile Neutrino Model

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→ ...and, in the MM, sterile mixing depends on the mass parameters

Minimal Sterile Neutrino Model

- We have performed a global fit in the context of the 3+2 mini-seesaw model
  Donini, Hernandez, JLP, Maltoni, Schwetz 2012; arXiv:1205.5230

  ► Minimal model allowed by data (3+1 already ruled out by 3-family oscillations).
  Donini, Hernandez, JLP, Maltoni 2011

- LBL and SBL can not be decoupled. Correlation between active and sterile mixing is not negligible.

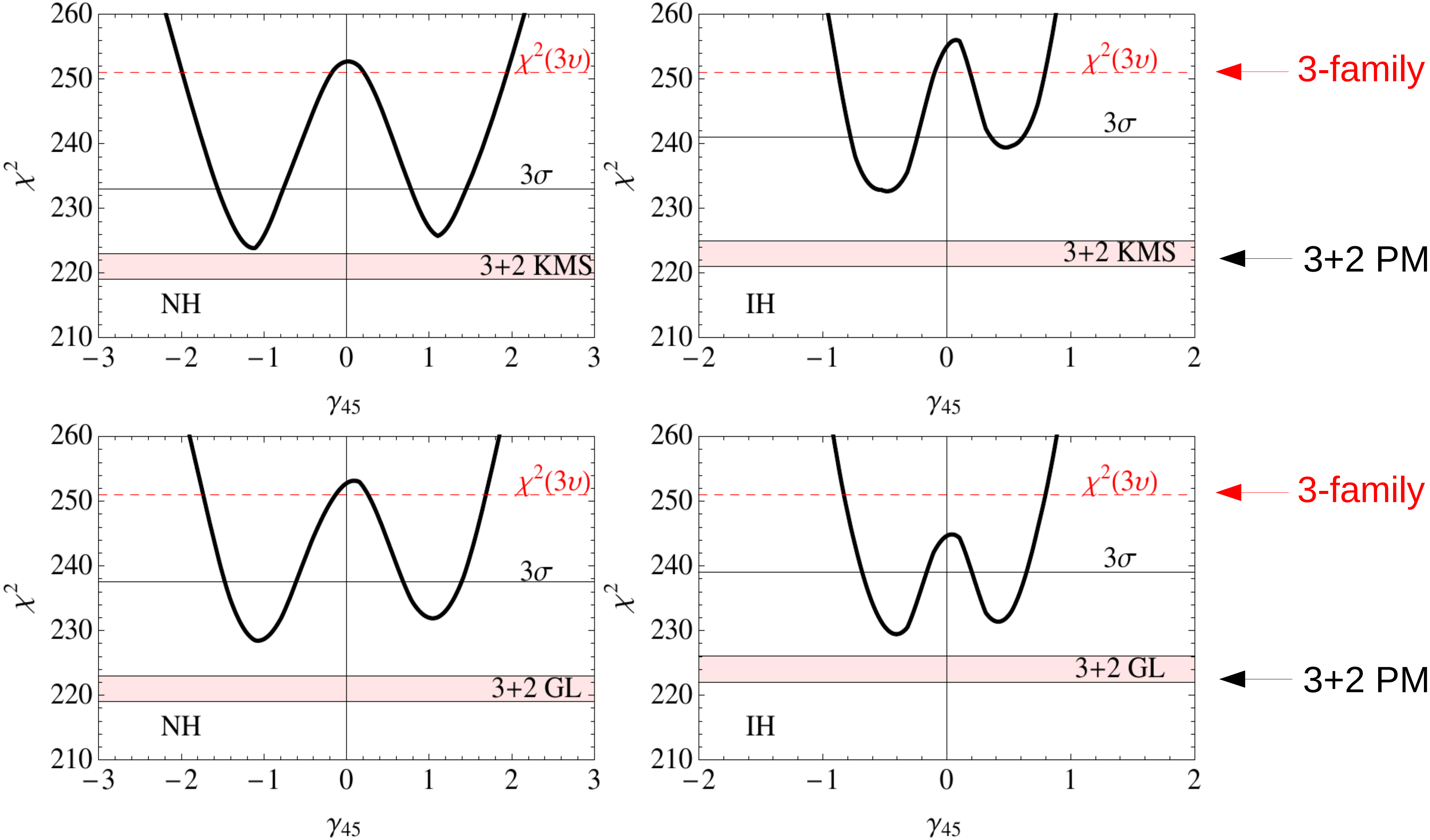
- We use a general parameterization which generalizes Casas-Ibarra to the case in which corrections are important (as in this case)

  see also Blennow, Fernandez-Martinez 2011

- We use M_1 and M_2 from the phenomenological KLM and GL best fits.

Minimal Sterile Neutrino Model

3+2 mini seesaw



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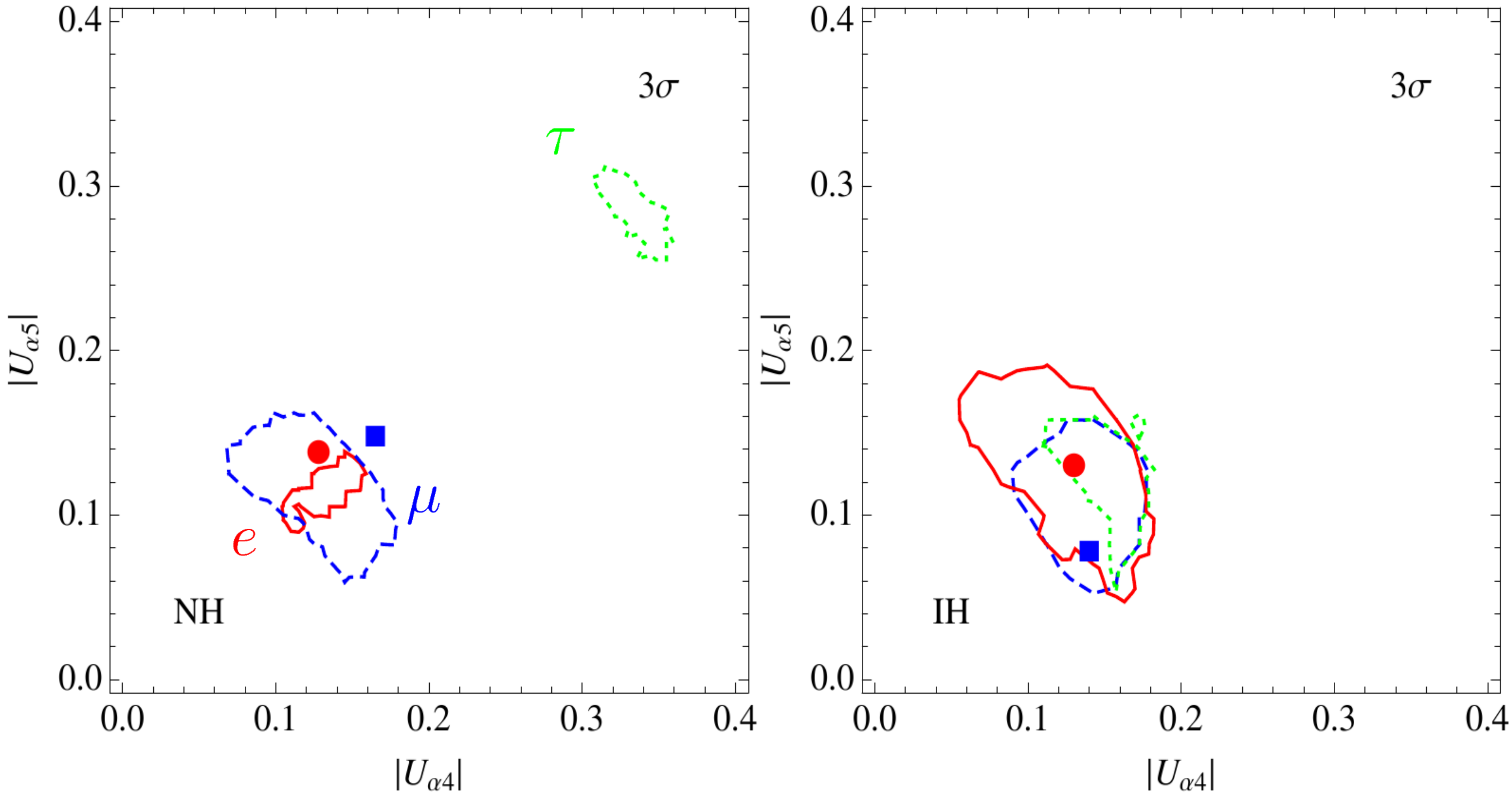
Minimal Sterile Neutrino Model

Prediction: large tau-mixing with extra states for NH!



Donini, Hernandez, JLP, Maltoni, Schwetz 2012; arXiv:1205.5230

Minimal Sterile Neutrino Model

- 3+2 mini-seesaw model improves 3ν scenario and close to phenomenological approach.

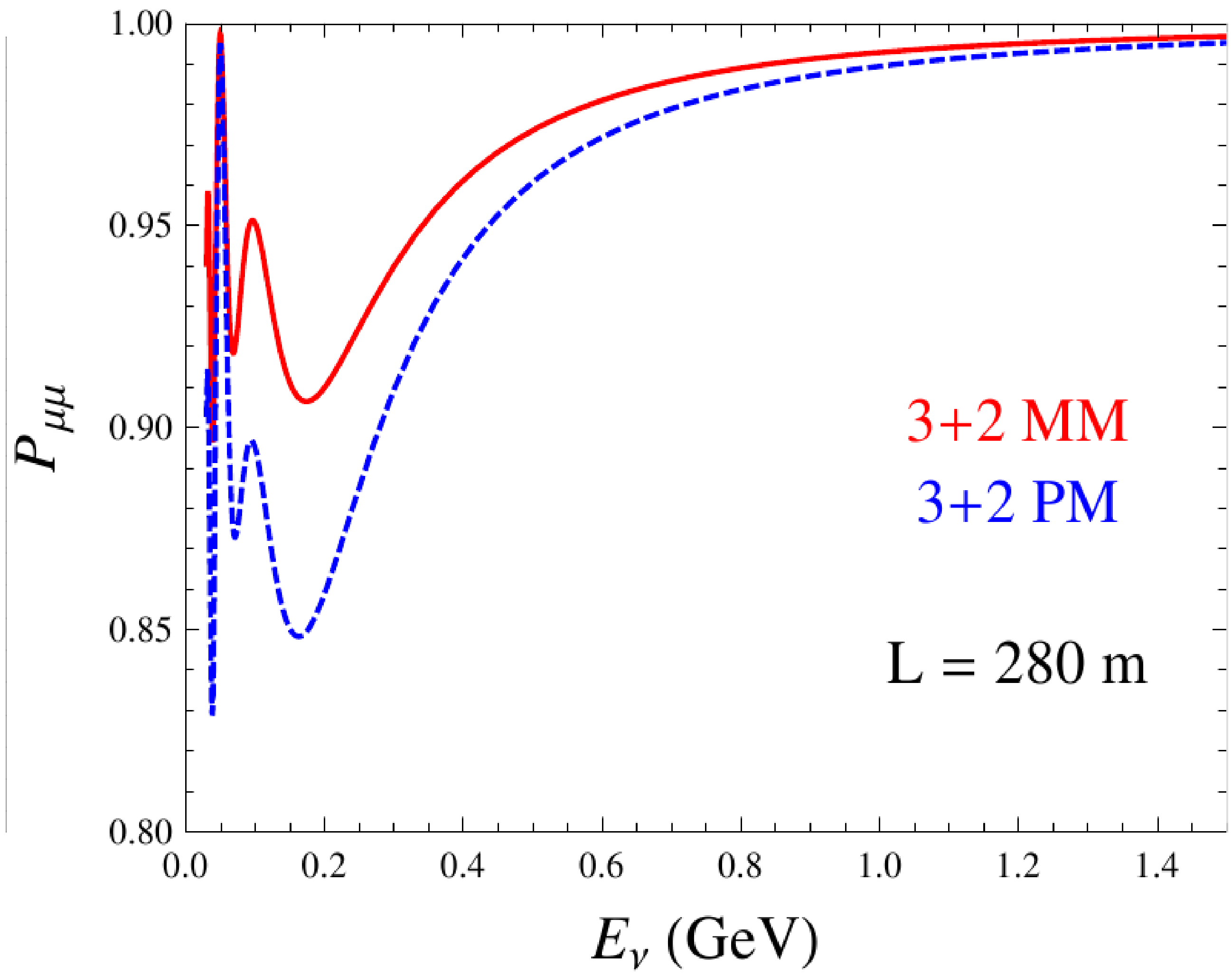
- Prediction! large tau-mixing with extra states for NH. Tau-detection would be needed to probe it.

- But large tension appearance/disappearance in μ sector remains. it seems not very difficult to confirm/rule out.

Donini, Hernandez, JLP, Maltoni, Schwetz 2012; arXiv:1205.5230

Minimal Sterile Neutrino Model

@T2K Near Detector



Donini, Hernandez, JLP, Maltoni, Schwetz 2012; arXiv:1205.5230

Conclusions

- Higher energy NP able to explain the smallness of neutrino masses, can give deviations from the unitarity of the PMNS matrix.

- It's relevant thus to test to what extent 3x3 unitarity is conserved. Future neutrino oscillation facilities could probe possible deviations.

- NSI: model independent way of parameterizing the New Physics effects in neutrino oscillations. Mild constraints but huge effects not expected theoretically.

- Models with M~ TeV, as inverse seesaw models, etc may give sizable effects: deviations from 3x3 unitarity close to present bounds. Excellent signals of new physics.

- Low energy NP may involved the presence of sterile neutrino. They strongly affect neutrino oscillations. *LSND/reactor anomaly and cosmology points to existence of this kind of NP.*

Conclusions

- $\nu_\mu \to \nu_\tau$ CP-asymmetry is a clean probe of the new phases associated to non-unitarity, coming from either seesaws, NSI or light sterile neutrinos.

- Near detectors really useful to constrain New Physics. Specially, non-unitarity effects coming form high or low energies.

- 3+2 mini-seesaw model provides a better global fit to neutrino oscillation data, including the LSND/reactor anomaly, than the 3-family scenario and very close to the 3+2 phenomenological approach

- Same tension between appearance and disappearance data remains in the muon-sector. Situation may be clarified in the near future using T2K near detector.

- The model predicts large sterile mixing with tau-neutrinos in the NH case.

Thank you!