



Beyond Standard Model Neutrinos



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2022**

Apoio:



Standard Model of Particle Physics

Electroweak theory

$$SU(2)_L \times U(1)_Y \quad W^{\mu,a} \quad B^\mu \quad L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad e_R^-$$



$$U(1)_{\text{em}} \quad W_\pm^\mu \quad Z^\mu \quad A^\mu \quad (\nu_\alpha)_L \quad e^- \quad \mu^- \quad \tau^- \quad u, d, c, s, b, t \quad H$$

Tres generaciones de la materia (fermiones)

	I	II	III	
masa →	2.4 MeV	1.27 GeV	171.2 GeV	
carga →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	
espín →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	
nombre →	u arriba	c encanto	t cima	γ fotón
Quarks				
	4.8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ abajo	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ extraño	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ fondo	0 0 1 g gluón
Bosones de gauge				
	<2.2 eV 0 $\frac{1}{2}$ ν _e neutrino electrónico	<0.17 MeV 0 $\frac{1}{2}$ ν _μ neutrino muónico	<15.5 MeV 0 $\frac{1}{2}$ ν _τ neutrino tauónico	91.2 GeV 0 1 Z ⁰ bosón Z
Leptones				
	0.511 MeV -1 $\frac{1}{2}$ e electrón	105.7 MeV -1 $\frac{1}{2}$ μ muón	1.777 GeV -1 $\frac{1}{2}$ τ tauón	80.4 GeV ± 1 1 W [±] bosón W

What we know about neutrinos at the end of 20th Century?

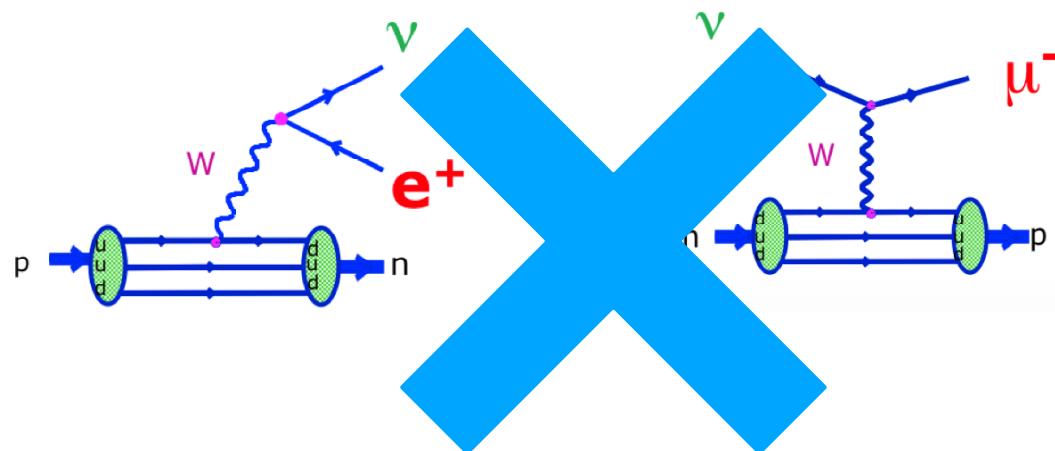
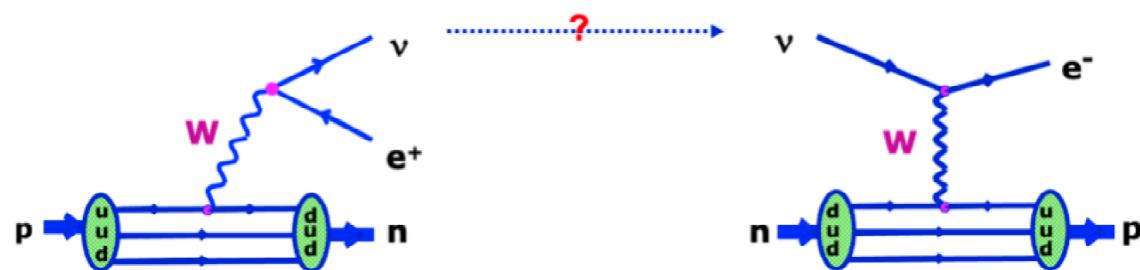


- There are 3 types of neutrinos: ν flavor: ν_e ν_μ ν_τ
- have ZERO mass e ZERO charge
- interact **only** by weak interactions:

See the review by David Vanegas
at this conference.



What we know about neutrinos at the end of 20th Century?

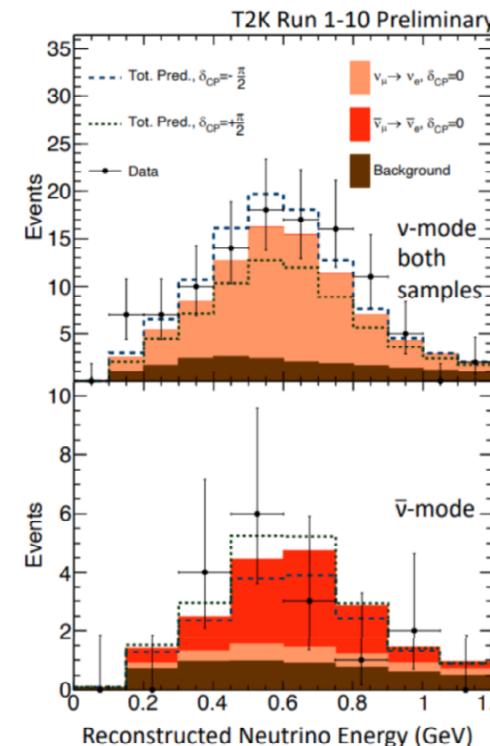
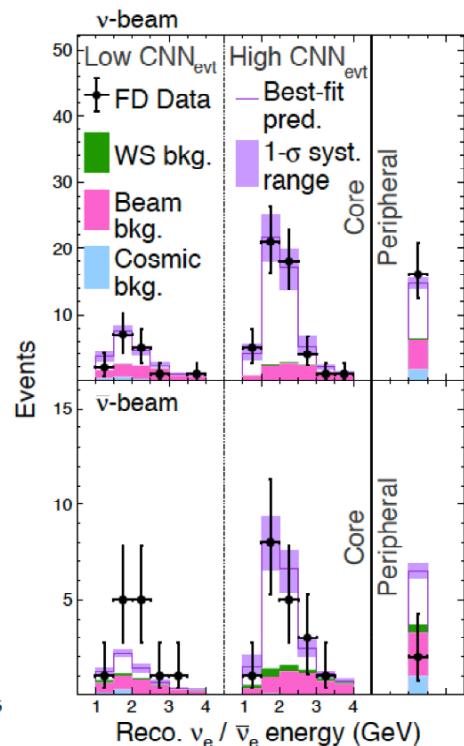
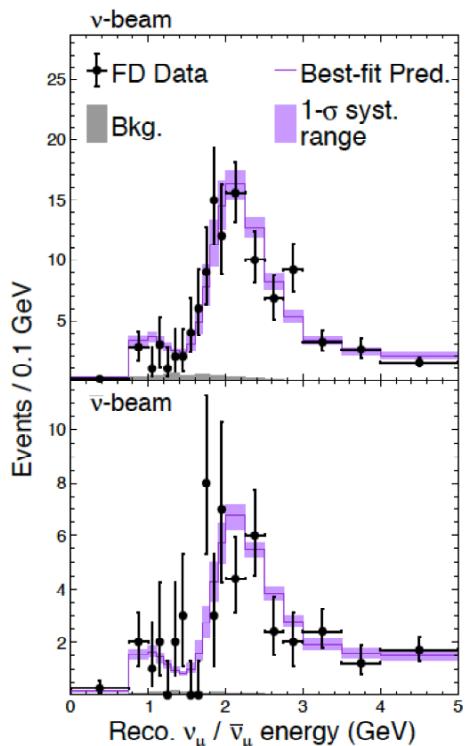
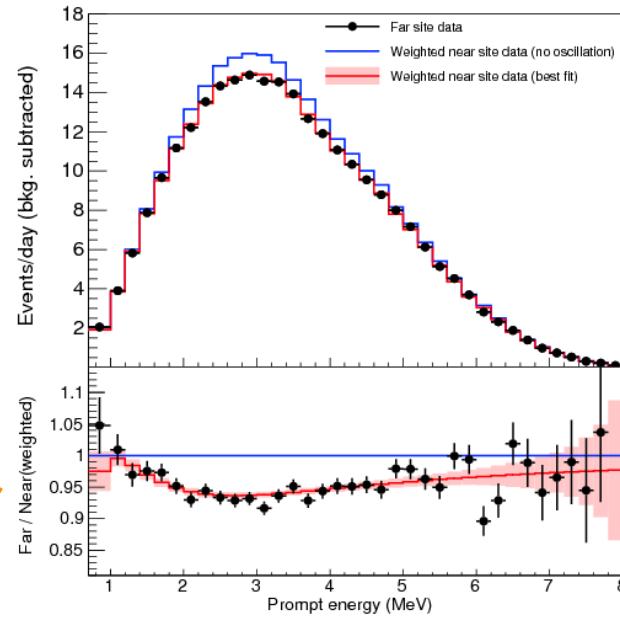
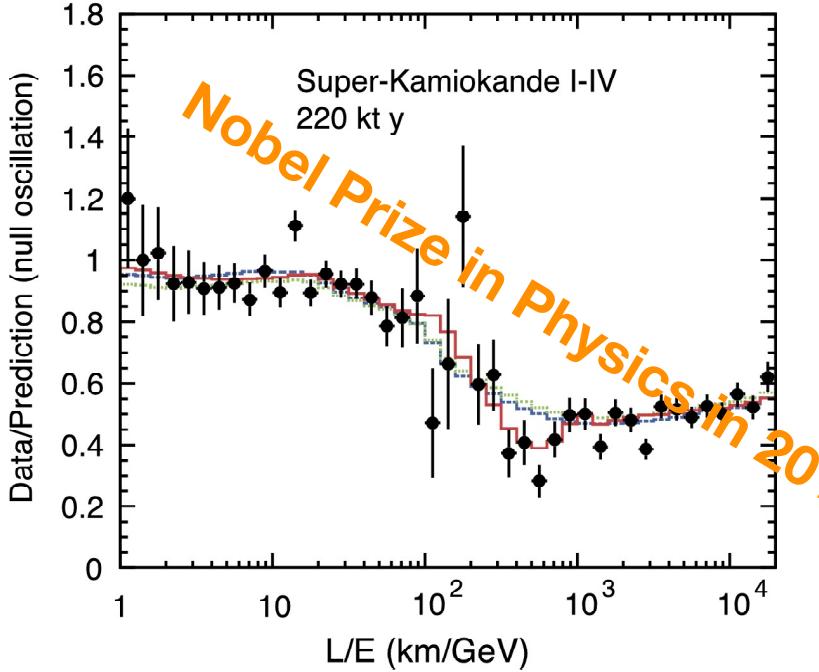


No Flavor change!!



But something change in recent years.... (from a perspective of 50 yrs old blue dude)

Neutrino oscillation



Neutrino oscillation discovery opens a plethora of new experiments and new questions



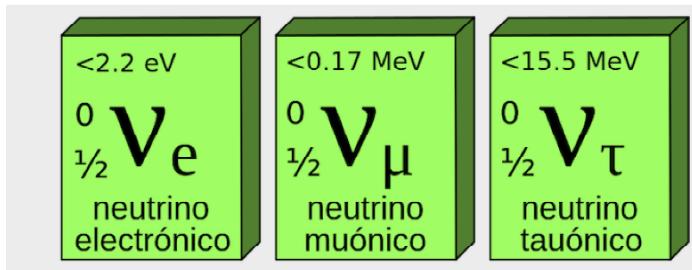
LArIAT



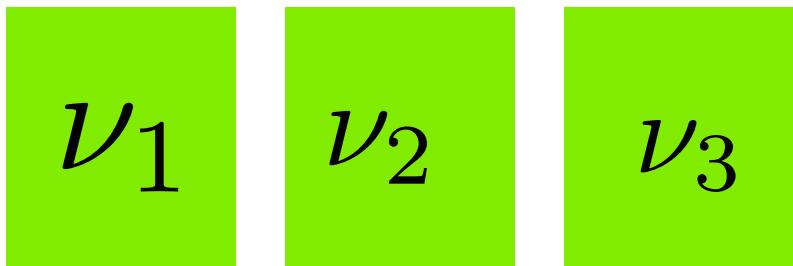
Hyper-Kamiokande

Neutrino oscillation discovery opens a plethora of new experiments and new questions

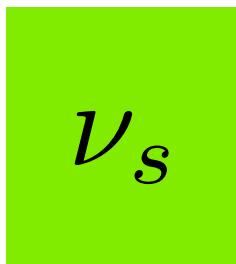
Flavor states



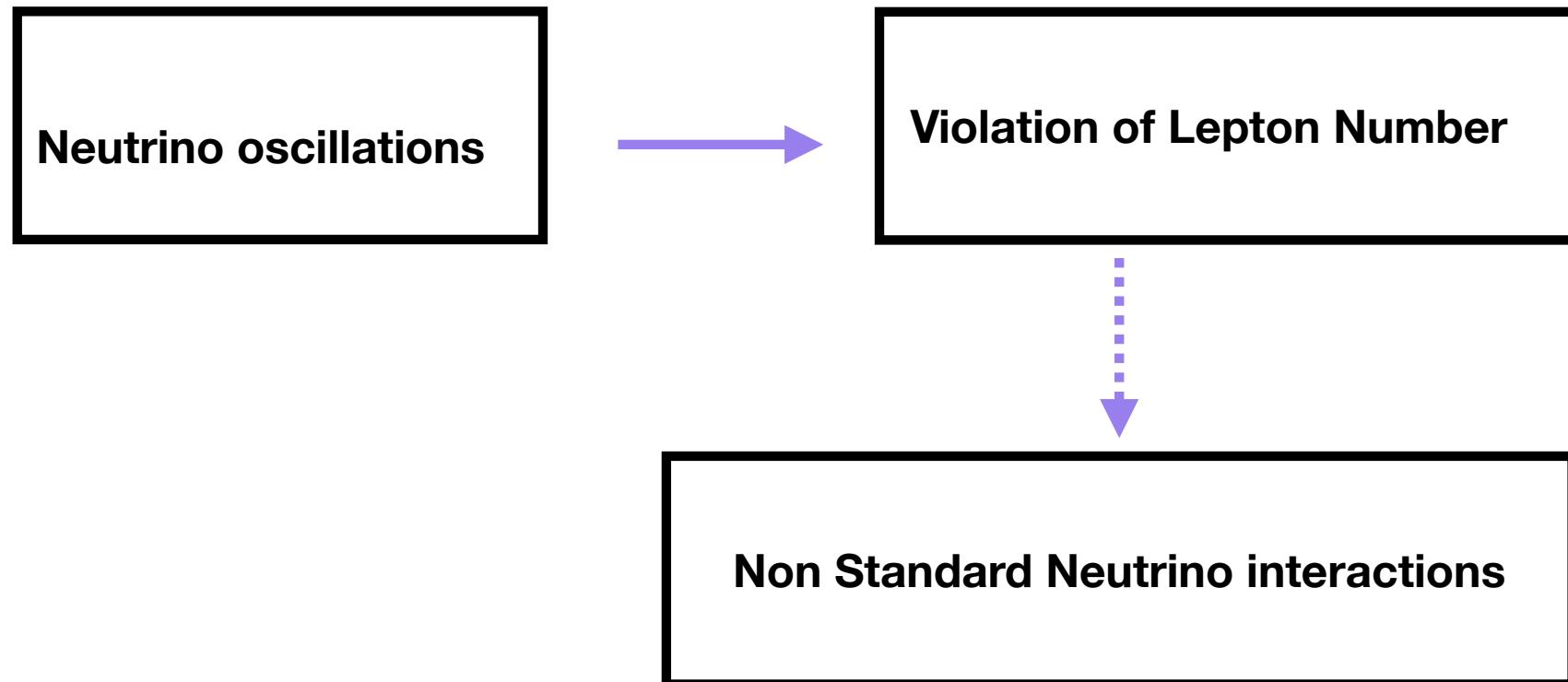
Mass states (to be included in PDG???)



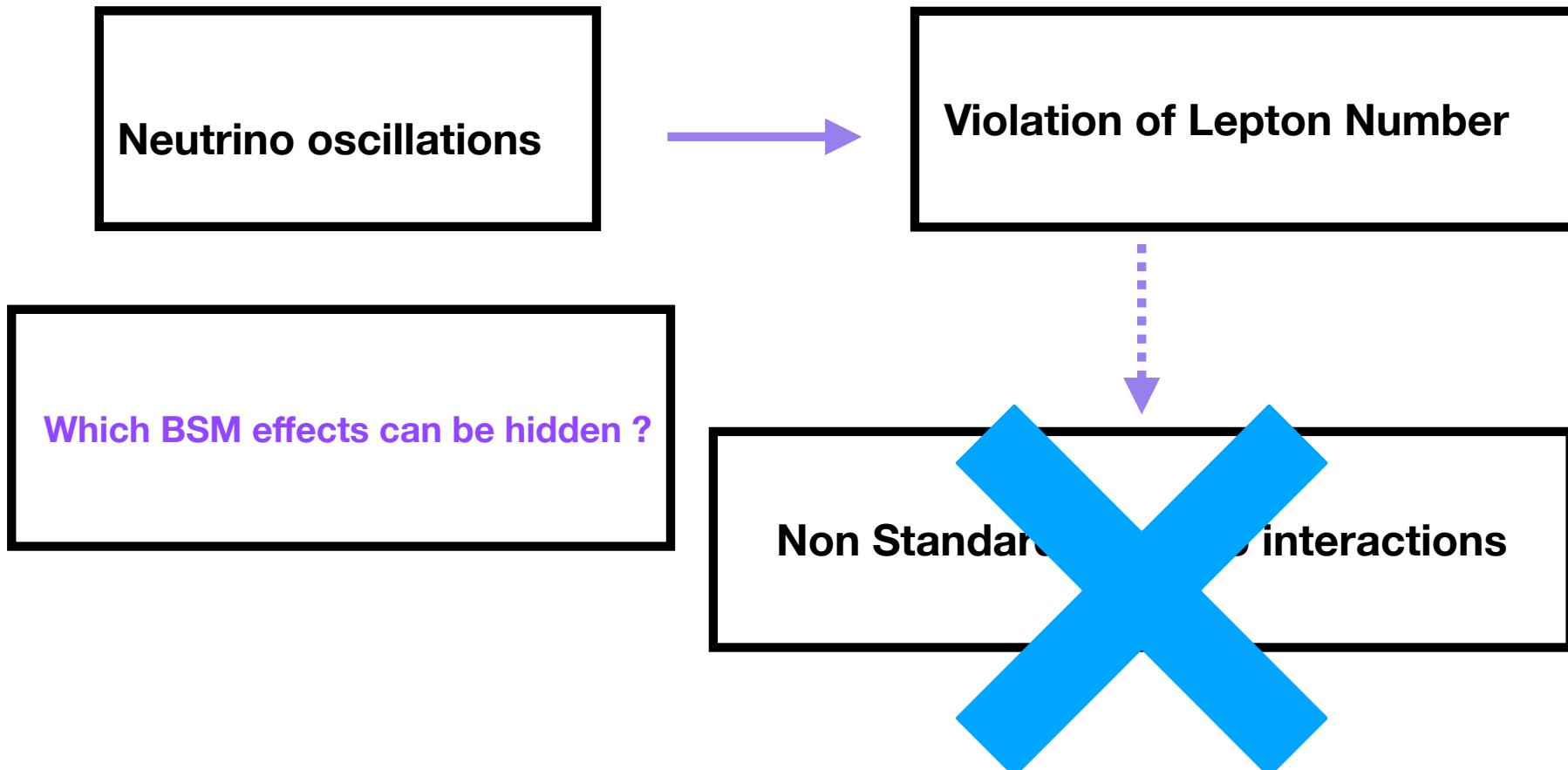
Hint of new states? Sterile neutrino



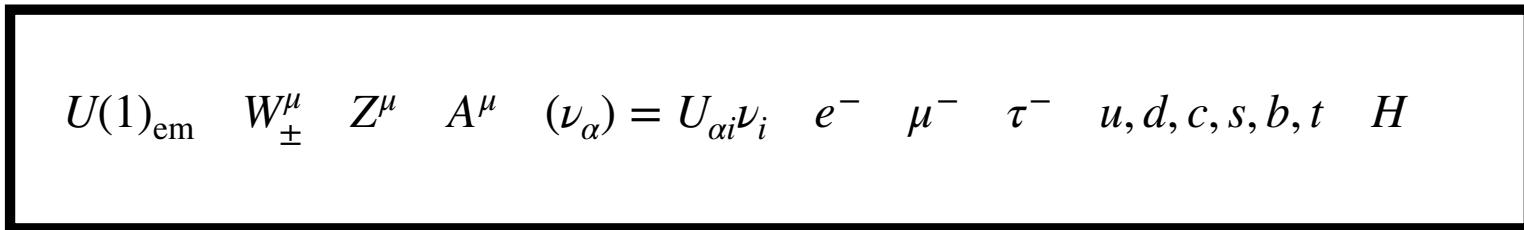
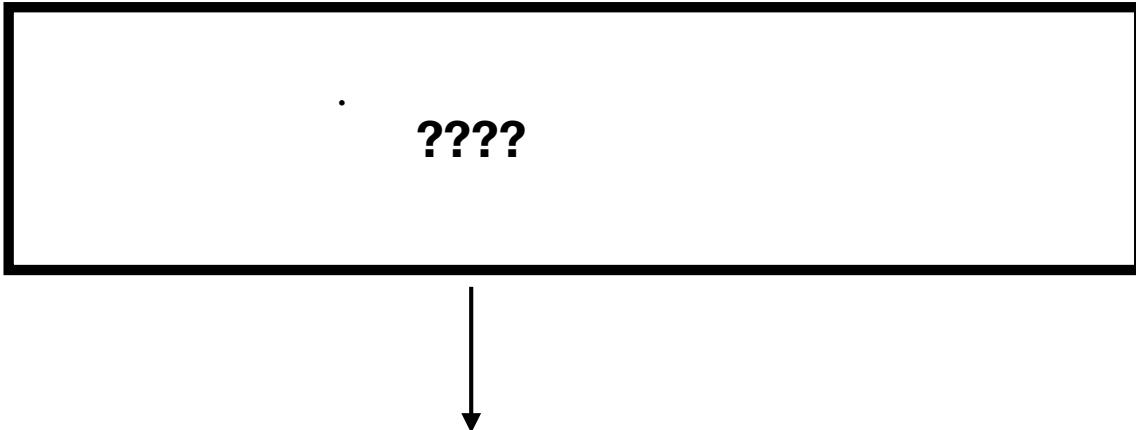
Neutrino oscillation discovery opens a plethora of new experiments and new questions



Neutrino oscillation discovery opens a plethora of new experiments and new questions



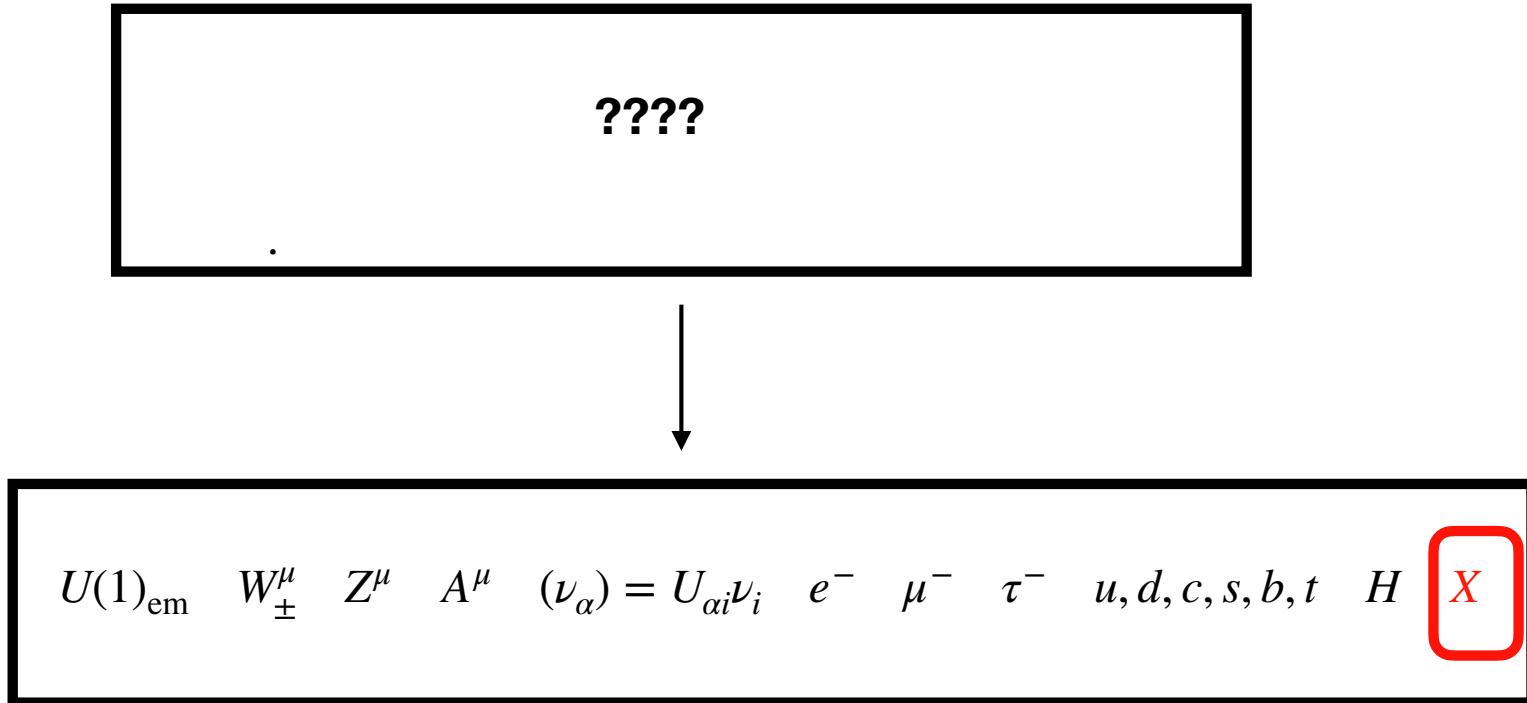
BSM in Neutrinos: First try: Non Standard Neutrino Interactions



$$\mathcal{L}_{\text{PMNS}} = 2\sqrt{2}G_f \left(\bar{u}_j V_{\text{CKM}}^{jk} \gamma^\mu P_L d_k \bar{l}_\alpha P_L \gamma_\mu \nu_\beta \right) = 2\sqrt{2}G_f \left(\bar{u}_j V_{\text{CKM}}^{jk} \gamma^\mu P_L d_k \bar{l}_\alpha P_L \gamma_\mu \textcolor{magenta}{U}_{\beta i}^{\text{PMNS}} \nu_i \right)$$

$\textcolor{magenta}{U}^{\text{PMNS}}$ (Pontecorvo, Maki, Nakagawa, Sakata) can be the source of CP violation for neutrinos. Not observed yet.

BSM in Neutrinos: First try: Non Standard Neutrino Interactions



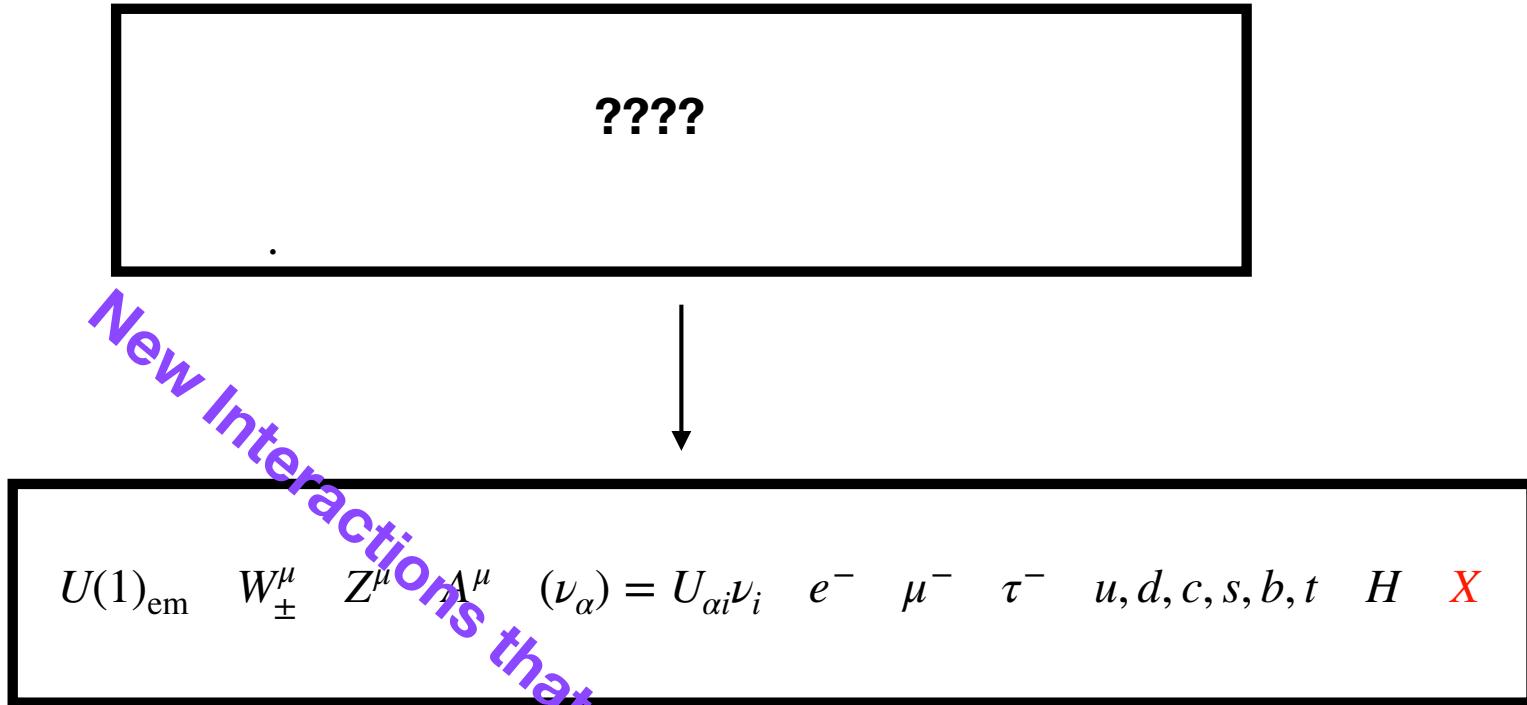
$$\mathcal{L}_{\text{BSM}} = 2\sqrt{2}G_f \left(\underbrace{\frac{1}{2} [c_S]_{\alpha\beta} \bar{u}_j V_{\text{CKM}}^{jk} d_k \bar{l}_{\alpha} P_L \nu_{\beta}}_{\text{SCALAR}} + \underbrace{\frac{1}{4} [c_T]_{\alpha\beta} \bar{u}_j V_{\text{CKM}}^{jk} \sigma^{\mu\nu} P_L d_k \bar{l}_{\alpha} P_L \sigma_{\mu\nu} \nu_{\beta}}_{\text{TENSORIAL}} \right)$$

In the usual oscillation model we have

$$\mathcal{L}_{\text{PMNS}} = 2\sqrt{2}G_f \left(\bar{u}_j V_{\text{CKM}}^{jk} \gamma^{\mu} P_L d_k \bar{l}_{\alpha} P_L \gamma_{\mu} \nu_{\beta} \right) = 2\sqrt{2}G_f \left(\bar{u}_j V_{\text{CKM}}^{jk} \gamma^{\mu} P_L d_k \bar{l}_{\alpha} P_L \gamma_{\mu} U_{\beta i}^{\text{PMNS}} \nu_i \right)$$

$[c_S]_{\alpha\beta}$ ($[c_T]_{\alpha\beta}$) are the scalar (tensorial) couplings is a complex matrix. Can induce CP violation.

BSM in Neutrinos: First try: Non Standard Neutrino Interactions



$$\mathcal{L}_{BSM} = 2\sqrt{2}G_f \left(\frac{1}{2} [c_S]_{\alpha\beta} \bar{u}_j V_{\text{CKM}}^{jk} d_k \bar{l}_\alpha P_L \nu_\beta + \frac{1}{4} [c_T]_{\alpha\beta} \bar{u}_j V_{\text{CKM}}^{jk} \sigma^{\mu\nu} P_L d_k \bar{l}_\alpha P_L \sigma_{\mu\nu} \nu_\beta \right)$$

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$[c_S]_{\alpha\beta}$ ($[c_T]_{\alpha\beta}$) are the scalar (tensorial) couplings is a complex matrix. Can induce CP violation.

How to include NSI in neutrino phenomenology?

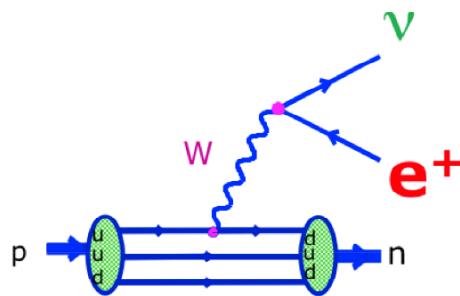
Usual way:

$$\mathcal{L}_{BSM} = 2\sqrt{2}G_f \left(\frac{1}{2} [\epsilon_S]_{\alpha\beta} \bar{u}_j V_{CKM}^{jk} d_k \bar{l}_\alpha P_L \nu_\beta + \frac{1}{4} [\epsilon_T]_{\alpha\beta} \bar{u}_j V_{CKM}^{jk} \sigma^{\mu\nu} P_L d_k \bar{l}_\alpha P_L \sigma_{\mu\nu} \nu_\beta \right)$$

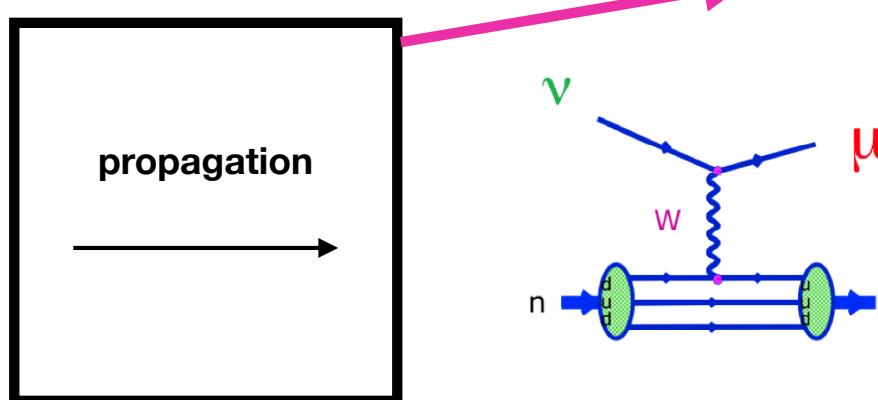
$$[\epsilon_S]_{\alpha\beta} = \frac{G_S}{G_f}$$

This parameter it is universal for all reactions.

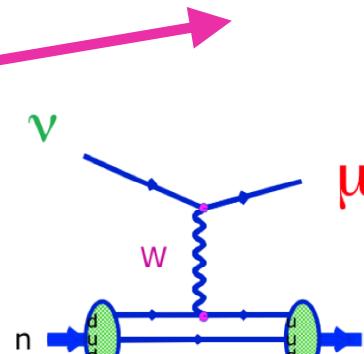
See E. Nardi et al.,
Phys. Rev. D 60 (1999) 093008



charged NSI



neutral NSI

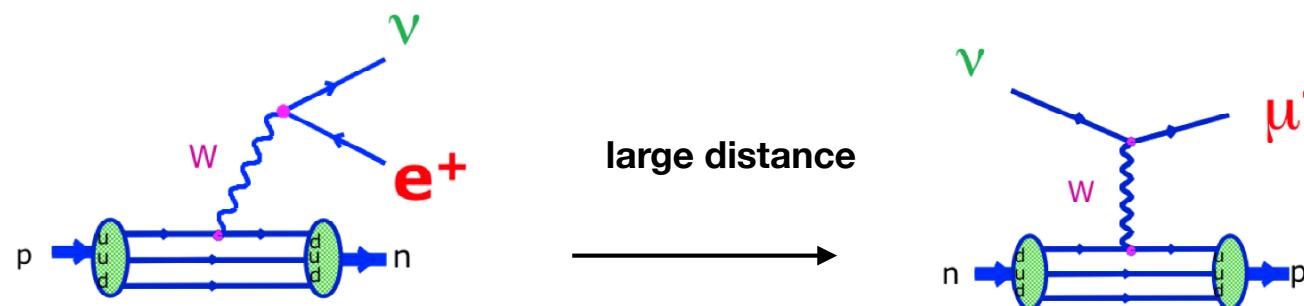


charged NSI

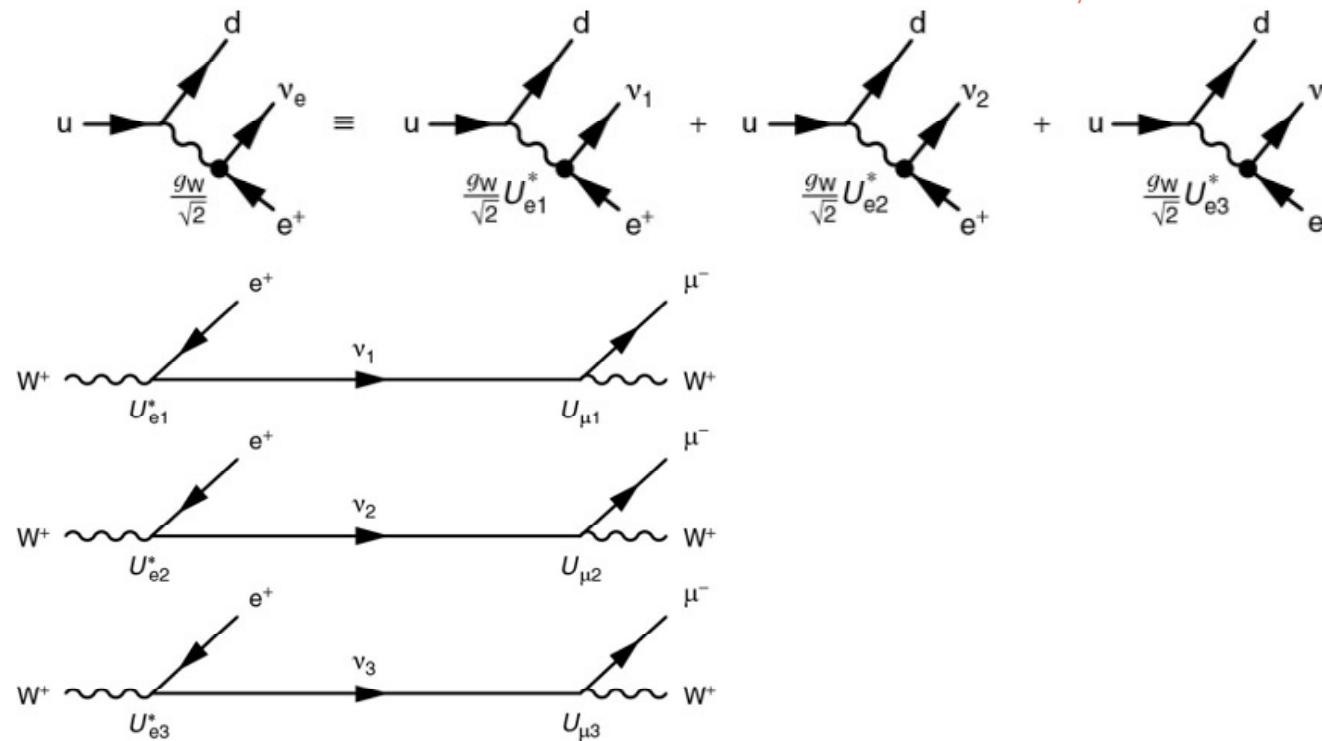
See M. Acero talk at this conference for NSI propagations for NOVA experiment.

How to include NSI in oscillation ?

Usual oscillation



When we observe this we describe as ν_e oscillate to ν_μ . The process can be decomposed as



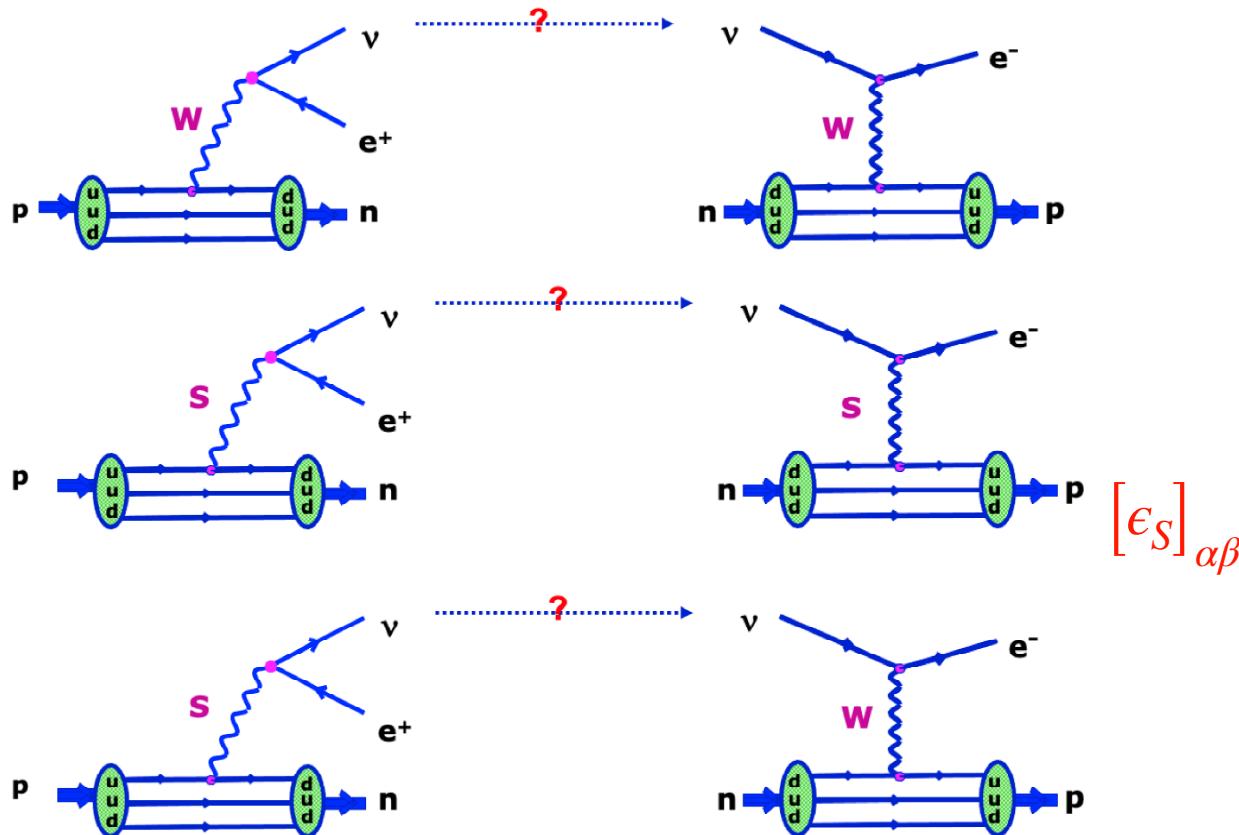
New way to include NSI at production and detections,

Follow from references below

$$\mathcal{L}_{\text{BSM}} = 2\sqrt{2}G_f \left(\frac{1}{2} [\epsilon_S]_{\alpha\beta} \bar{u}_j V_{\text{CKM}}^{jk} d_k \bar{l}_\alpha P_L \nu_\beta + \frac{1}{4} [\epsilon_T]_{\alpha\beta} \bar{u}_j V_{\text{CKM}}^{jk} \sigma^{\mu\nu} P_L d_k \bar{l}_\alpha P_L \sigma_{\mu\nu} \nu_\beta \right)$$

We will explicitly compute the amplitudes processes, $\mathcal{A}_{\text{total}} = \mathcal{A}_{\text{PMNS}} + \mathcal{A}_{\text{Scalar}}^{\text{BSM}}$

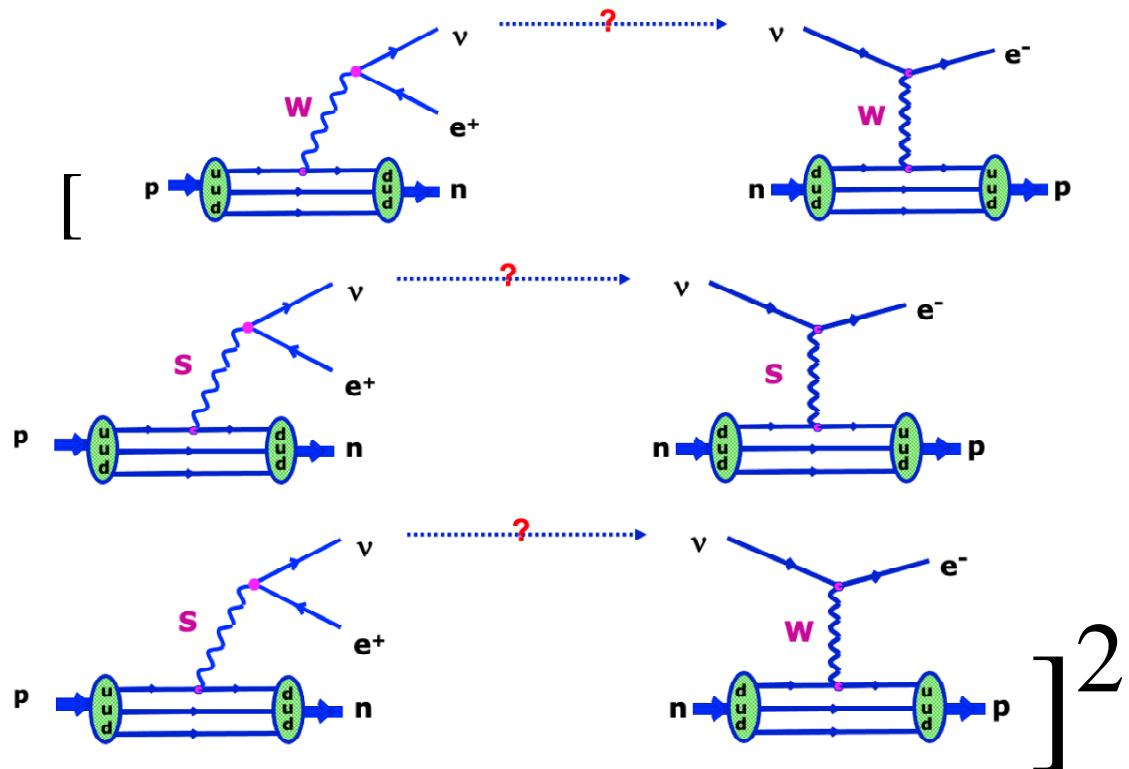
$$(\mathcal{A}_{\text{total}}^{\text{P,D}})_{\alpha i} = (\mathcal{A}_{\text{PMNS}})^{\text{P,D}}_{\alpha i} + (\mathcal{A}_{\text{BSM}})^{\text{P,D}}_{\alpha i} = U_{\alpha i} (*) \mathcal{M}_W^{\text{P,D}} + [\epsilon_X U]_{\alpha i} (*) \mathcal{M}_X^{\text{P,D}}$$



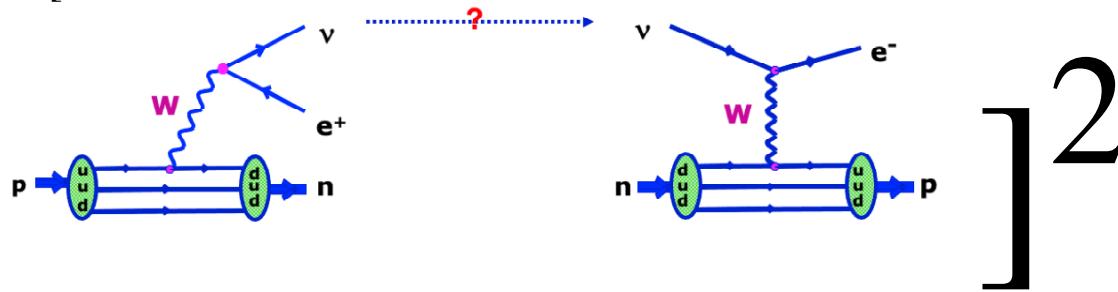
- A. A. Falkowski, M. Gonzalez-Alonso, and Z. Tabrizi, [JHEP 05, 173, arXiv:1901.04553 \(2019\) \[hep-ph\]](#)
B. A. Falkowski, M. Gonzalez-Alonso, and Z. Tabrizi, [JHEP 11, 048, arXiv:1910.02971 \(2020\) \[hep-ph\]](#)

The rate with NSI for detecting ν_β when it was produced ν_α

$$R_{\alpha\beta} =$$



$$R_{\alpha\beta}^{\text{SM}} = [$$



- A. A. Falkowski, M. Gonzalez-Alonso, and Z. Tabrizi, JHEP 05, 173, arXiv:1901.04553 316 [hep-ph]
B. A. Falkowski, M. Gonzalez-Alonso, and Z. Tabrizi, JHEP 11, 048, arXiv:1910.02971 [hep-ph]

We compute the rate of events

$$\frac{R_{\alpha\beta}}{\phi_\alpha^{\text{SM}} \sigma_\beta^{\text{SM}}} = \sum_{k,l} e^{-i\phi_{kl}} [V_\alpha^{kl}(P_X)] \times [V_\beta^{kl}(D_X)]^*$$

with

$$V_\alpha^{kl}(P_X) = U_{\alpha k}^* U_{\alpha l} + p_{XL} (\epsilon_X U)_{\alpha k}^* U_{\alpha l} + p_{XL}^* U_{\alpha k}^* (\epsilon_X U)_{\alpha l} + p_{XX} (\epsilon_X U)_{\alpha k}^* (\epsilon_X U)_{\alpha l} \text{ and}$$

$$\phi_{kl} = \frac{\Delta m_{kl}^2}{2E_\nu}$$

the difference in this approach are the p-factors

$$p_{XY} = \frac{\int d\Pi_P A_X^P \bar{A}_Y^P}{\int d\Pi_P |A_L^P|^2} \quad d_{XY} = \frac{\int d\Pi_D A_X^D \bar{A}_Y^D}{\int d\Pi_D |A_L^D|^2},$$

We compute the rate of events

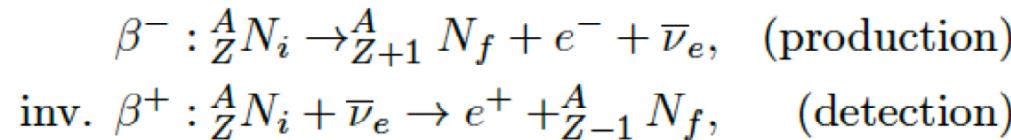
$$\frac{R_{\alpha\beta}}{\phi_\alpha^{\text{SM}} \sigma_\beta^{\text{SM}}} = \sum_{k,l} e^{-i\phi_{kl}} [V_\alpha^{kl}(\mathbf{P}_X)] \times [V_\beta^{kl}(\mathbf{D}_X)]^*$$

with

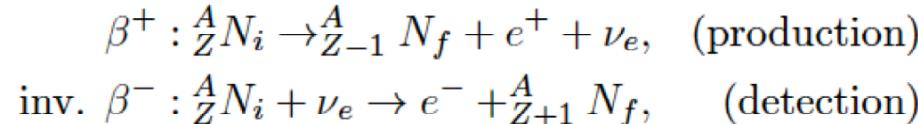
$$p_{XY} = \frac{\int d\Pi_P A_X^P \bar{A}_Y^P}{\int d\Pi_P |A_L^P|^2} \quad d_{XY} = \frac{\int d\Pi_D A_X^D \bar{A}_Y^D}{\int d\Pi_D |A_L^D|^2},$$

For experiments

Reactors:



Solar neutrinos



$$p_{SL}^{\beta^\pm} = 0 \quad p_{SS}^{\beta^\pm} = \frac{g_S^2}{3g_A^2} \quad p_{TL}^{\beta^\pm} = -\frac{g_T}{g_A} \frac{m_e}{f(E_\nu)} \quad p_{TT}^{\beta^\pm} = \frac{g_T^2}{g_A^2}$$

$$d_{SL}^{\beta^\pm} = \frac{g_S g_V}{g_V^2 + 3g_A^2} \frac{m_e}{E_e} \quad d_{TL}^{\beta^\pm} = \frac{3g_T g_A}{g_V^2 + 3g_A^2} \frac{m_e}{E_e}$$

$$d_{SS} = \frac{g_S^2}{g_V^2 + 3g_A^2} \quad d_{TT} = \frac{3g_T^2}{g_V^2 + 3g_A^2}$$

where $E_e = E_\nu \mp m_e$ and $f(E_\nu)$ β^- spectra .

Let's compare $\bar{\nu}_e \rightarrow \bar{\nu}_e$ with ν_e with ν_e

The rate of neutrinos with NSI

$$\frac{R_{\alpha\beta}}{\phi_{\alpha}^{\text{SM}} \sigma_{\beta}^{\text{SM}}} = \sum_{k,l} e^{-i\phi_{kl}} [V_{\alpha}^{kl}(P_X)] \times [V_{\beta}^{kl}(D_X)]^* = N^{\text{non-osc}} - \sum_{k>l} N_{kl}^{\text{osc}} \sin^2 \left(\frac{\Delta m_{kl}^2 L}{2E} \right) + \sum_{k>l} N_{kl}^{\text{CP}} \sin \left(\frac{\Delta m_{kl}^2 L}{4E} \right)$$

com $V_{\alpha}^{kl}(P_X) = U_{\alpha k}^* U_{\alpha l} + P_{XL}(\epsilon_X U)_{\alpha k}^* U_{\alpha l} + P_{XL}^* U_{\alpha k}^* (\epsilon_X U)_{\alpha l} + P_{XX}(\epsilon_X U)_{\alpha k}^* (\epsilon_X U)_{\alpha l}$ and

In the usual neutrino oscillation due PMNS,

$$N_{kl}^{\text{CP}} \propto \Im \left(U_{\alpha k}^* U_{\alpha l} U_{\beta k} U_{\beta l}^* \right) \quad N_{kl}^{\text{CP}} \Big|_{\alpha \rightarrow \beta} \propto \Im \left(\left| U_{\alpha k}^* \right|^2 \left| U_{\alpha l} \right|^2 \right) = 0$$

In the usual neutrino oscillation due NSI,

$$N_{\text{solar}}^{\text{CP}} \propto \left[(d_{XL} - p_{XL}) \Im[\tilde{\epsilon}_X]_{e\mu}, \left| [\tilde{\epsilon}_X]_{e\mu} \right|^2 (d_{XX} p_{XL} - d_{XL} p_{XX}) \right] \Im[\tilde{\epsilon}_X]_{e\mu}$$

NSI interaction can CP violation into neutrinos.

Game summary : we can have CP violation due NSI interaction.

This is similar super-weak theory of Wolfenstein made for quarks.

$[\epsilon_S]_{\alpha\beta}$ ($[\epsilon_T]_{\alpha\beta}$) are the scalar (tensorial) couplings is a complex matrix.

Can induce CP violation.

We use solar neutrinos, $\nu_e \rightarrow \nu_e$ Super-Kamiokande, SNO, Gallex, SAGE, Borexino
anti-neutrinos from reactors atores, $\bar{\nu}_e \rightarrow \bar{\nu}_e$ medium baseline (Daya Bay, RENO, Double Chooz)
longbaseline (KamLand)

to have bounds on NSI parameters and to see the effect of CP violation from NSI



Analysis of neutrino experiments

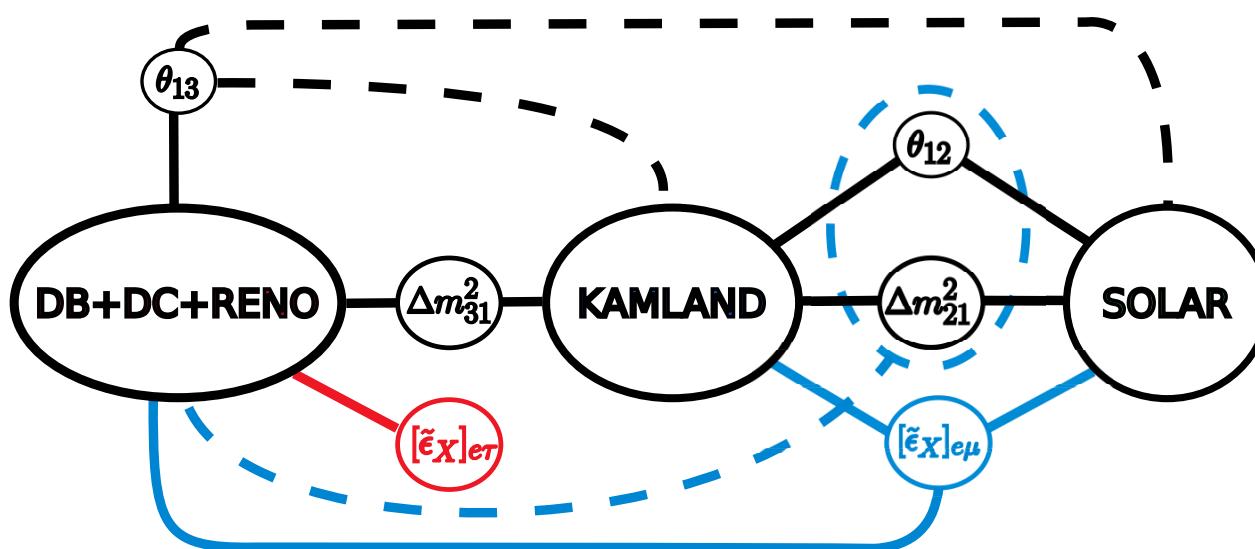
We use

$$\chi^2_{\text{KamLand}} = \sum_i \frac{(d_i - n_i - b_i)^2}{d_i} + \frac{a_i^2}{\sigma_i^2} \quad \chi^2_{\text{MBR}} = \sum_{\text{exp}=\{\text{DB,DC,RENO}\}} (\chi_{\text{exp}}^{\text{shape}})^2 + (\chi_{\text{exp}}^{\text{rate}})^2 + \frac{(1 - \alpha)^2}{\sigma_a^2}$$

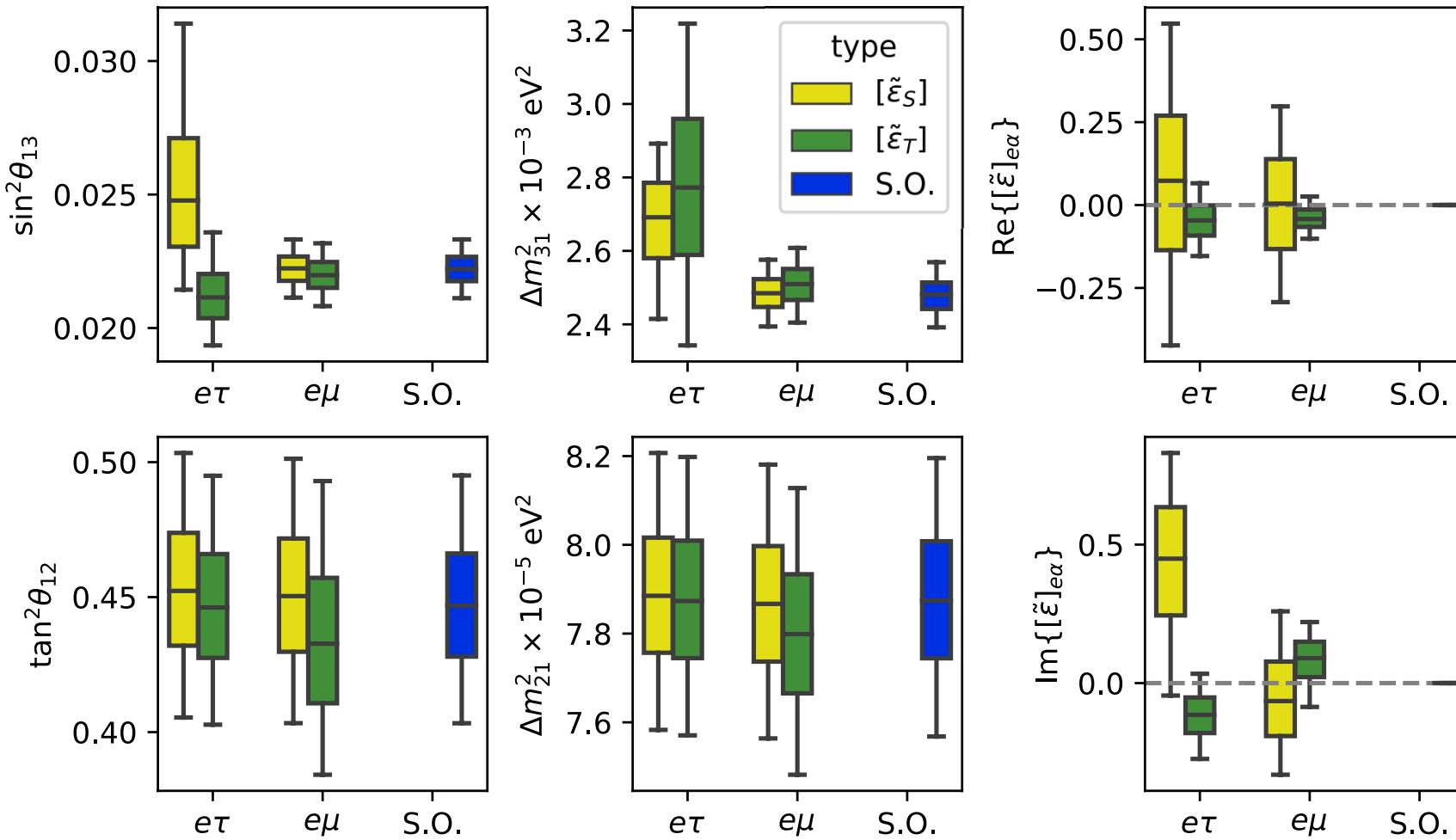
Combining

$$\chi^2_{\text{global}} = \chi^2_{\text{MBR}} + \chi^2_{\text{KamLand}} + \chi^2_{\text{Sun}}.$$

we have the parameters $\theta_{12}, \theta_{13}, \Delta m_{21}^2, \Delta m_{31}^2$ and from NSI, $\Re [\tilde{\epsilon}_S]_{\alpha\beta}, \Im [\tilde{\epsilon}_S]_{\alpha\beta}$. we define $\tilde{\epsilon}_X = \epsilon_X U_{23}(\theta_{23}, \delta)$.



Results



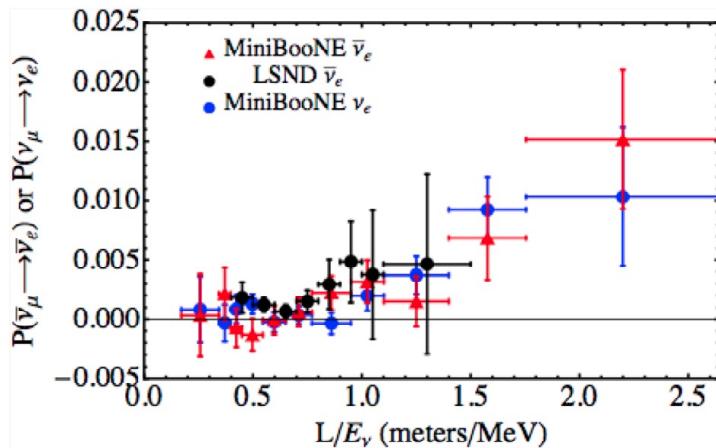
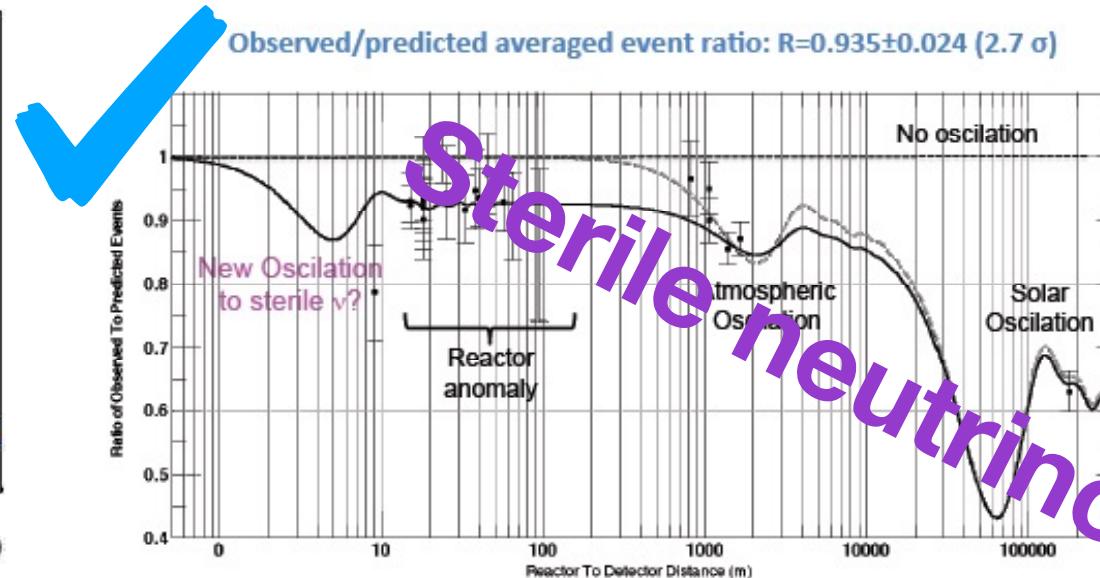
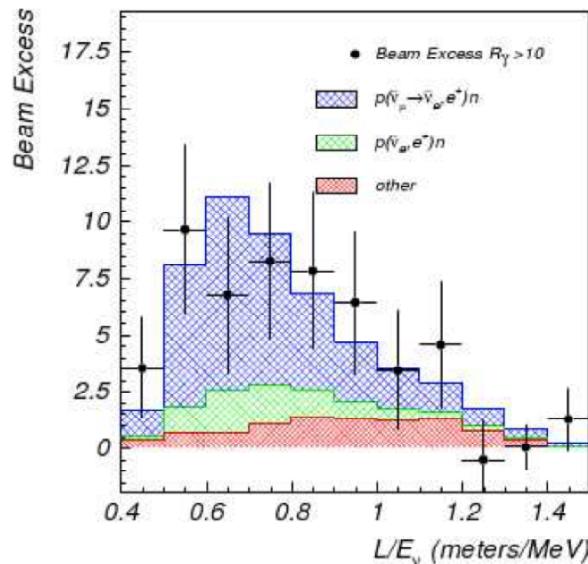
Values of $\sin^2\theta_{13}$ and Δm_{31}^2 are changed compared with standard values. There is a light improvement when we have non-zero imaginary NSI coupling

There are other signal of BSM ?

Not yet, search for sterile neutrinos, NSI (Non-standard neutrino interactions), Non-unitary scenarios, open quantum systems....

ν_s

Hints from LSND,MINI-BOONE, Reactor Anomaly!

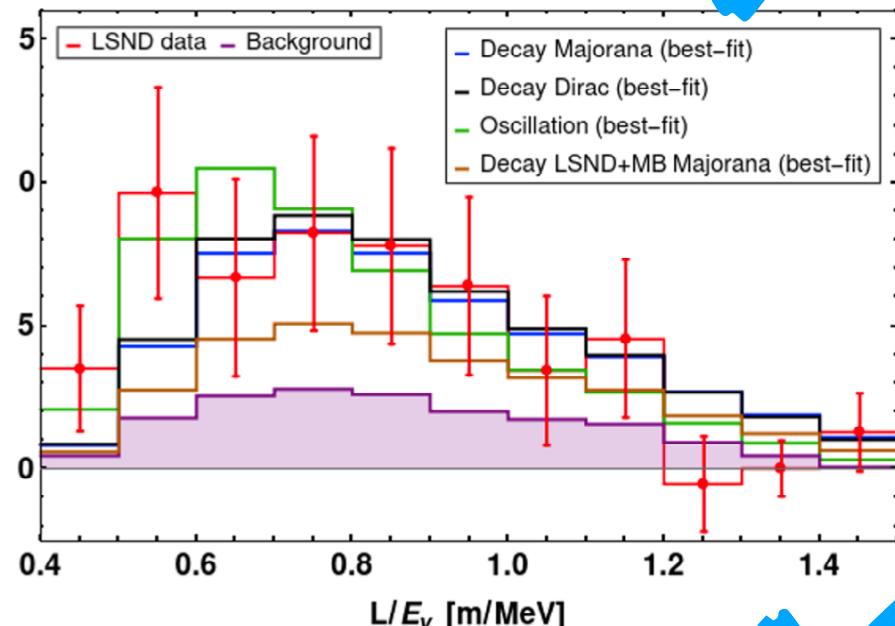


These data does not fit in the global fit shown in this conference by David Vanegas at COMHEP.

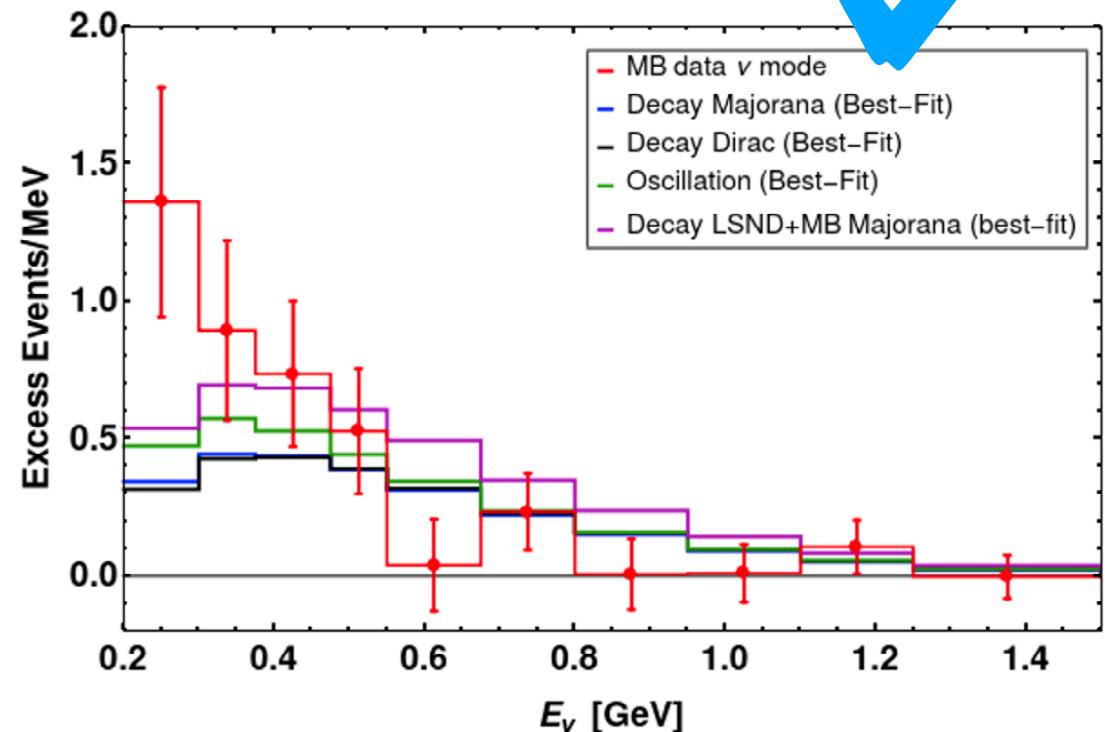


Sterile neutrinos: Appearance of electron neutrinos

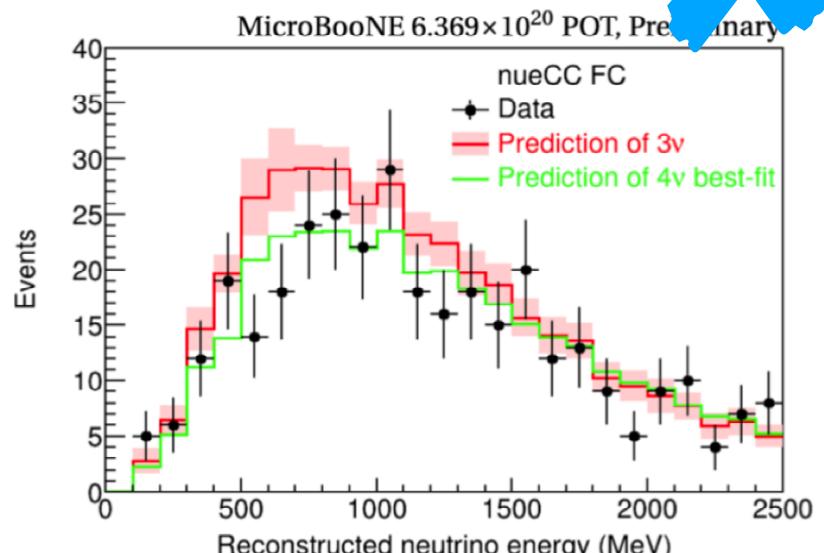
LSND experiment



Mini-BOONE experiment



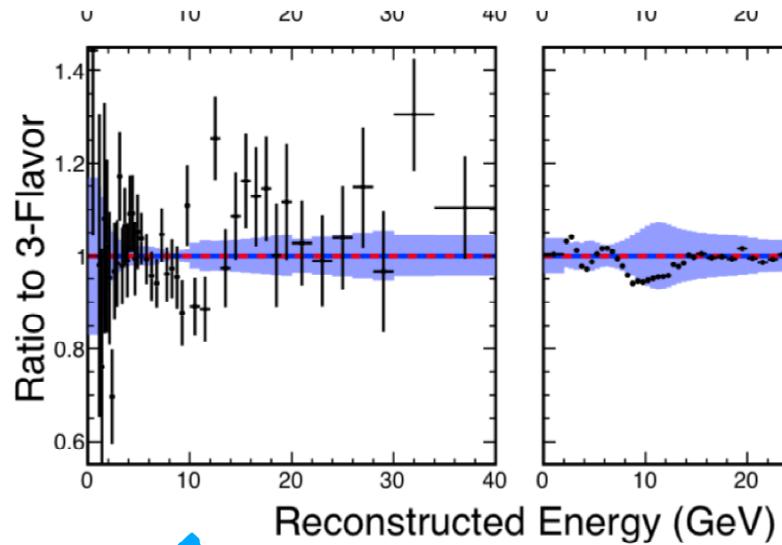
MICRO-BOONE experiment



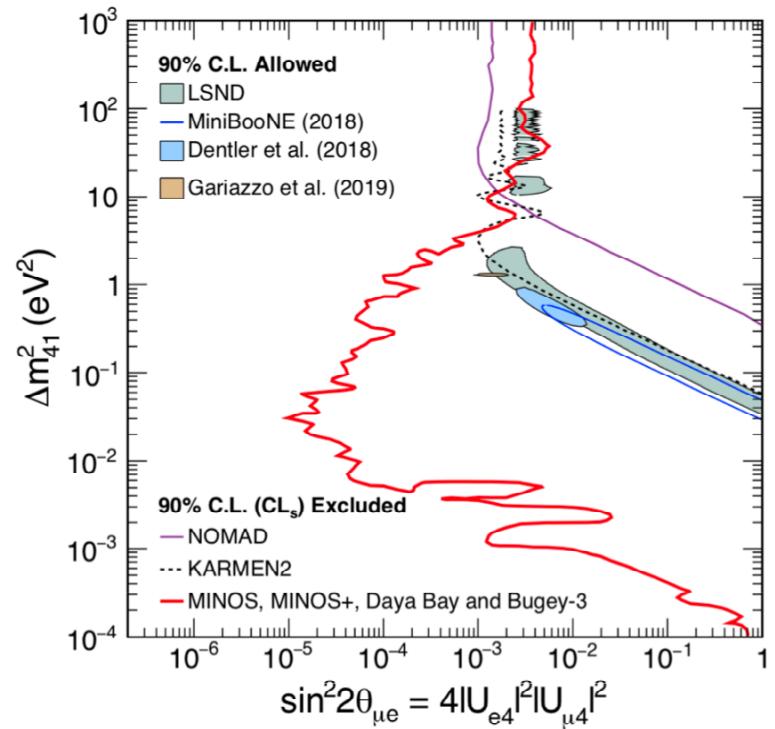
4σ

Sterile neutrinos: Disappearance of electron neutrinos

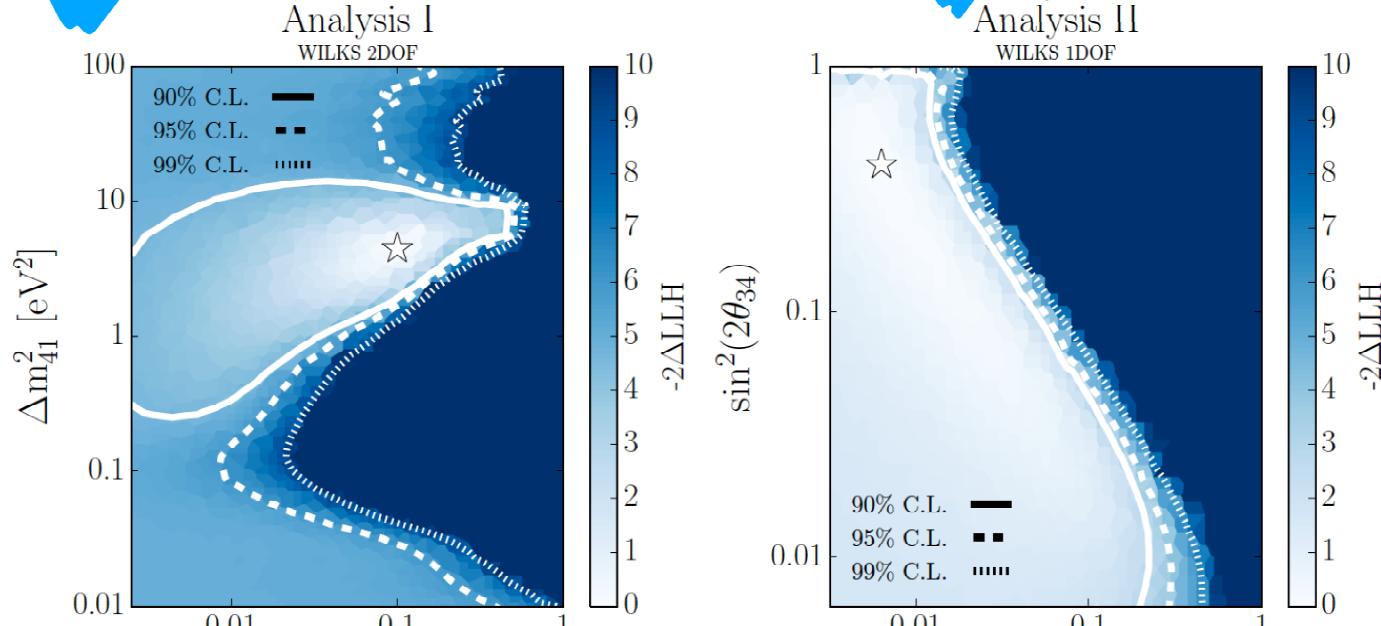
MINOS experiment



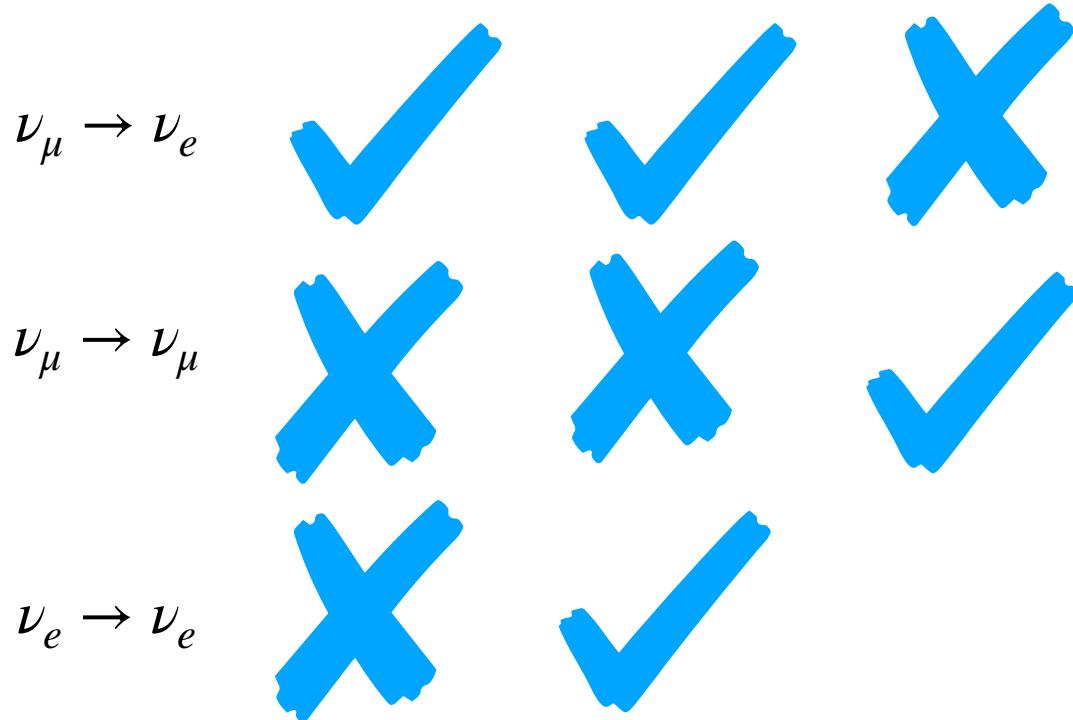
DAYA-BAY experiment



ICECUBE experiment



Sterile neutrinos: How to understand this mess?



General constraint

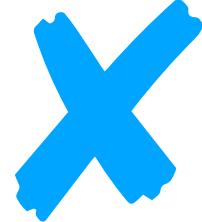
$$\sin^2(2\theta_{\mu e}) = 4 |U_{e4}^2| |U_{\mu 4}^2|$$

$$\sin^2(2\theta_{\mu\mu}) = 4 |U_{\mu 4}|^2$$

$$\sin^2(2\theta_{ee}) = 4 |U_{e4}^2|$$



$$\sin^2(2\theta_{\mu e}) = \frac{\sin^2(2\theta_{ee}) \sin^2(2\theta_{\mu\mu})}{4}$$



Neutrino decay phenomenology

Can neutrino decay to be the solution of short-baseline electron appearance?

Main Idea

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

(orange arrow)

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Assumption:

MeVish neutrino state

$$\nu_\mu = \dots + U_{\mu 4} \nu_4$$

(orange arrow)

$$\nu_\mu \rightarrow \nu_{1,2,3} + \phi$$

$$\nu_\mu \rightarrow \bar{\nu}_{1,2,3} + \phi$$

(orange arrow)

$$\nu_e / \bar{\nu}_e$$



Oscillation scenario:

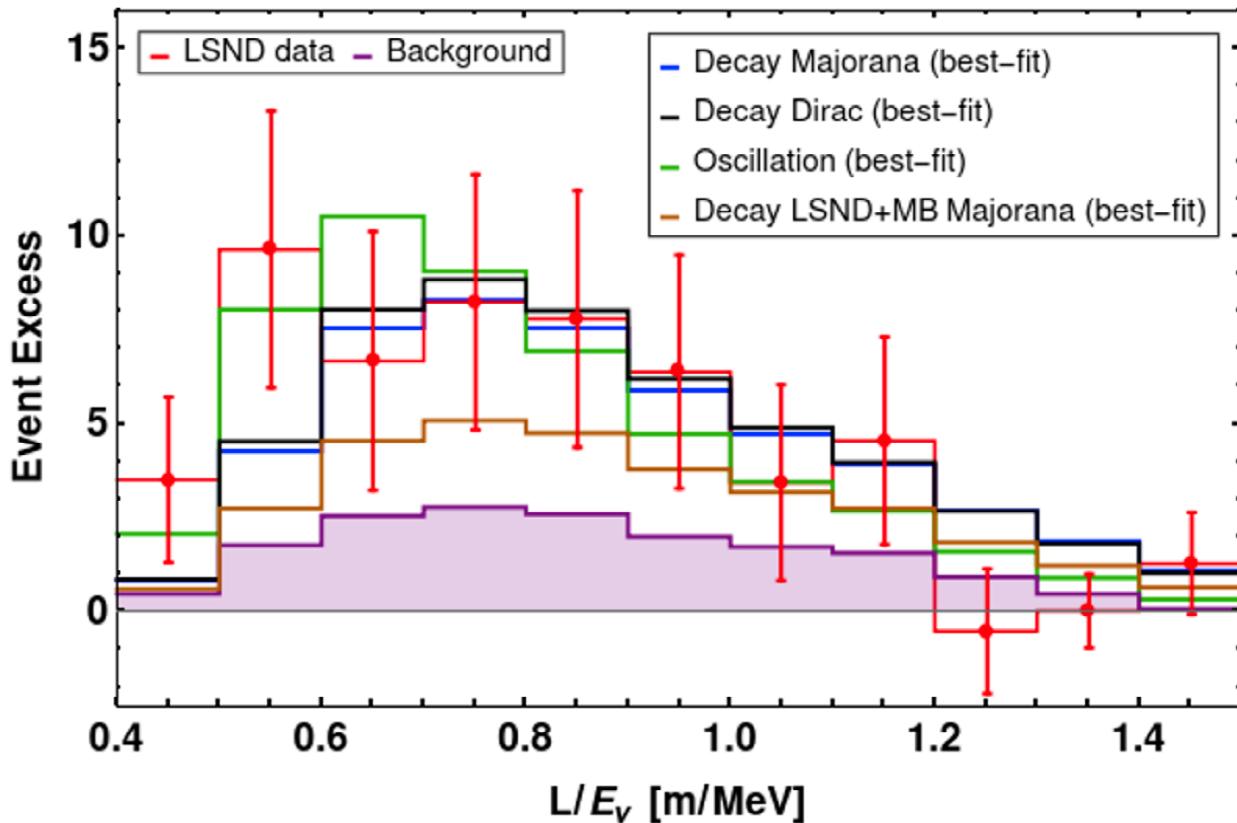
electron neutrino appearance

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

G. Stenico, Suprabh Prakash et al *JHEP* 07 (2020) 141

Better solution than oscillation scenario

Neutrino decay scenario for LSND and MINI-BOONE



Better solution than oscillation scenario

Program to describe LSND and MINI-BOONE
available under request, [G. Stenico](#) (Texas University at Austin)

Standard Model

Eletroweak theory

$$SU(2)_L \times U(1)_Y \quad W^{\mu,a} \quad B^\mu \quad L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad e_R^-$$



$$U(1)_{\text{em}} \quad W_\pm^\mu \quad Z^\mu \quad A^\mu \quad (\nu_\alpha)_L \quad e^- \quad \mu^- \quad \tau^- \quad u, d, c, s, b, t \quad H$$

$$\mathcal{L}_{CKM} = 2\sqrt{2}G_f \left(\bar{u}_j V_{CKM}^{jk} \gamma^\mu P_L d_k \bar{l}_\alpha P_L \gamma_\mu \nu_\beta \right) = 2\sqrt{2}G_f \left(\bar{u}_j V_{CKM}^{jk} \gamma^\mu P_L d_k \bar{l}_\alpha P_L \gamma_\mu \nu_i \right)$$

G_f Fermi constant, P_L left-handed projector, V_{CKM}^{jk} complex matrix source of matrix CP violation .

There is no mixing of leptons.

Conclusions

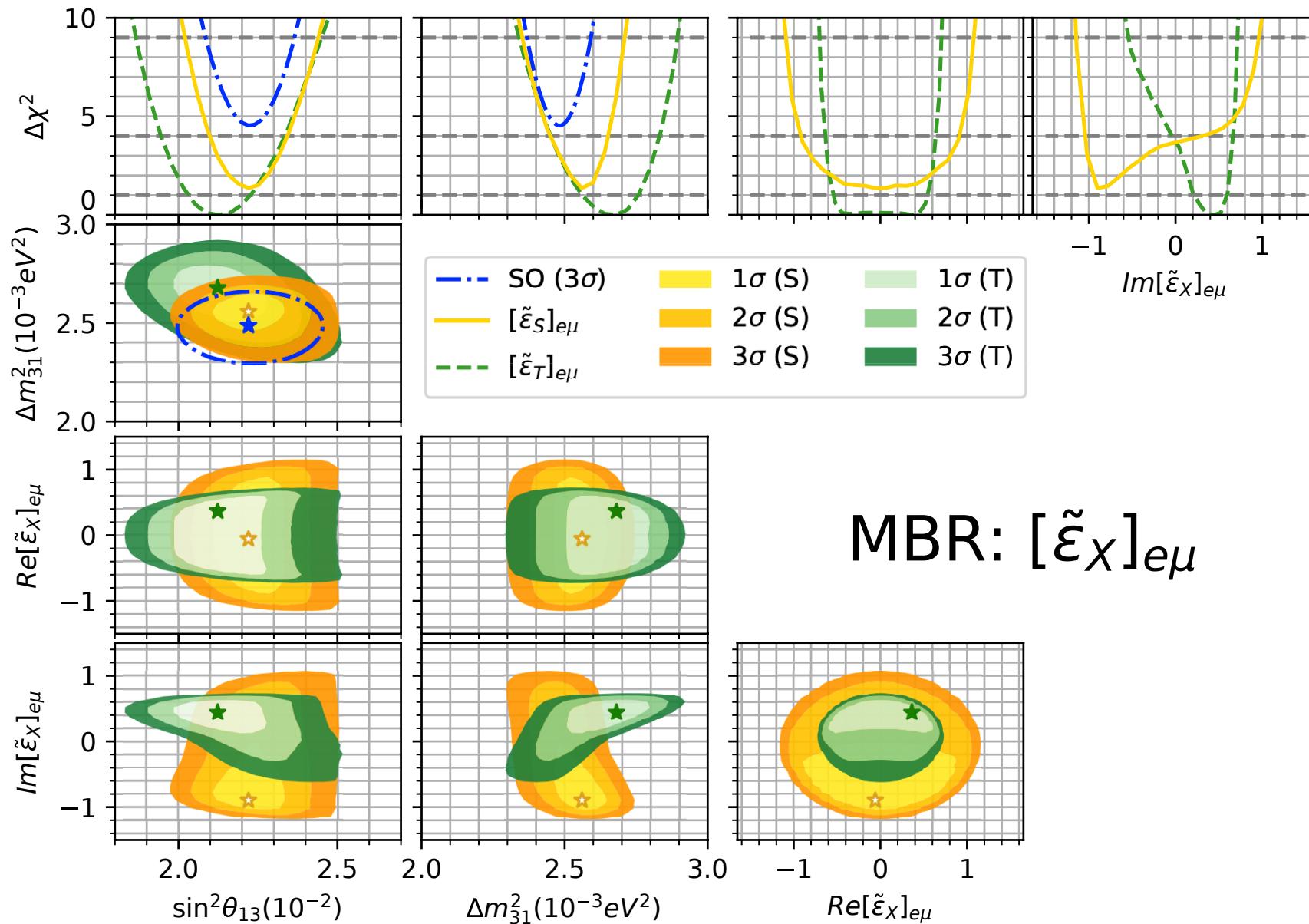
BSM neutrinos is a very active field : QFT description, sterile neutrinos, decaying neutrinos, quantum decoherence (open quantum system), wave-packet description (QFT and QM)

We reached a precision that allow us to revisite assumptions made in our phenomenology: coherence, QFT effects,

No BSM effect found yet, but some hints are appearing,

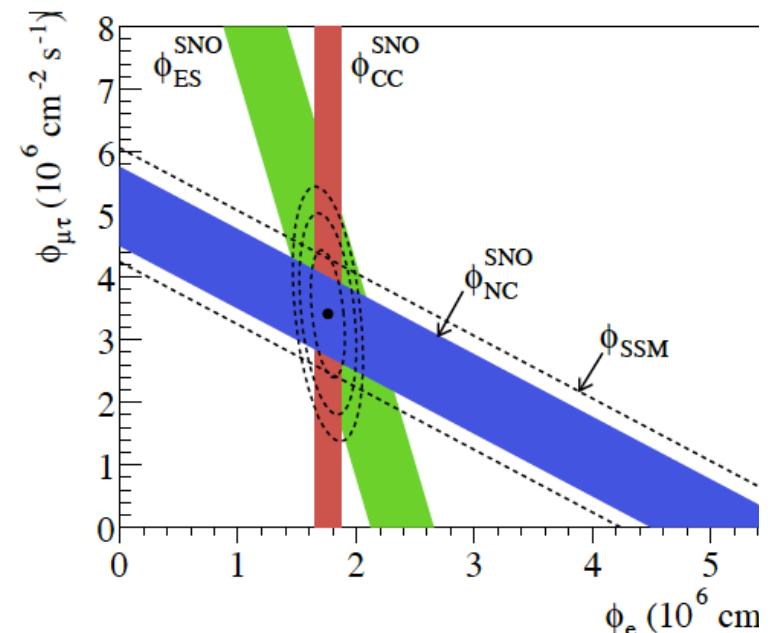
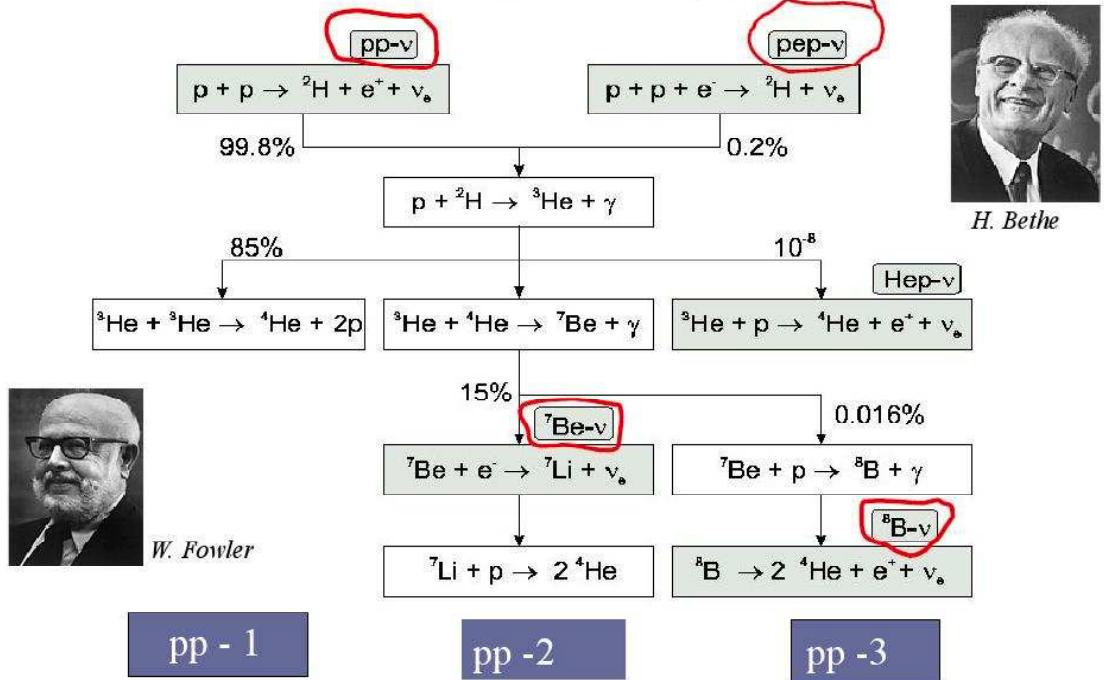
NSI production and detection bounds

NSI production and detection bounds



Experimental Data from solar neutrinos, $\nu_e \rightarrow \nu_e$

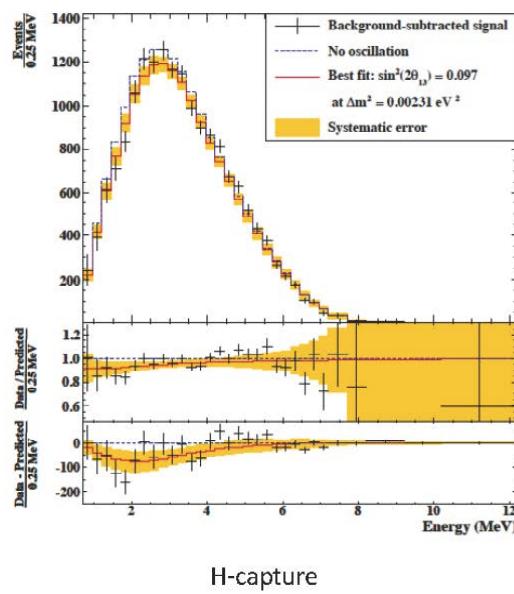
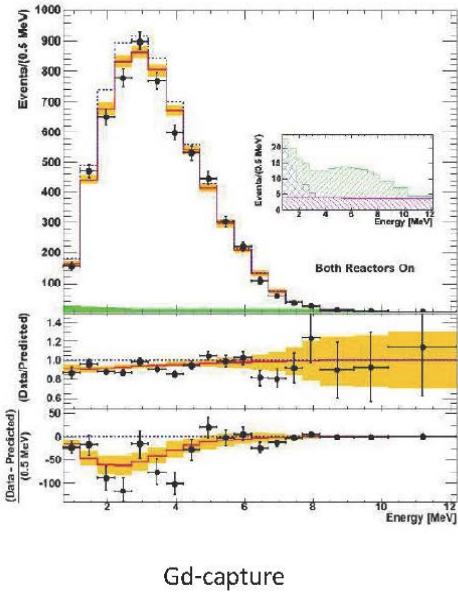
The dominating solar pp - cycle



com as reações

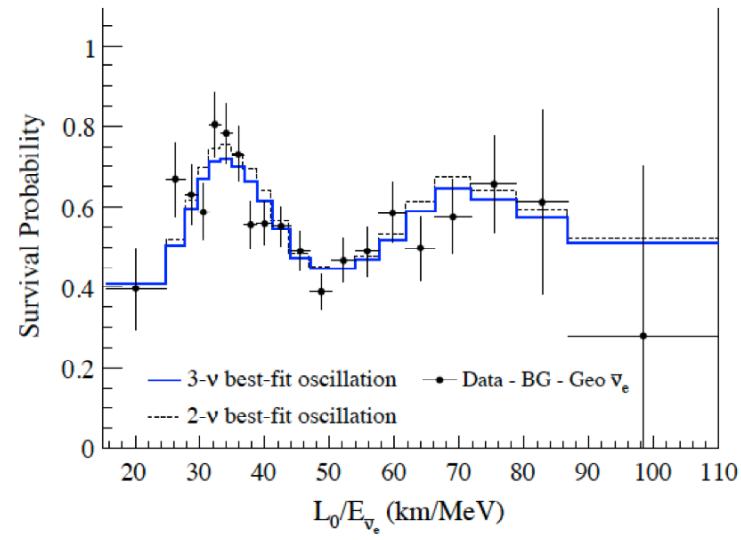
- [CC: $\nu_e + ^2_1\text{H} \rightarrow p + p + e^-$]
- [NC: $\nu + ^2_1\text{H} \rightarrow p + n + \nu$]
- [ES: $\nu + e^- \rightarrow \nu + e^-$]

Experiments Data from reactors anti-neutrinos , $\bar{\nu}_e \rightarrow \bar{\nu}_e$ medium baseline

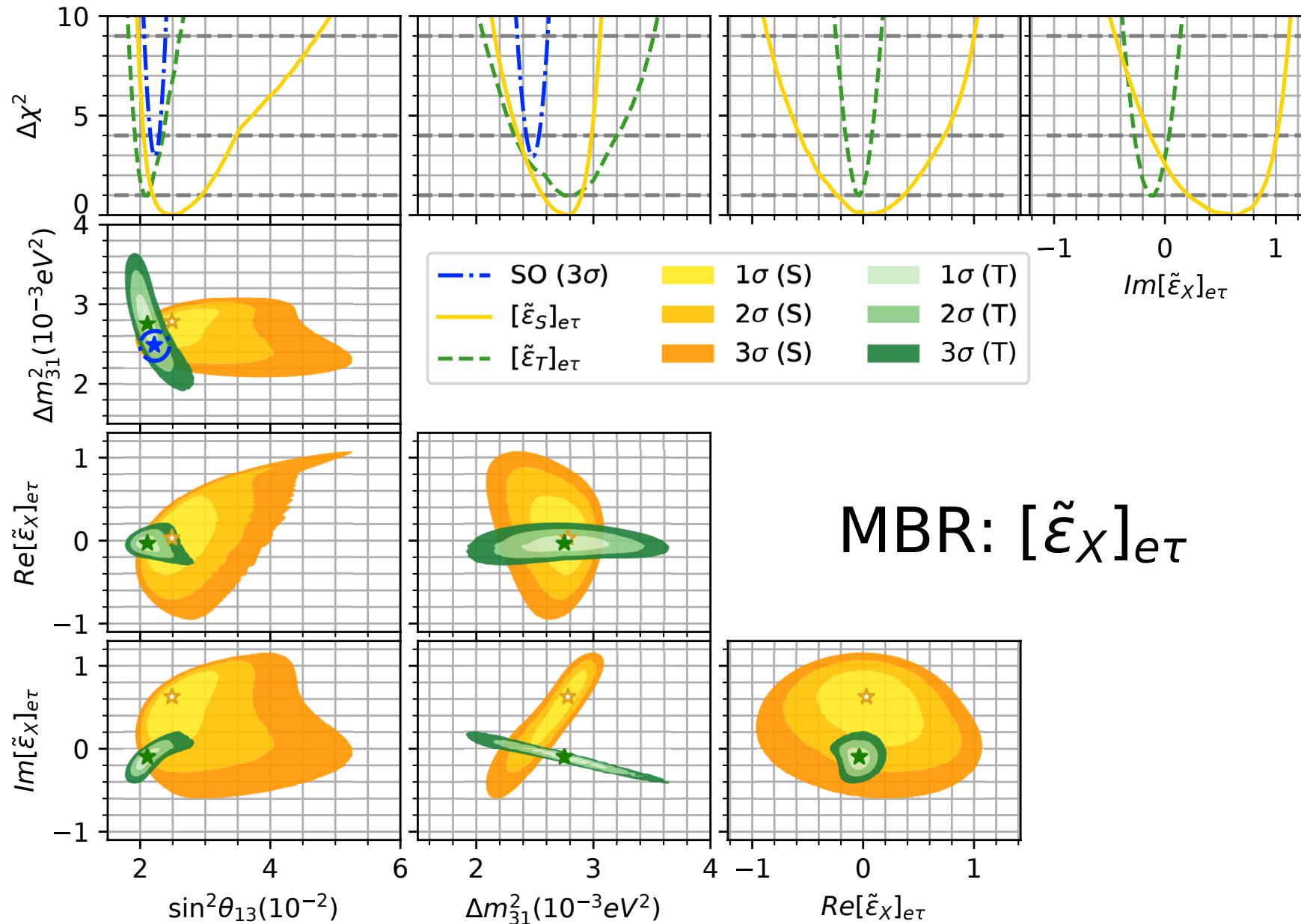


experiments data from Daya Bay, RENO and Double Chooz.

long-baseline



Results



MBR: $[\tilde{\epsilon}_X]_{e\tau}$

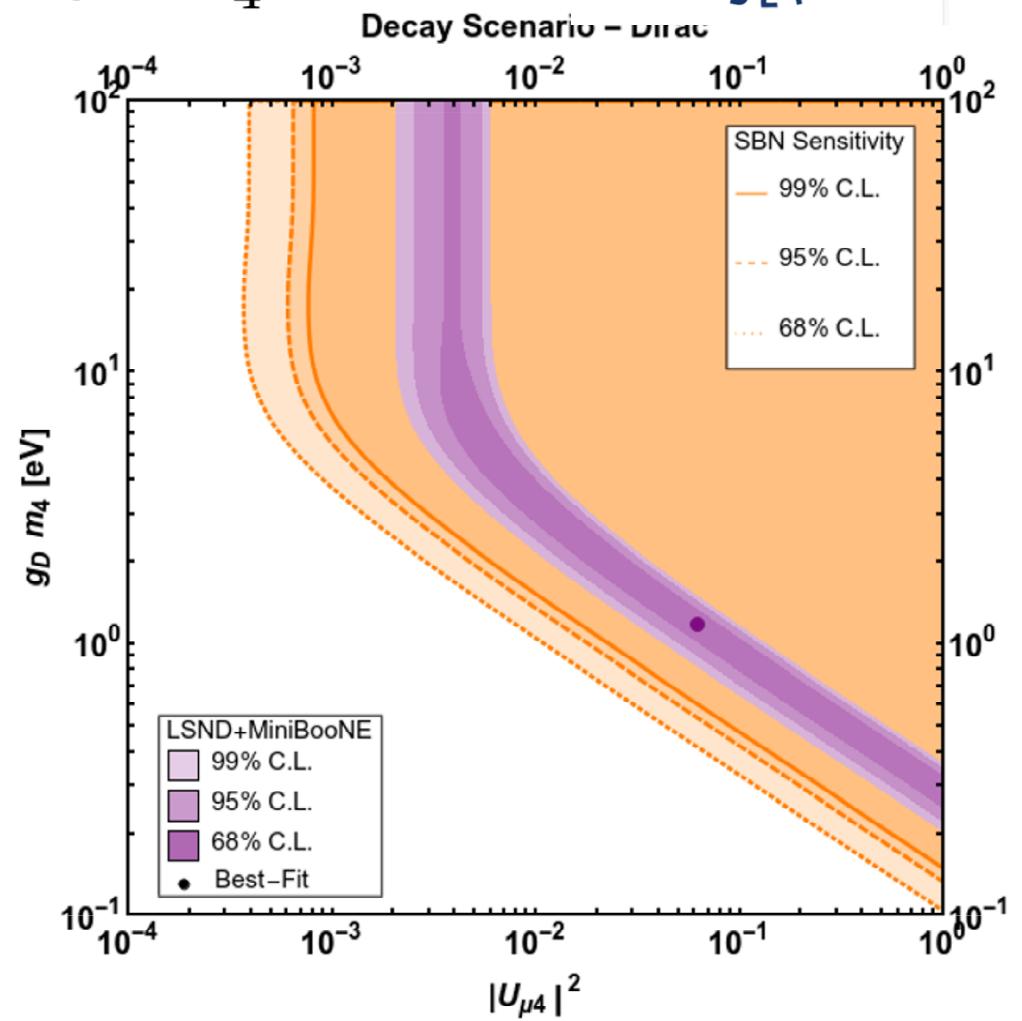
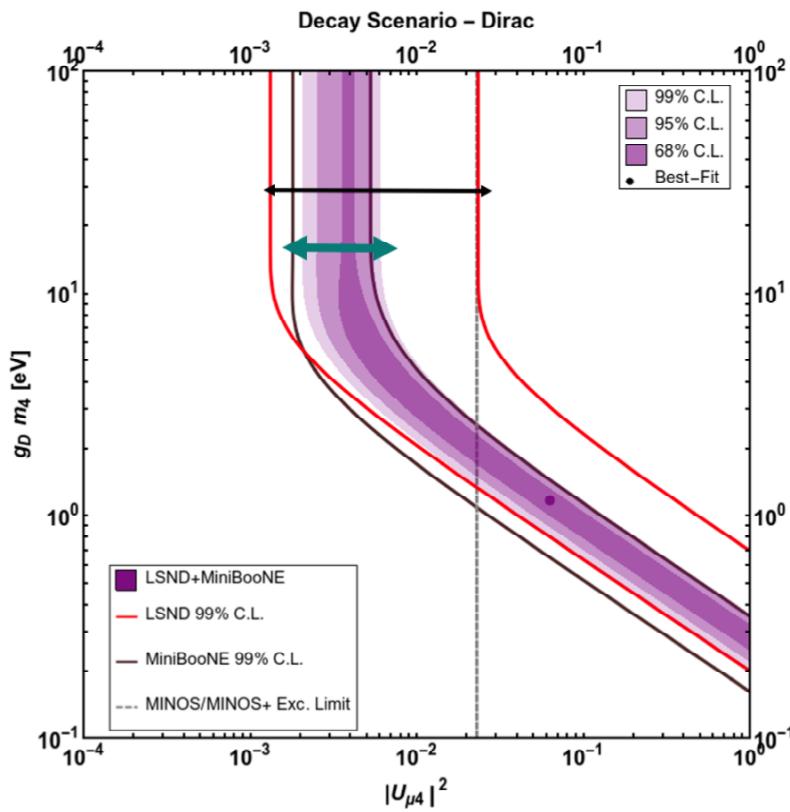
Facts: allowed region enlarged, degenerescência entre $\Im[\tilde{\epsilon}_X]_{e\tau}$ e outros parâmetros.

Neutrino decay scenario for short-baseline neutrinos:

Sterile neutrino

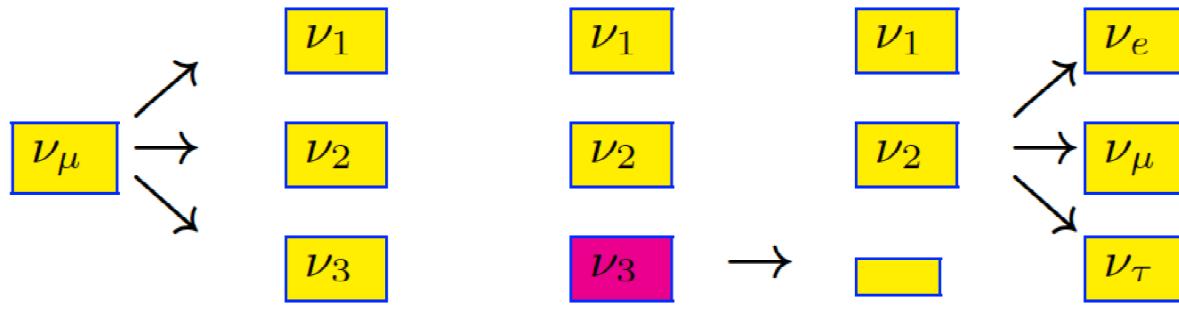
**LSND
MINI-BOONE**

$$\Gamma_{4e} = \left[\frac{(g_M m_4)^2}{16\pi E_4} + \frac{(g_D m_4)^2}{32\pi E_4} \right]$$

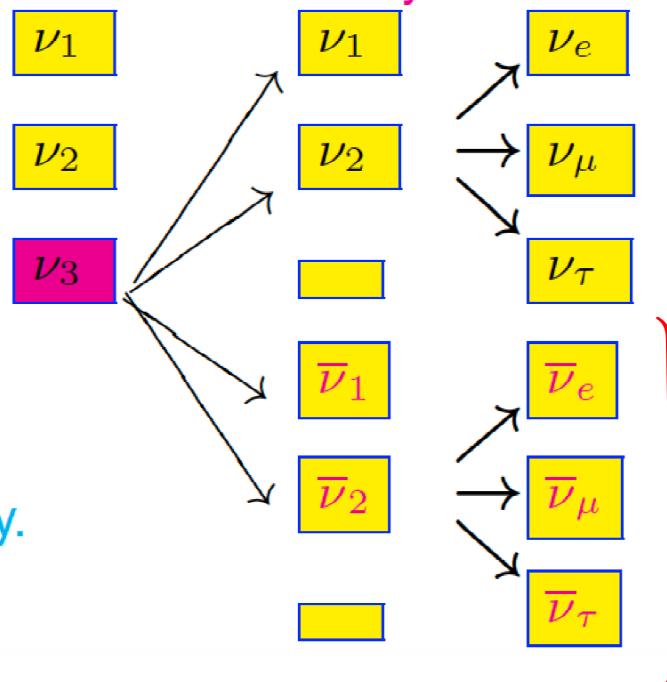


Program to describe SBND
available under request, [G. Stenico](#) (Texas University at Austin)

Oscillation



Invisible decay scenario



Assuming complete decay.

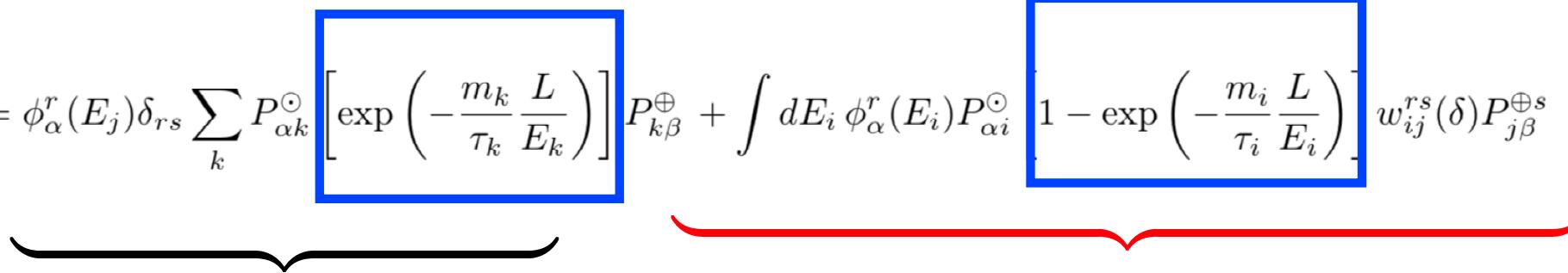
We assume ν_3 is unstable.

anti-neutrinos!!

Neutrino decay scenario for solar neutrinos: solar anti-neutrinos

Neutrino flux including neutrino as unstable particle

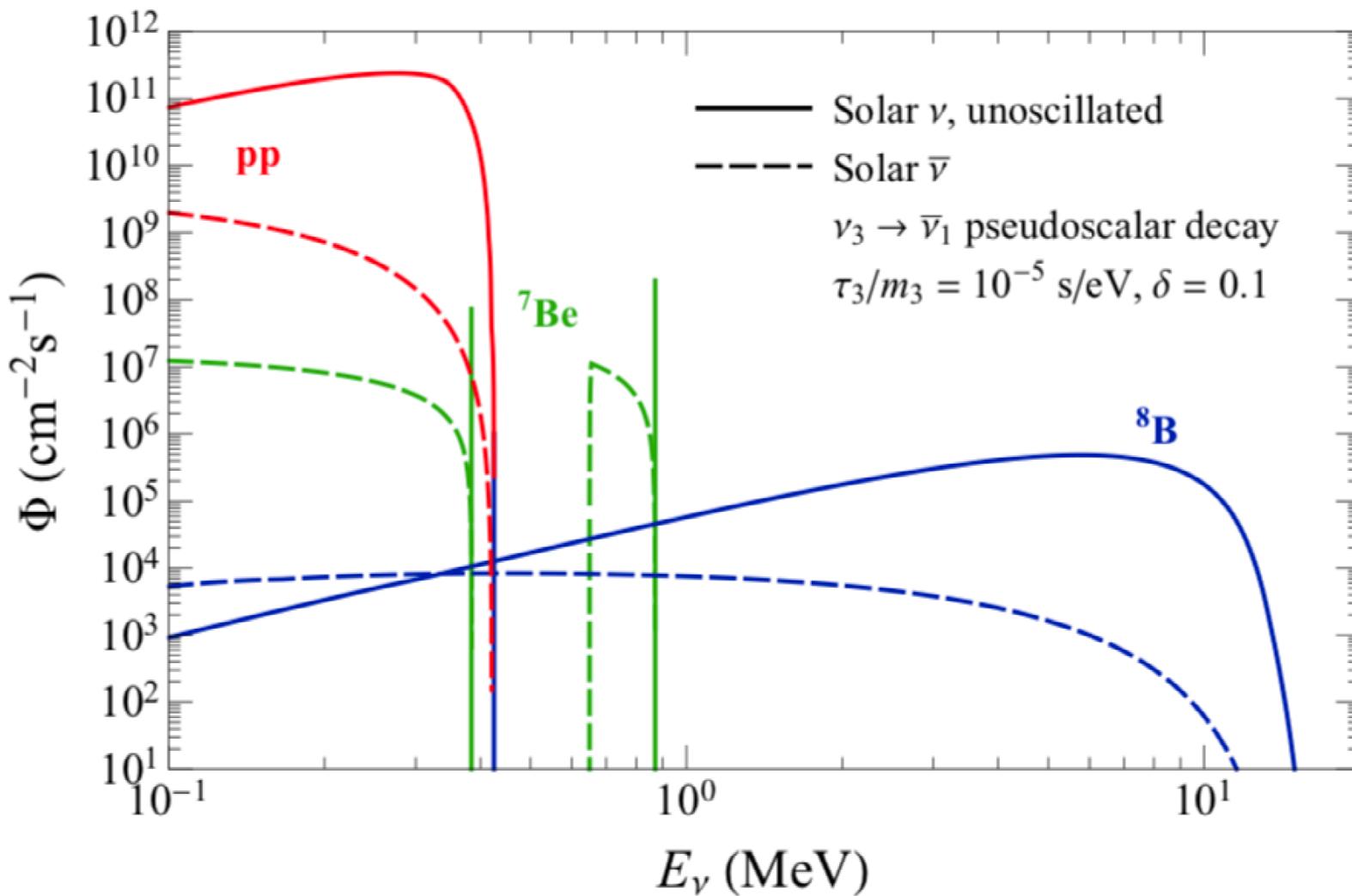
$$\phi_{\beta}^s(E_j) = \phi_{\alpha}^r(E_j) \delta_{rs} \sum_k P_{\alpha k}^{\odot} \left[\exp \left(-\frac{m_k}{\tau_k} \frac{L}{E_k} \right) \right] P_{k\beta}^{\oplus} + \int dE_i \phi_{\alpha}^r(E_i) P_{\alpha i}^{\odot} \left[1 - \exp \left(-\frac{m_i}{\tau_i} \frac{L}{E_i} \right) \right] w_{ij}^{rs}(\delta) P_{j\beta}^{\oplus s}$$



decaying neutrinos (invisible decay)

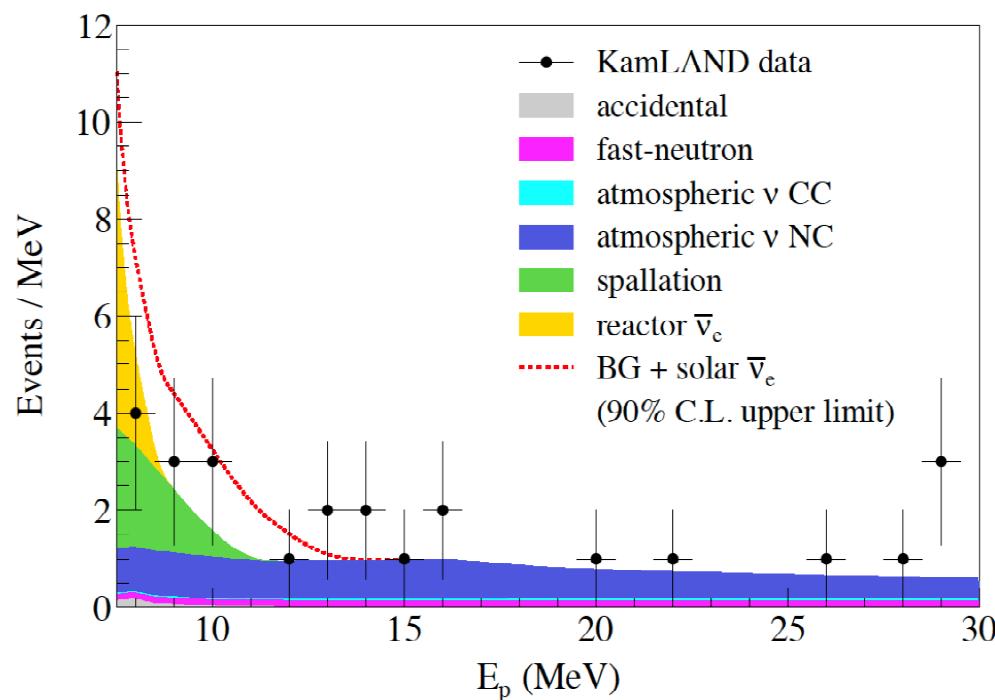
decaying neutrinos (visible decay)

Neutrino flux (solid curves), Anti-neutrino flux (in dashed curves)

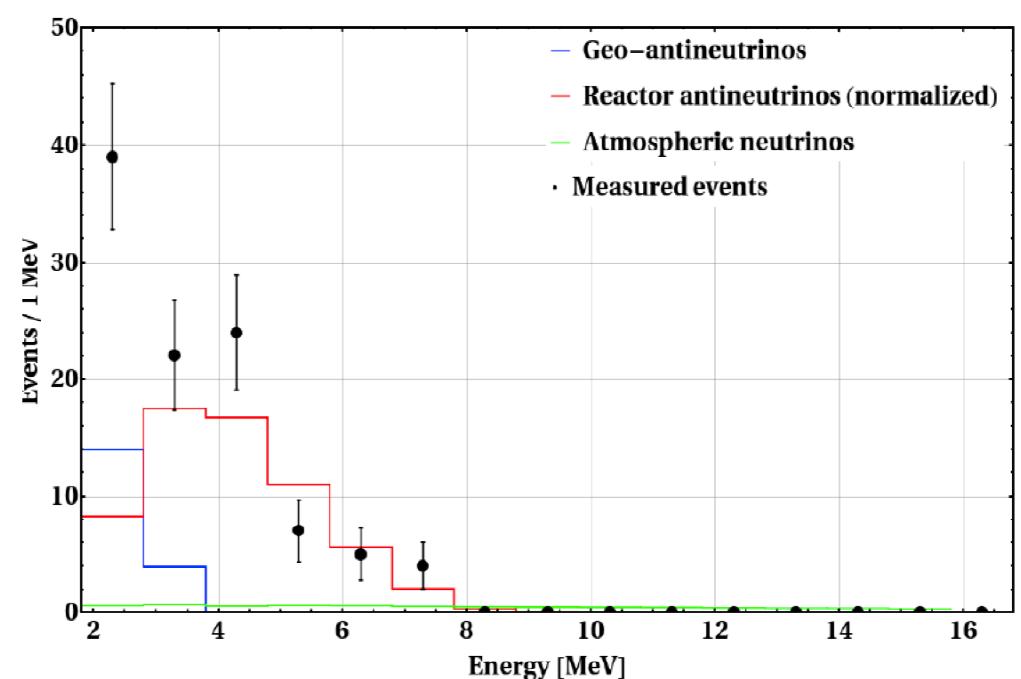


Experimental information for measurements of anti-electron neutrino from the sun

KamLand



Borexino



- [30] A. Gando *et al.* (KamLAND), *Astrophys. J.* **745**, 193 (2012), arXiv:1105.3516 [astro-ph.HE].
- [32] M. Agostini *et al.* (Borexino), *Astropart. Phys.* **125**, 102509 (2021), arXiv:1909.02422 [hep-ex].