# Non Standard Neutrino Interactions

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# Particelle Sfuggenti

# Neutrini... una storia lunga quasi un secolo

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1956 Rivelazione del neutrino elettronico

1959 Ipotesi dell'Oscillazione dei neutrini

1960 Solar neutrino problem

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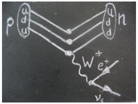

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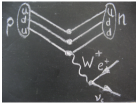

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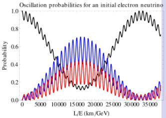

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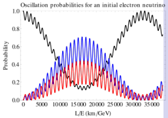

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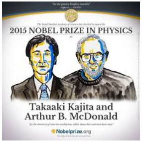


# Modello Standard... e Oltre?

$$\mathcal{L}_{\text{EW}} = \underbrace{-\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}}_{\text{gauge sector}} \underbrace{+(D_\mu\phi)^\dagger(D^\mu\phi) + \mu^2(\phi^\dagger\phi) - \lambda(\phi^\dagger\phi)^2}_{\text{Higgs sector}}$$

$$+ i \underbrace{\sum\nolimits_f (\bar{f}\, \not{D}\, f)}_{\text{matter sector}} \underbrace{- y_e^{ij}\bar{L}_i e_{jR}\phi - y_d^{ij}\bar{Q}_i d_{jR}\phi - y_u^{ij}\bar{Q}_i u_{jR}\tilde{\phi} + \text{h.c.}}_{\text{Yukawa sector}},$$

# Modello Standard... e Oltre?

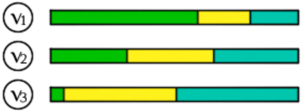
$$\mathcal{L}_\nu = -\frac{g}{\sqrt{2}}\bar{\nu}_L \not{W}^+ e_L - y_e^{ij}\bar{\nu}_L e_{j\,R}\phi + \text{h.c.}$$

NO $\nu_R \leftrightarrow$ NO termine di massa per $\nu$

## Solar Neutrino Problem

Discrepanza fra il numero di $\nu_e$ prodotti dal Sole per bruciamento nucleare e $\nu_e$ rivelati a terra.

**3:1**



# Modello Standard... e Oltre?

# Neutrino Oscillation Probability

## Oscillation Probability in Vacuum

Lagrangiana di corrente carica viene modificata dai termini di massa

$$\mathcal{L}^{\mathbf{CC}} = -2\sqrt{2}G_{\mathbf{F}} \left[ (\bar{d}\gamma_\mu P_L u) \left( \bar{\nu}_i U^{ij}_{\mathbf{PMNS}} \gamma^\mu P_L e_j \right) + (\bar{e}\gamma_\mu P_L \nu) \left( \bar{\nu}_i U^{ij}_{\mathbf{PMNS}} \gamma^\mu P_L e_j \right) \right] + \mathrm{h.c.}$$

$$\mathcal{P}_{\ell\ell'} = |\langle \nu_{\ell'}(0) \,|\, \nu_\ell(t) \rangle|^2 = \delta_{\ell\ell'} - \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) |\langle \nu_{\ell'}(0) \,|\, \nu_\ell(t) \rangle|^2$$

$\rightarrow$ Emerge discrepanza fra autostati di sapore e di massa

## Oscillation Probability in Matter

I termini di corrente neutra modificano l'hamiltoniano

$$\mathcal{L}^{\mathbf{NC}} = -2\sqrt{2}G_{\mathbf{F}} \left[ \left( \bar{\nu}_e \gamma_\mu P_{L\,(R)} \nu_e \right) \left( \bar{e}\gamma^\mu P_L e \right) \right] + \mathrm{h.c.} \rightarrow H^m = H^0 + \begin{pmatrix} \sqrt{2} G_F N_e & 0 \\ 0 & 0 \end{pmatrix}$$

ma solo per $\nu_e$:

$$P_{e\mu} = \sin^2 2\theta_m \sin^2 \left( \frac{\Delta m_m^2 L}{4E} \right)$$

$\rightarrow$ Si modifica l'evoluzione temporale degli autostati di massa

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# Going Beyond the Standard Model: Why?

Esistono sia argomenti *fenomenologici* che *teorici* a mettere in crisi il Modello Standard

- Neutrino masses and mixing
- B anomalies
- ...

- Hierarchy problem
- Flavour puzzle
- ...

**La scala di nuova fisica si pone a $\Lambda > 1$ TeV**

**Non Standard Neutrino Interactions**

Interazioni sottodominanti, **lepton flavor violating**, che modificano osservabili di interesse in tutti gli esperimenti sui neutrini.

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| Produzione diretta di particelle in processi di alta energia | Effetti indiretti di particelle su processi di bassa energia |
|---|---|
| Modelling approach | Effective Field Theory Approach |

Dato che $\Lambda_{\text{NP}} \simeq 1\text{TeV} \gg m_{\text{EW}}$, possiamo usare l'approccio EFT:

$$\text{Assunzioni:} \begin{cases} \text{Invarianza sotto } G_{\text{SM}} \\ \text{Presenza di tutti i d.o.f. dello SM} \\ \text{NO a nuove particelle} \end{cases} \rightarrow \text{Model Independent}$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} C^{(5)} Q^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} Q_i^{(6)} + \dots$$

La base di operatori in d=6 produce deviazioni dallo SM

[1]Grzadkowski et al., 2010

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# EFT approach to Neutrino Physics

Il set completo di operatori che modifica le interazioni dei neutrini $\bar{\nu}$ :

- $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$
- $\nu_\mu + e^- \to \nu_\mu + e^-$
- $P_{\mu\mu}$, $P_{\mu\tau}$
- $\pi^- \to \mu^- + \bar{\nu}_\mu$
- $\nu_\alpha N \to e_\alpha^- N$
- ...

**Purely Leptonic Operators**

$$[Q_{\ell\ell}]_{prst} \equiv (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{\ell}_s \gamma^\mu \ell_t)$$

$$[Q_{\ell e}]_{prst} \equiv (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{e}_s \gamma^\mu e_t)$$

**Semi-Leptonic Operators**

$$[Q^{(1)}_{\ell q}]_{prst} \equiv (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$$

$$[Q^{(3)}_{\ell q}]_{prst} \equiv (\bar{\ell}_p \gamma_\mu \tau^I \ell_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$

$$[Q_{\ell edq}]_{prst} \equiv (\bar{\ell}^j_p e_r)(\bar{d}_s q^j_t)$$

$$[Q^{(1)}_{\ell equ}]_{prst} \equiv (\bar{\ell}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$$

$$[Q^{(3)}_{\ell equ}]_{prst} \equiv (\bar{\ell}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$$

$\rightarrow$ Usando le **Equazioni del Gruppo di Rinormalizzazione** si ottiene la $\mathcal{L}_{low}$ per studiare effetti su processi di bassa energia (**Operator Mixing**)

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$$[Q_{\ell q}^{(1)}]_{prst} \equiv (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$$
$$[Q_{\ell q}^{(3)}]_{prst} \equiv (\bar{\ell}_p \gamma_\mu \tau^I \ell_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$
$$[Q_{\ell edq}]_{prst} \equiv (\bar{\ell}_p^j e_r)(\bar{d}_s q_t^j)$$
$$[Q_{\ell equ}^{(1)}]_{prst} \equiv (\bar{\ell}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$$
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# Modified Oscillation Probability

## Source/Detector NSIs

Le NSIs di corrente carica modificano gli stati di sapore alla sorgente e al detector:

$$\mathcal{L}^{\mathbf{CC}}_{\mathbf{NSI}} = -2\sqrt{2}G_{\mathbf{F}}\,(\delta_{\alpha\beta} + \epsilon_{\alpha\beta})\,\left[(\bar{\ell}\gamma^{\mu}P_L\nu)\,(\bar{\nu}\gamma_{\mu}P_L e) + (\bar{\ell}\gamma^{\mu}P_L\nu)\,(\bar{u}\gamma_{\mu}P_L d)\right] + \text{h.c.}$$

$$|\nu^{p=s,d}_{\alpha}\rangle \simeq \sum_{\beta}(\delta_{\alpha\beta} + \epsilon^{p}_{\alpha\beta})\,|\nu_{\beta}\rangle \quad \rightarrow \quad \langle\nu^{s}_{\alpha}|\nu^{d}_{\beta}\rangle = \epsilon_{\alpha\beta} \simeq \begin{cases} 1 & \alpha = \beta \\ \epsilon^{s}_{\alpha\beta} + \epsilon^{d}_{\alpha\beta} & \alpha \neq \beta \end{cases}$$

Gli autostati di flavour non sono ortogonali!

## Matter NSIs

Le NSIs di corrente neutra modificano l'hamiltoniano di materia:

$$\mathcal{L}^{\mathbf{NC}}_{\mathbf{NSI}} = -2\sqrt{2}G_{\mathbf{F}}\sum_{f}\left[\epsilon^{f\,L}_{\alpha\beta}\,(\bar{\nu}_{\alpha}\gamma_{\mu}P_L\nu_{\beta})\,(\bar{f}\gamma^{\mu}P_L f) + \epsilon^{f\,R}_{\alpha\beta}\,(\bar{\nu}_{\alpha}\gamma_{\mu}P_L\nu_{\beta})\,(\bar{f}\gamma^{\mu}P_R f)\right] + \text{h.c.}$$

$$H^{\mathbf{NSI}}_{m} = H_m + \begin{pmatrix} V_{\mu\mu} & V_{\mu\tau} \\ V^{*}_{\mu\tau} & V_{\tau\tau} \end{pmatrix} \text{ where } \begin{cases} V_{\alpha\beta} = \sqrt{2}G_F N_d(x)\,\epsilon^{m}_{\alpha\beta} \\ \epsilon^{m}_{\alpha\beta} = \sum_f \frac{N_f(x)}{N_d(x)}\,(\epsilon^{L}_{\alpha\beta} + \epsilon^{R}_{\alpha\beta}) \end{cases}$$

L'evoluzione nel mezzo si modifica anche per $\nu_{\mu}$ e $\nu_{\tau}$!

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$$|\nu_{\alpha}^{p=s,d}\rangle \simeq \sum_{\beta}(\delta_{\alpha\beta} + \epsilon_{\alpha\beta}^{p})\,|\nu_{\beta}\rangle \quad \rightarrow \quad \langle\nu_{\alpha}^{s}|\nu_{\beta}^{d}\rangle = \epsilon_{\alpha\beta} \simeq \begin{cases} 1 & \alpha = \beta \\ \epsilon_{\alpha\beta}^{s} + \epsilon_{\alpha\beta}^{d} & \alpha \neq \beta \end{cases}$$

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$$H_m^{\mathbf{NSI}} = H_m + \begin{pmatrix} V_{\mu\mu} & V_{\mu\tau} \\ V_{\mu\tau}^{*} & V_{\tau\tau} \end{pmatrix} \text{ where } \begin{cases} V_{\alpha\beta} = \sqrt{2}G_F N_d(x)\,\epsilon_{\alpha\beta}^{m} \\ \epsilon_{\alpha\beta}^{m} = \sum_f \frac{N_f(x)}{N_d(x)}\,(\epsilon_{\alpha\beta}^{L} + \epsilon_{\alpha\beta}^{R}) \end{cases}$$

L'evoluzione nel mezzo si modifica anche per $\nu_{\mu}$ e $\nu_{\tau}$!

# Modified Oscillation Probability

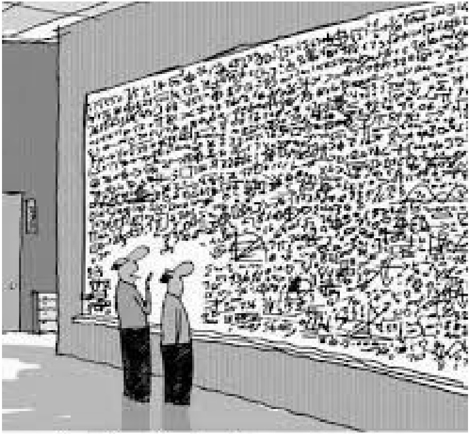
La Survival Probability si modifica, rispetto al caso standard, come segue:

$$
\begin{aligned}
P_{\mu\mu}(L) = 1 &- \sin^2(2\theta_0)\sin^2 x \\
&- \frac{1}{2}\sin^2(2\theta_0)\sin(2x)[(\epsilon^m_{\mu\mu} - \epsilon^m_{\tau\tau})\cos(2\theta_0) - 2\Re(\epsilon^m_{\mu\tau})\sin(2\theta_0)]V_d L \\
&+ \frac{1}{2}\sin(4\theta_0)\frac{\sin^2 x}{x}[2\Re(\epsilon^m_{\mu\tau})\cos(2\theta_0) + (\epsilon^m_{\mu\mu} - \epsilon^m_{\tau\tau})\sin(2\theta_0)]V_d L \\
&- \sin(4\theta_0)\sin^2 x\Re(\epsilon^s_{\mu\tau} + \epsilon^d_{\mu\tau}) - \sin(2\theta_0)\sin(2x)\Im(\epsilon^s_{\mu\tau} - \epsilon^d_{\mu\tau}),
\end{aligned}
$$

where $x = \frac{\Delta m^2 L}{4E}$

$$P_{\mu\mu} + P_{\mu\tau} \neq 1 \rightarrow \text{Si perde l'unitarieta'!}$$

# Modified Oscillation Probability

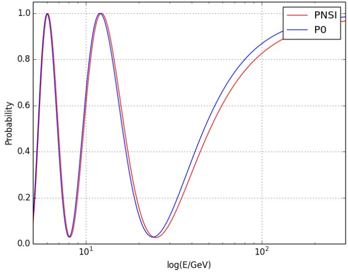


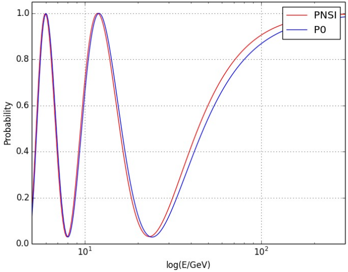
And that, in simple terms, is how neutrino non standard interactions work...,

# Modified Oscillation Probability

Confrontando i set-up trovati nel mio studio e in letteratura, valutiamo la discrepanza fra il caso standard e non-standard

Neutrino (left) and Antineutrino (right) $P_{\mu\mu}$, with $\epsilon^m_{\mu\tau} = 10^{-3}$ at IC



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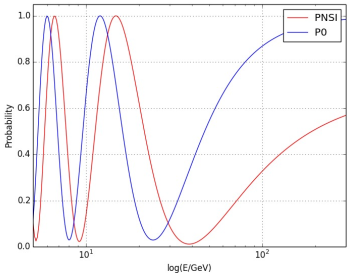
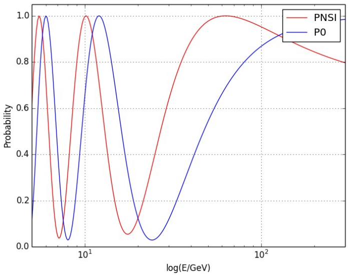
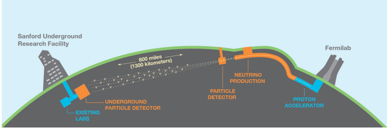
Neutrino (left) and Antineutrino (right) $P_{\mu\mu}$, with $\epsilon^m_{\mu\tau} = 10^{-2}$ at IC



# The Deep Underground Neutrino Experiment

**DUNE**: esperimento di tipo long baseline composto da due detector, Near e Far. Partira' nel 2027 a Fermilab.




Il numero di eventi attesi si calcola usando [DUNE Collaboration, 2016]

$$N = \text{time} \times \#\text{targets} \times \text{efficiency} \times \int_{E_i}^{E_f} \mathrm{d}E_\nu \, \frac{\mathrm{d}\phi(E_\nu)}{\mathrm{d}E_\nu} \, \sigma(E_\nu)$$

Nel range di energia $E_\nu = [0.25, 8.25]$ GeV:

- 3 anni: tempo dell'operazione per fasci di $\nu + \bar{\nu}$
- $1.1 \times 10^{21}$ protoni: numero di target
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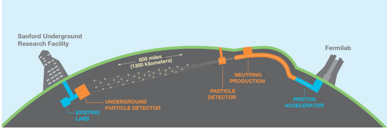


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# Prospettive di DUNE

## Modified oscillation probability @DUNE

Near Detector + Far Detector

=

misure di precisione & misure di oscillazione

- Migliore analisi di **modifiche alla** $P_{\mu\tau}$ e sul problema della **degenerazione dei parametri** [4]Flores et al., 2018
- Studi sull'effetto del Profilo di Densita' di Massa sulle NSIs [5]Chatterjee et al., 2018
- Possibile rivelazione del neutrino sterile

Attacco combinato a tutti problemi della fisica dei neutrini

# Prospettive di DUNE

# Come si puo' migliorare?

## Allegerire le assunzioni

Le assunzioni fatte erano:

$$\begin{cases} \mathcal{L}_{\text{eff}} \text{ invariante sotto } G_{\text{SM}} \\ \mathcal{L}_{\text{eff}} \text{ deve includere tutti SM d.o.f.} \\ \text{Nessuna nuova particella sotto scala } \Lambda \end{cases}$$

→ Si generano ora nuovi operatori i.e. diverse NSIs

## Approccio Model Dependent

Si possono implementare i risultati nei modelli di Nuova Fisica, perdendo in generalita' ma risultando piu' predittivi [7]Farzan et al. 2017:

◇ Neutral Scalar Boson ◇ Leptoquark ◇ $Z'$ light boson

→ Possibili studi comparativi fra NSIs e altre anomalie dello SM [8]

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# Science is no religion


https://www.hep.physik.uni-siegen.de/grupen/

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[3] A. Falkowski et al., "Future DUNE constraints on EFT" *arXiv:1802.08296* (2018)

[4] L. J. Flores et al., "Exploring NSI degeneracies in long-baseline experiments" *arXiv:1806.07951v2* (2018)

[5] A. Chatterjee et al., "Impact of Matter Density Profile Shape on NSI at DUNE", *arXiv:1809.09313v2* (2018)

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[7] Y. Farzan et al., "Neutrino oscillation and Non-Standard Interactions", *Front. in Phys.* (2018)

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# BACK-UP SLIDES

# EFT Approach : An important assumption

NP couples only to the third generations at $\Lambda$ scale

Theoretical Motivation: This assumption holds in many BSM flavor models (e.g. U(1) and U(2) flavor models)

Phenomenological Motivation: In order to simultaneously explain 20% NP in CC ($R_D$) and NC ($R_K$) in $B$ physics [Feruglio et al., 2016]

- $\tau/\ell$ LFUV in CC $b \to c$ transitions: tree-level in the SM:

$$R_D^{\tau,\ell} = \frac{\mathcal{B}(\bar{B} \to D\tau\bar{\nu})_{\text{exp}}/\mathcal{B}(\bar{B} \to D\tau\bar{\nu})_{\text{SM}}}{\mathcal{B}(\bar{B} \to D\ell\bar{\nu})_{\text{exp}}/\mathcal{B}(\bar{B} \to D\ell\bar{\nu})_{\text{SM}}} = 1.34 \pm 0.17$$

- $\mu/e$ LFUV in NC $b \to s$ transitions: one-loop in the SM:

$$R_K^{\mu,e} = \frac{\mathcal{B}(B \to K\mu\bar{\mu})_{\text{exp}}}{\mathcal{B}(B \to Ke\bar{e})_{\text{exp}}} = 0.745 \pm 0.036$$

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# Description of $\Lambda$ scale operators in $\mathcal{L}_{\text{eff}}$

In literature, $\mathcal{L}_{\text{NSI}}$ contains only $Q_{\ell\ell}$ and $Q_{\ell e}$ $\rightarrow$ We considered the complete basis of 4-fermions operators inducing (V-A) lepton currents.

There is an asymmetry between leptonic and semi-leptonic operators:

- $Q_{\ell\ell}$ contains both neutral and charged currents
- Scalar leptonic operator derives from $Q_{\ell e}$ by Fierz transformation

$$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{e}_s \gamma^\mu e_t) = 2(\bar{\ell}_p\, e_t)(\bar{e}_s\, \ell_r)\,,$$

- Tensor leptonic operator is ruled out because of $U(1)_{\text{Y}}$

$$(\bar{\ell}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{\ell}^k \sigma^{\mu\nu} e) \qquad Y_{\text{tot}} = 1\,.$$

$\rightarrow$ Changing particle content, produces different operators $\leftarrow$

# Building the low energy EFT Lagrangian: tools

We want a Lagrangian at the scale of $\nu$ physics: $\sim 2$ GeV

- Renormalization Group Equations allow to evolve the Wilson coefficients:

$$\dot{C}_i \equiv \mu \frac{\mathrm{d}}{\mathrm{d}\mu} C_i(\mu) = \gamma_{ij} C_j(\mu) \quad \text{Operator Mixing}$$

- When crossing a mass scale, running from $\Lambda$ to 2 GeV, we have to integrate out the corresponding d.o.f. and match the high-energy effective theory into the low-energy one.

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# Building the low energy EFT Lagrangian: effect

Effect on the Lagrangian produced by running and matching:

$\Lambda$

$$\mathcal{L}^{0}_{\text{eff}}(\Lambda) = \frac{1}{\Lambda^2}\Big(C_\ell[Q_{\ell\ell}]_{3333} + C_1[Q^{(1)}_{\ell q}]_{3333} + C_3[Q^{(3)}_{\ell q}]_{3333} + C_e[Q_{\ell e}]_{3333} + C_s[Q_{\ell edq}]_{3333} + C_{s1}[Q^{(1)}_{\ell equ}]_{3333} + C_{s3}[Q^{(3)}_{\ell equ}]_{3333}\Big).$$

$SU(2)_L$ RGE and integration of $W$, $Z$, $H$ and $t$ + matching

$m_{\text{EW}}$

$$\mathcal{L}(m_{\text{EW}}) = \mathcal{L}^{0}_{\text{eff}}(\Lambda) + \frac{1}{16\pi^2\Lambda^2}\ln\frac{\Lambda}{m_{\text{EW}}}\sum_i \xi_i Q_i(\Lambda).$$

QED RGE and integration of $b$ + matching

2 GeV

$$\mathcal{L}_{\text{eff}}(2\,\text{GeV}) = \mathcal{L}(m_{\text{EW}}) + \frac{1}{16\pi^2\Lambda^2}\ln\frac{m_{\text{EW}}}{\mu}\sum_i \delta\xi_i Q_i.$$

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Renormalization Group Equations (RGE) are a powerful tool

- Allows the cancellation of the dimensional regularization scale $\mu$
- In order to recollect the theory at different scales

The RGE for the Wilson coefficients reads

$$\dot{C}_i \equiv \mu \frac{d}{d\mu} C_i(\mu) = \gamma_{ij} C_j(\mu)$$

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Operator Mixing

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# Operator Mixing

Operator mixing in the RGE produces new operators

- $\psi^2 X \phi$ **Operators**: Their evolution depends on $Q^{(3)}_{\ell equ}$ and they produce magnetic moment-type couplings
- $\psi^2 \phi^3$ **Operators**: Their evolution depends on $Q^{(1)}_{\ell equ}$ and they modify the Yukawa coupling of leptons
- $\psi^2 \phi^2 D$ **Operators**: Their evolution depends on $Q_{\ell\ell}$, $Q_{\ell e}$, $Q^{(1,3)}_{\ell q}$ and they modify gauge coupling to W and Z

$\rightarrow$ A source of LFV @tree level in C current is introduced

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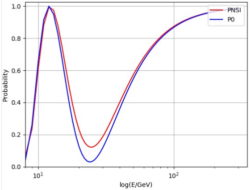
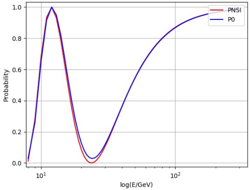
# NSIs at IceCube

Neutrino (L) and Antineutrino (R) $P_{\mu\mu}$ parametrized with $\epsilon^m_{\mu\mu} - \epsilon^m_{\tau\tau} = 10^{-2}$

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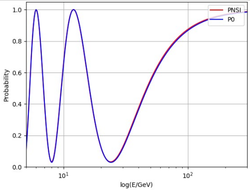


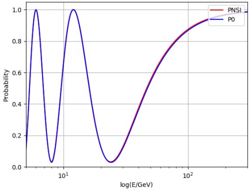

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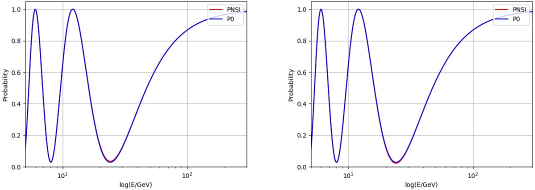


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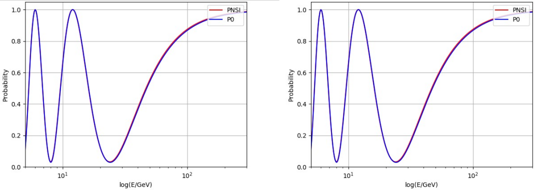

# NSIs at DUNE: $\nu$ scattering off electrons

The predicted number of events is $N_{\nu e} = 1.69 \times 10^6$

We considered as observable the following ratio

$$R_e = 2\frac{x_i\sigma^{\nu}_{\mathbf{NSI}} + \bar{x}_i\sigma^{\bar{\nu}}_{\mathbf{NSI}}}{x_i\sigma^{\nu}_{\mathbf{SM}} + \bar{x}_i\sigma^{\bar{\nu}}_{\mathbf{SM}}} = 1+\delta R_e(\epsilon^{2211}_L, \epsilon^{2211}_R)$$

$\epsilon^{\mathbf{2211}}_{L\,(R)}$ **couples to** $(\bar{\nu}_\mu\gamma^\mu P_L\nu_\mu)(\bar{e}\gamma_\mu P_{L\,(R)}e)$

Given $N_{\nu e}$, the constraint on $\delta R_e$ can be translated in terms of $\Lambda$:

$$-8.0\times 10^{-4} < -12\times 10^{-4}\left(\frac{1\,\text{TeV}}{\Lambda}\right)^2 \times$$
$$\times\left[(C_1+3C_3)+(0.13)(C_e-C_{\ell\ell})\right] < 8.0\times 10^{-4}$$

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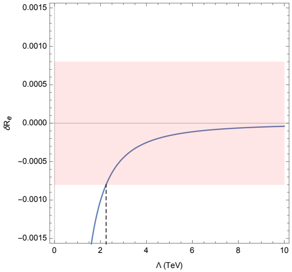

# NSIs at DUNE: $\nu$ scattering off nuclei



The predicted number of events is $N_{\nu N} = 4.25 \times 10^8$

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$$R_N = \frac{x\sigma^{NC} + \bar{x}\bar{\sigma}^{NC}}{x\sigma^{CC} + \bar{x}\bar{\sigma}^{CC}} = R_N^{\mathbf{SM}} \left(1 + \delta R_N \left(\delta V_{ud}, \epsilon_{CC}, \epsilon^{\nu}_{L(R)}\right)\right)$$

$\delta V_{ud}$ is the correction given by the $\pi$ decay

$\epsilon_{CC}$ couples to $(\bar{\nu}_\alpha \gamma_\mu P_L \ell_\alpha)(\bar{d}\gamma^\mu P_L u)$

$\epsilon^{\nu}_{L(R)}$ couples to $\sum_q (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{q}\gamma^\mu P_{L(R)} q)$

Given $N_{\nu N}$, the constraint on $\delta R_N$ can be translated in terms of $\Lambda$:

$$-9.6 \times 10^{-5} < -14.5 \times 10^{-4} \left(\frac{1\text{TeV}}{\Lambda}\right)^2 \times \times \left[(C_1 + C_3) + (0.01)(C_e + 2C_{\ell\ell})\right] < +9.6 \times 10^{-5}$$

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