Leptonic neutral-current probes in a short-distance DUNE-like setup

Based on 2402.00114 by SCCh, O. G. Miranda and J.W.F. Valle
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Salvador Centelles Chuliá

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MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

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   - Neutrino masses
   - Observational footprints
2. Non-unitarity formalism
3. NU at DUNE ND
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5. Backup

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Neutrino masses

- Neutrino oscillations entering the precision (<1%) era. Simplest explanation for the L/E profile are massive neutrinos.
- For now, the neutrino mass mechanism is a mistery:
    - Tree level, radiative, extra dimensional origin...?
    - The scale(s) of relevant NP
    - Neutrino nature: Dirac or Majorana
    - Lepton number conservation/violation
- **Neutrino mixing with new states could be the window to NP**

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Observational footprints

- Let us assume that neutrinos mix with some new **heavy gauge singlet** states. This mixing can be naturally % level in low scale seesaw frameworks!
- Observational footprints are mainly
  - Collider direct production of m_ν mediators
  - cLFV (paradigmatically but not only $\mu^- \to e^- \gamma$)
  - Non-standard effects in neutrino propagation
- None of these observations would be a statement on neutrino nature! See e.g. [1][2]

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[1] J. Bernabeu et al. "Lepton Flavor Nonconservation at High-Energies in a Superstring Inspired Standard Model". In: *Phys. Lett. B* 187 (1987), pp. 303–308. DOI: 10.1016/0370-2693(87)91100-2.

[2] Salvador Centelles Chuliá, Rahul Srivastava, and Avelino Vicente. "The inverse seesaw family: Dirac and Majorana". In: *JHEP* 03 (2021), p. 248. DOI: 10.1007/JHEP03(2021)248. arXiv: 2011.06609 [hep-ph].

Basic formulation

- 3 active neutrinos mix with m new (heavy) states
- The **unitary** mixing matrix is $(3+m) \times (3+m)$
- The upper 3 rows form a rectangular matrix K which characterizes the $\ell_\alpha - W - \nu_i$ interactions. See Concha's talk!

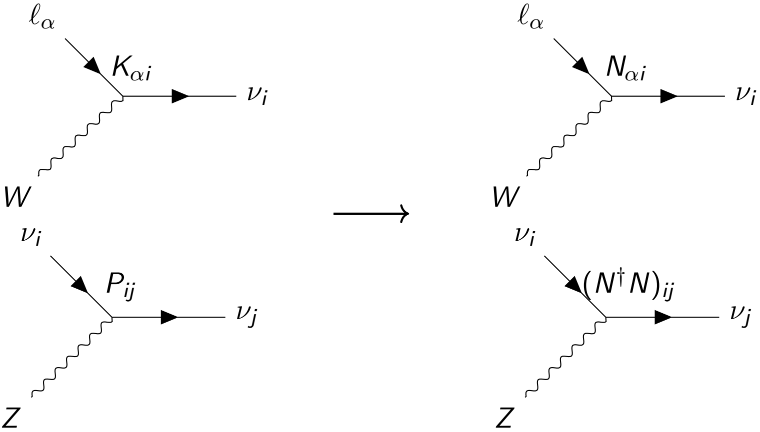
$$K = \begin{pmatrix} N & S \end{pmatrix}$$

$$K\, K^\dagger = 1_{3\times 3}$$

- The Z boson interaction is characterized by the $(3+m) \times (3+m)$ matrix $P = K^\dagger\, K \neq 1$

Basic formulation

- If $E \ll M$ only the first 3×3 block of K and P can play a role, N and $N^\dagger N$, respectively.



Basic formulation

Important phenomenological consequences!

- CC can change flavour even at zero distance.
- NC is no longer diagonal.
- Observables at zero-distance depend on $(N^\dagger N)$. In the unitary limit this is the identity.
- Naive guess: Number of neutrino events in a given experiment is reduced compared to the unitary case. Not true!

Basic formulation

- N plays a central role in this setup
- We parametrize N as [3]

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

- In the unitary limit, $N = I$ and U is the unitary matrix responsible for the standard oscillations.
- Advantage of this parametrization: very clean theoretical interpretation in terms of mixing angles.
- The order of each parameter in the seesaw expansion is

$$\alpha_{ii}^2 \sim 1 - \varepsilon^2; \quad |\alpha_{ij}|^2 \sim \varepsilon^4$$

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[3] F. J. Escrihuela et al. “On the description of nonunitary neutrino mixing”. In: *Phys. Rev. D* 92.5 (2015). [Erratum: Phys.Rev.D 93, 119905 (2016)], p. 053009. DOI: `10.1103/PhysRevD.92.053009`. arXiv: `1503.08879 [hep-ph]`.

1. Introduction

2. Non-unitarity formalism
   - Basic formulation
   - Neutrino scattering on a lepton target at zero distance (2402.00114)

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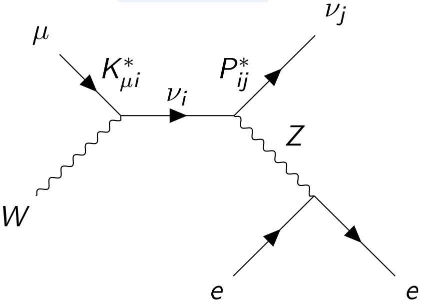
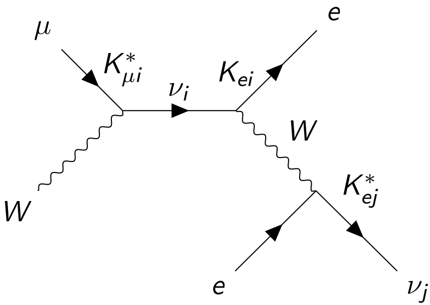
Elastic scattering

- We now consider the family of processes $\nu_\alpha + e^- \to \nu_j + e^-$ and $\bar{\nu}_\alpha + e^- \to \bar{\nu}_j + e^-$ at zero distance
- For concreteness, let's focus on the incoming muon neutrino case.

$1 - \mathcal{O}\left(\varepsilon^2\right)$



$\mathcal{O}\left(\varepsilon^4\right)$



Elastic scattering

In the SM the cross section is given by

$$\left(\frac{d\sigma}{dT}\right)^{\text{SM}} = \frac{2G_\mu^2 m_e}{\pi}\left(g_L^2 + g_R^2\left(1-\frac{T}{E\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right)$$

And in the presence of non-unitarity

$$\left(\frac{d\sigma}{dT}\right)^{\text{NU}} = \frac{\mathcal{P}_{\mu e}^{\text{NC}}}{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}\left(\frac{d\sigma}{dT}\right)^{\text{SM}} + \frac{2m_e G_\mu^2}{\pi}\frac{\mathcal{R}e\left[\mathcal{P}_{\mu e}^{\text{int}}\right]}{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}\left\{\frac{\mathcal{P}_{\mu e}^{\text{CC}}}{\mathcal{R}e\left[\mathcal{P}_{\mu e}^{\text{int}}\right]} + 2g_L - g_R\frac{m_e T}{E_\nu^2}\right\}$$

Elastic scattering

- The energy spectrum of the electron is modified!
- This feature is not shared by Ceνens (pure NC) or inelastic scattering on nucleus (pure CC).
- However, this difference would be extremely hard to observe.
- It is also theoretically suppressed. Indeed, performing the the seesaw expansion and keeping only terms of $\mathcal{O}\left(\varepsilon\right)^2$ we find

$$\left(\frac{d\sigma}{dT}\right)^{\text{NU}} \approx \left(2\alpha_{22}^2 - \alpha_{11}^2\right)\left(\frac{d\sigma}{dT}\right)^{\text{SM}} + \mathcal{O}\left(\varepsilon^4\right)$$

Inelastic scattering

- If $E_\nu > 10$ GeV we also have the purely CC process $\nu_\alpha + e^- \to \nu_j + \mu^-$
- For incoming μ neutrinos, the probability factor is given by

$$P_{\alpha\mu} = (N^\dagger N)_{ee}(N^\dagger N)_{\alpha\mu}(N^\dagger N)_{\mu\alpha}$$

$$\begin{aligned} P_{\mu\mu} &\approx 2\alpha_{22}^2 + \alpha_{11}^2 - 2 \sim 1 - \mathcal{O}\left(\varepsilon^2\right) \\ \sigma &\approx P_{\mu\mu}\frac{G_F^2}{\pi}\left(2E_\nu m_e - m_\mu^2\right) \end{aligned}$$

Summary

- $\nu_\mu + e \to \nu_j + e$, mainly NC (at first order in seesaw expansion)
- $\nu_\mu + e \to \nu_j + \mu$, purely CC
- Final number of events could be bigger or smaller than the expected in the SM (due to the redefinition of G_F):

$$\begin{aligned} e^- \text{ events, NC: } \frac{\#}{\#_{SM}} &\approx 2\alpha_{22}^2 - \alpha_{11}^2 \sim 1 \pm \mathcal{O}(\varepsilon^2) \\ \mu^- \text{ events, CC: } \frac{\#}{\#_{SM}} &\approx \alpha_{22}^2 \sim 1 - \mathcal{O}(\varepsilon^2) \end{aligned}$$

Disclaimer...

We will now analyze how the Near Detector (ND) of DUNE can constraint the NU parameters. However:

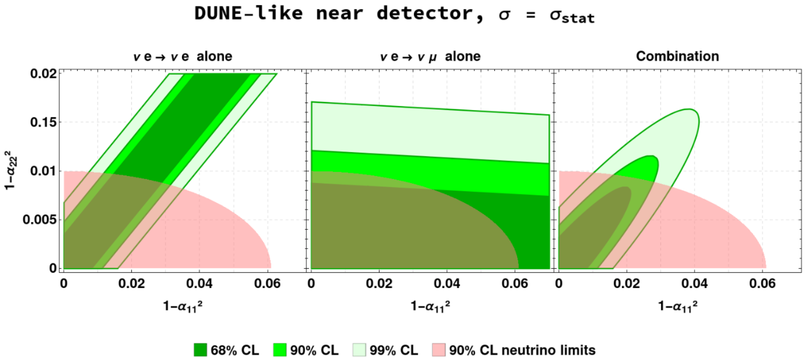
- Neutrino scattering with leptons has lower statistics compared to inelastic scattering with nucleus (way lower cross section)
- The experiment is not optimized to search for scattering on leptons
- Big flux uncertainties
- Constraints on NU from EW precision measurements will be stronger than those from neutrino physics constraints.

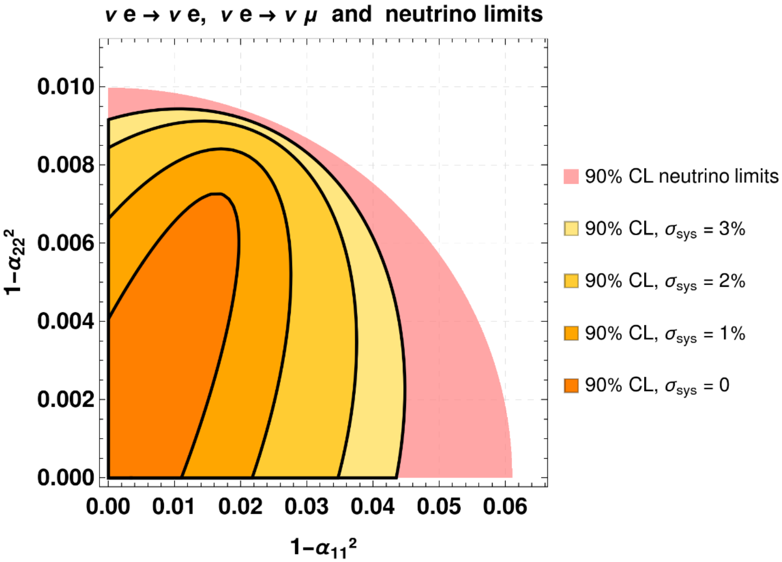
… but!

- It is generally a good idea to find and explore complementary probes of a given phenomena
- Background under control (it is a cleaner process)
- Relatively less analyzed process compared to nucleus scattering

Analysis

- We compute the expected number of events in the SM for each flavour component of the flux (3.5 years per mode).
- We compute the NU (global) factors at order ε^2.
- We extract the sensitivity on NU parameters.
- We compare them with current neutrino limits.


DUNE-like near detector, σ = σ_{stat}
$\nu e \to \nu e$ alone
$\nu e \to \nu \mu$ alone
Combination
$1-\alpha_{22}^2$
0.02
0.15
0.01
0.005
0
0
0.02
0.04
0.06
$1-\alpha_{11}^2$
68% CL
90% CL
99% CL
90% CL neutrino limits


$\nu\, e \to \nu\, e,\ \ \nu\, e \to \nu\, \mu$ and neutrino limits
0.000
0.002
0.004
0.006
0.008
0.010
$1-\alpha_{22}^2$
0.00
0.01
0.02
0.03
0.04
0.05
0.06
$1-\alpha_{11}^2$
90% CL neutrino limits
90% CL, σ_{sys} = 3%
90% CL, σ_{sys} = 2%
90% CL, σ_{sys} = 1%
90% CL, σ_{sys} = 0

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Take home ideas

- Low scale seesaws: A well motivated and broad class of models leading to rich phenomenology. Non-unitarity effects can be at the % level.
- We have studied the effect of NU through the leptonic neutral current for the first time.
- The expected sensitivity will be competitive and complementary with other oscillation experiments (in particular on α_{11}^2).

Thanks!

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   - SM prediction
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   - Background
   - Indirect effects
   - High and low scale seesaws

Parametrization of αs in terms of mixing angles

- A unitary matrix of order n can be parametrized with $\frac{n(n-1)}{2}$ angles and $n(n+1)$ phases.
- The complex rotation ω_{ij} has a mixing angle in the plane $i-j$ and a phase.
- An (unphysical) diagonal matrix of phases times all the possible ω (in some order) parametrizes any unitary matrix

Parametrization of αs in terms of mixing angles

- We can choose the ordering to be (NS × NS)(S × NS)($\omega_{23}\omega_{13}\omega_{12}$)
- We identify the right hand side with the 'standard' mixing
- The first block cannot affect the 'active-active' 3 × 3 block
- The second block we subdivide in products of $\omega_{3j}\omega_{2j}\omega_{1j}$, which is lower tringular
- And a product of lower triangular matrices is also lower triangular
- diagonal entries are simply multiplications of cosines while off diagonal elements are proportional to sines (but are more complicated and include phases)

Parametrization of αs in terms of mixing angles

- As a simple example in the $3+1$ scheme we get
- $\alpha_{ii} = c_{i4}$
- $\alpha_{ij} = s_{i4} s_{j4} e^{i(\phi_{i4} - \phi_{j4})}$

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Ceνens

- $\nu_\alpha + N \to \nu_j + N$
- The COHERENT collaboration already detected the coherent scattering off nucleons in 2017 [4]
- Several experiments, including Coνus in Heidelberg [5]
- For future sensitivity analysis see e.g. [6]

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[4] D. Akimov et al. "Observation of Coherent Elastic Neutrino-Nucleus Scattering". In: *Science* 357.6356 (2017), pp. 1123–1126. DOI: `10.1126/science.aao0990`. arXiv: `1708.01294 [nucl-ex]`.

[5] H. Bonet et al. "Novel constraints on neutrino physics beyond the standard model from the CONUS experiment". In: *JHEP* 05 (2022), p. 085. DOI: `10.1007/JHEP05(2022)085`. arXiv: `2110.02174 [hep-ph]`.

[6] O. G. Miranda et al. "Future CEvNS experiments as probes of lepton unitarity and light-sterile neutrinos". In: *Phys. Rev. D* 102 (2020), p. 113014. DOI: `10.1103/PhysRevD.102.113014`. arXiv: `2008.02759 [hep-ph]`.

Neutrino limits

- See the analysis in[7]
- Combines data from long (NOvA, T2K, MINOS) and short baseline (NOMAD, NuTeV) experiments
- At 90% CL:

$$
\begin{aligned}
1-\alpha_{11}^2 &\leq 6\times 10^{-2}\\
1-\alpha_{22}^2 &\leq 1\times 10^{-2}.
\end{aligned}
$$

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[7] D. V. Forero et al. "Nonunitary neutrino mixing in short and long-baseline experiments". In: *Phys. Rev. D* 104.7 (2021), p. 075030. DOI: `10.1103/PhysRevD.104.075030`. arXiv: `2103.01998 [hep-ph]`.

Number of events in the SM and probability factors

$\mathcal{N}_\mathrm{U}$	ν mode		$\bar{\nu}$ mode		$\mathcal{N}_\mathrm{NU}/\mathcal{N}_\mathrm{U}$	Seesaw order	Main contribution
$\nu_a + e^- \to \nu_j + e^-$	**events**	$\boldsymbol{\sigma}$	**events**	$\boldsymbol{\sigma}$	$\mathcal{P}\, G_F^2/G_\mu^2$		
ν_e	2.800	80	1.530	50	$2\alpha_{11}^2 - \alpha_{22}^2$	$1 \pm \mathcal{O}\left(\varepsilon^2\right)$	NC + CC
ν_μ	31.400	700	5.800	100	$2\alpha_{22}^2 - \alpha_{11}^2$	$1 \pm \mathcal{O}\left(\varepsilon^2\right)$	NC
$\bar{\nu}_e$	430	20	780	30	$2\alpha_{11}^2 - \alpha_{22}^2$	$1 \pm \mathcal{O}\left(\varepsilon^2\right)$	NC + CC
$\bar{\nu}_\mu$	3.200	80	20.000	400	$2\alpha_{22}^2 - \alpha_{11}^2$	$1 \pm \mathcal{O}\left(\varepsilon^2\right)$	NC
total	37.800	800	28.000	600			

$\mathcal{N}_\mathrm{U}$	ν mode		$\bar{\nu}$ mode		$\mathcal{N}_\mathrm{NU}/\mathcal{N}_\mathrm{U}$	Seesaw order	Main contribution
$\nu_a + e^- \to \nu_j + \mu^-$	**events**	$\boldsymbol{\sigma}$	**events**	$\boldsymbol{\sigma}$	$\mathcal{P}\, G_F^2/G_\mu^2$		
ν_e	0	0	0	0	$\lvert\alpha_{21}\rvert^2$	$\mathcal{O}\left(\varepsilon^4\right)$	$\mathcal{O}\left(\varepsilon^4\right)$
ν_μ	17.900	400	14.200	300	α_{22}^2	$1 - \mathcal{O}\left(\varepsilon^2\right)$	CC
$\bar{\nu}_e$	380	20	230	20	α_{11}^2	$1 - \mathcal{O}\left(\varepsilon^2\right)$	CC
$\bar{\nu}_\mu$	0	0	0	0	$\lvert\alpha_{21}\rvert^2$	$\mathcal{O}\left(\varepsilon^4\right)$	$\mathcal{O}\left(\varepsilon^4\right)$
total	18.300	400	14.400	300			

Comparison with existing constraints

- Oscillations
  - Long baseline experiments
  - Short baseline (zero distance)
- Lepton flavour universality
  - π & K decays into μ^- and e^-
  - τ^- decays (hadrons or leptons) $\leftarrow$ function of (α_{33})
  - β decays and CKM unitarity 
- EW precision observables
  - W mass, s_W, Γ_Z...
  - CDF-II W mass [8]

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[8] Mattias Blennow et al. “Right-handed neutrinos and the CDF II anomaly”. In: *Phys. Rev. D* 106.7 (2022), p. 073005. DOI: `10.1103/PhysRevD.106.073005`. arXiv: `2204.04559 [hep-ph]`.

LFU

- See [9] for a nice update
- We can translate the decay rates of pions (or Kaons) to electrons and muons into couplings with the W. The experimental result

$$\left(\frac{g_e}{g_\mu}\right)^2 = 0.998 \pm 0.002$$

- In the SM this ratio is 1. In the presence of non-unitarity

$$\left(\frac{g_e}{g_\mu}\right)^2 = 1 + \alpha_{11}^2 - \alpha_{22}^2$$

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[9] Douglas Bryman et al. "Testing Lepton Flavor Universality with Pion, Kaon, Tau, and Beta Decays". In: *Ann. Rev. Nucl. Part. Sci.* 72 (2022), pp. 69–91. DOI: `10.1146/annurev-nucl-110121-051223`. arXiv: `2111.05338 [hep-ph]`.

LFU

- We can also compare the effective coupling of β and μ decays. In the SM

$$\left(\frac{G_\beta}{G_\mu}\right)^2 = \sum_i |V_{ui}|^2 = 1$$

- Different measurements of nuclear processes give

$$\sum_i |V_{ui}|^2 = 1 - (19.5 \pm 5.3) \times 10^{-4}$$

- Known as the **Cabibbo anomaly**. This anomaly only gets worse in the presence of (leptonic) non-unitarity

$$\left(\frac{G_\beta}{G_\mu}\right)^2 = 2 - \alpha_{22}^2 > 1$$

Combination of all constraints

- Including all the LFU and EW precision measurements gives a much stronger constraints than the ones obtained from DUNE-PRISM or oscillations [10]

$$\begin{aligned} &95\%\ \text{CL:} \\ 1-\alpha_{11}^2 &\leq 2\times 10^{-3} \\ 1-\alpha_{22}^2 &\leq 2\times 10^{-4} \end{aligned}$$

- Caveat: The constraints are pushed towards zero due to the Cabibbo anomaly. Would be interested in seeing a similar analysis excluding the CKM unitarity test.

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[10] Mattias Blennow et al. "Bounds on lepton non-unitarity and heavy neutrino mixing". In: *JHEP* 08 (2023), p. 030. DOI: 10.1007/JHEP08(2023)030. arXiv: 2306.01040 [hep-ph].

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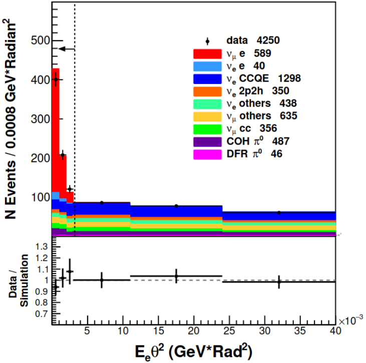
Background reduction

We can take advantage of the fact that the electron scattering will be mainly forward. See for example[11]



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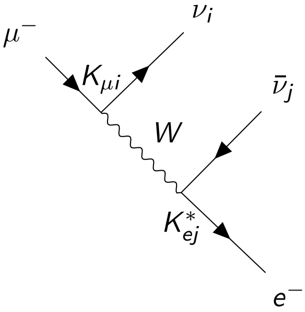
[11] L. Zazueta et al. “Improved constraint on the MINERνA medium energy neutrino flux using $\bar{\nu}e^- \to \bar{\nu}e^-$ data”. In: *Phys. Rev. D* 107.1 (2023), p. 012001. DOI: `10.1103/PhysRevD.107.012001`. arXiv: `2209.05540 [hep-ex]`.

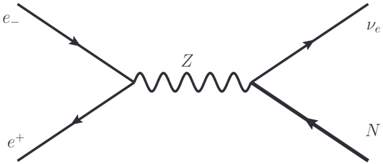
Redefinition of G_F

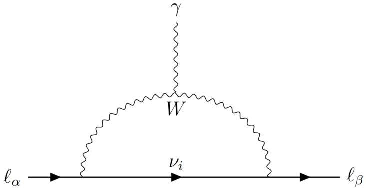
- G_F is measured through the μ^- decay.
- Lepton non-unitarity modifies this decay. The effective muon decay G_μ is related to the 'real' G_F by



$$G_\mu^2 = (N^\dagger N)_{\mu\mu}(N^\dagger N)_{ee} G_F^2 \to \frac{G_F^2}{G_\mu^2} = \frac{1}{(N^\dagger N)_{\mu\mu}(N^\dagger N)_{ee}} \geq 1$$

Observational footprints





- Typically suppressed by the 'active-heavy' mixing.

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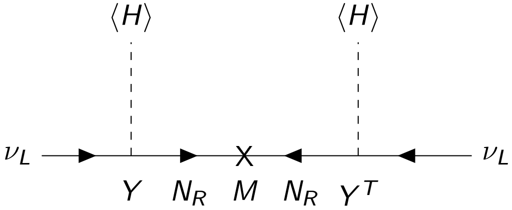
Type I seesaw

- The type-I seesaw is a paradigmatic example of a high scale seesaw



Type I seesaw

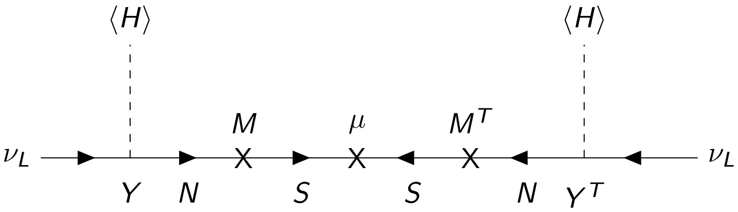
$$M_\nu = \begin{pmatrix} 0 & Y\,v \\ Y^T\,v & M \end{pmatrix},\; U^T M_\nu U = m_d,\; U = \begin{pmatrix} N & S \\ X & Y \end{pmatrix}$$

- N and S are the 'active-active' and 'active-sterile' mixings. By construction $N^\dagger N = 1 - S^\dagger S$.
- In the seesaw expansion we loosely define the parameter $\varepsilon \sim O(Y\,v/M)$ and diagonalize perturbatively, finding

$$m_\nu = v^2 Y^T M^{-1} Y, \quad S^* = Yv\, M^{-1} V \sim \varepsilon, \quad \varepsilon^2 \sim O(m\nu/M)$$

Inverse seesaw

- The inverse seesaw is a paradigmatic example of a low scale seesaw.



Inverse seesaw

- Introduces a new scale $\mu \ll \Lambda_{\text{EW}}$

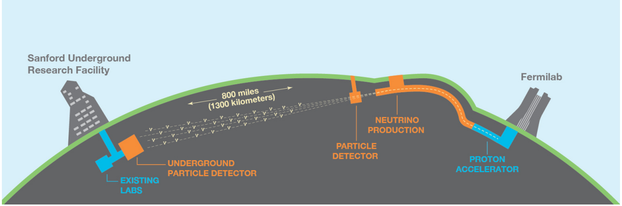
$$M_\nu = \begin{pmatrix} 0 & Y\,v & 0 \\ Y^T\,v & \mu' & M \\ 0 & M^T & \mu \end{pmatrix}$$

- In the seesaw expansion (one gen)

$$m_\nu = \frac{Y^2 v^2}{M^2}\,\mu, \qquad S = \left(\frac{Y\,v}{M^2}\,\mu \quad \frac{Yv}{M}\right) \sim \left(\frac{m_\nu}{Y\,v} \quad \varepsilon\right)$$

- The second component can be % level, even if $m_\nu \to 0$

The DUNE experiment



- DUNE (Deep Underground Neutrino Experiment) is an ambitious neutrino experiment under construction. Will determine the mass ordering and improve precision on θ_{23}, δ_{CP} and θ_{13} [12]
- Two beam modes (neutrino/antineutrino), mainly ν_μ or $\bar{\nu}_\mu$

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[12] B. Abi et al. "Long-baseline neutrino oscillation physics potential of the DUNE experiment". In: *Eur. Phys. J. C* 80.10 (2020), p. 978. DOI: 10.1140/epjc/s10052-020-08456-z. arXiv: 2006.16043 [hep-ex].

The near detector

- Mainly for cross-checking the neutrino flux, but we can use it to do BSM analysis too
- Will be the first purely leptonic test of "zero distance neutral oscillations"