Can we discover LNV with LHC far detectors?

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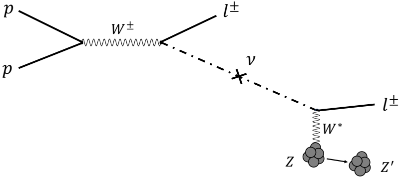
Motivation

- Observation of ν oscillation
  $\Rightarrow$ non-vanishing m_ν, BSM physics, seesaw mechanisms
- If we observe LNV $\Rightarrow$ BSM physics, often related to active/sterile neutrinos' nature $\Rightarrow$ Dirac (LNC) or Majorana (LNC/LNV)?
- Searches for LNV:
  - $0\nu\beta\beta$ decay
  - Collider searches for same-sign leptons
- $\nu's$ almost stable & $N's$ can be long-lived for the local detector
- To fill the gap we can use "far detectors"
- Two classes of far detectors at the LHC
  - Neutrino detectors (ν scattering): `FASER`ν, `SND@LHC`, `FLArE`, . . .
  - LLP detectors (N displaced decay): `FASER`, `ANUBIS`, `MATHUSLA`, . . .
- Can we use far detectors to search for LNV?
- Consider Majorana neutrinos in the following

Neutrino detectors: $\nu - Z$ scattering

- Target: tungsten or liquid argon
- Neutrino-nucleus (charged-current) deep inelastic scattering
- Measure the outgoing charged lepton to determine the lepton number of the incoming neutrino
- Event correlation between the `ATLAS` IP and the neutrino detectors
- Consider $pp \to W \to l\nu, \nu Z \to lZ'$



- Triggered by the prompt lepton from W-boson decay (`ATLAS`)
  - $p_T^e > 27.3$ GeV and $|\eta^e| < 2.5$
  - $p_T^\mu > 27$ GeV and $|\eta^\mu| < 2.5$
- Helicity flip suppression is strong:

$$\epsilon_{\text{h. f.}} = m_\nu^2/(4E_\nu^2)$$

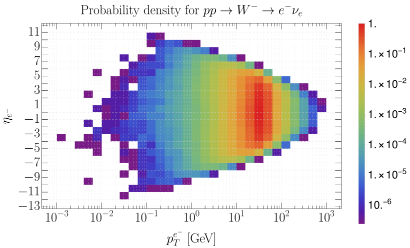
Neutrino detectors: computation

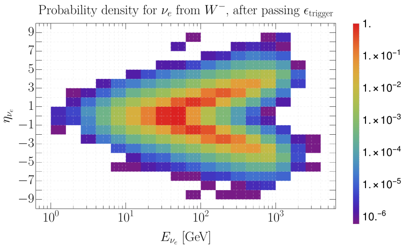
neutrino detectors	material	A [cm^2]	m_{det} [ton]	η_{min}	η_{max}	$\mathcal{L}$ [fb^{-1}]
FASERν	tungsten	25×25	1.2	8.5	∞	150
SND@LHC	tungsten	40×40	0.85	7.2	8.4	150
FASERν2	tungsten	40×40	20	8.5	∞	3000
AdvSND(far)	tungsten	100×55	5	7.2	8.4	3000
FLArE-10	liquid argon	100×100	10	7.5	∞	3000
FLArE-100	liquid argon	160×160	100	7	∞	3000

$$\begin{aligned} P_{\text{scatt.}} &= \frac{\sigma_{\nu Z}}{A}\frac{m_{\text{det}}}{m_Z} \\ N_S^{\nu} &= \sigma_\nu \cdot \mathcal{L} \cdot \epsilon_{\text{trigger}} \cdot \epsilon_{\text{window}} \cdot \langle \epsilon_{\text{h. f.}} \cdot P_{\text{scatt.}} \rangle \end{aligned}$$

- $\sigma_{\nu Z}$ extracted from arXiv:1908.02310 (`FASER` collaboration)
- $\langle \epsilon_{\text{h. f.}} \cdot P_{\text{scatt.}} \rangle$ obtained with `Pythia8` Monte-Carlo simulation
- $\epsilon_{\text{trigger}} \sim 40\%$ ($m_\nu = 0.1$ eV)
- Scattering detection efficiency assumed to be 1

Kinematical distributions


Probability density for $pp \to W^- \to e^- \nu_e$


Probability density for ν_e from W^-, after passing $\epsilon_{\text{trigger}}$

ϵ_{window}

ϵ_{window}	e^+	e^-	μ^+	μ^-
FASERν	1.3×10^{-6}	6.0×10^{-7}	1.7×10^{-6}	5.8×10^{-7}
SND@LHC	1.5×10^{-5}	6.0×10^{-6}	2.0×10^{-5}	4.6×10^{-6}
FASERν2	1.3×10^{-6}	6.0×10^{-7}	1.7×10^{-6}	5.8×10^{-7}
AdvSND(far)	1.5×10^{-5}	6.0×10^{-6}	2.0×10^{-5}	4.6×10^{-6}
FLArE-10	7.6×10^{-6}	5.4×10^{-6}	1.3×10^{-5}	1.7×10^{-6}
FLArE-100	2.7×10^{-5}	8.9×10^{-6}	3.3×10^{-5}	8.1×10^{-6}

Signal-event numbers for pure SM CC interactions

N_S^ν	e^+	e^-	μ^+	μ^-
FASERν	1.1×10^{-32}	7.0×10^{-32}	3.1×10^{-32}	3.4×10^{-32}
SND@LHC	7.5×10^{-32}	9.0×10^{-32}	7.6×10^{-32}	8.4×10^{-32}
FASERν2	1.5×10^{-30}	9.1×10^{-31}	4.1×10^{-30}	4.4×10^{-30}
AdvSND(far)	2.6×10^{-30}	3.1×10^{-30}	2.6×10^{-30}	2.9×10^{-30}
FLArE-10	7.6×10^{-31}	3.1×10^{-30}	1.6×10^{-30}	1.7×10^{-30}
FLArE-100	1.8×10^{-29}	2.0×10^{-29}	1.5×10^{-29}	1.8×10^{-29}

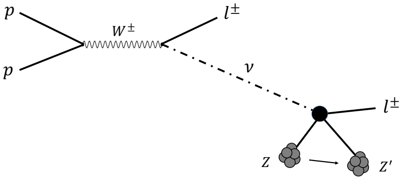
Table: SM interactions with an active neutrino with a mass of 0.1 eV

- 30 orders of magnitude smaller than 1!
- The main cause is the helicity flip:

$$\epsilon_{\text{h. f.}} = m_\nu^2/(4E_\nu^2) \sim 10^{-25} \text{ for } m_\nu = 0.1 \text{ eV and } E_\nu = 100 \text{ GeV}$$

- Consider LNV dim-7 operators instead:
  production via W-boson CC & decay via $\epsilon_{ij}(L^i C\gamma_\mu e)(\overline{d}\gamma^\mu u)H^j$

Signal-event numbers with the LNV dim-7 operator



N_S^ν	e^+	e^-	μ^+	μ^-
FASERν	1.5×10^{-14}	8.5×10^{-15}	7.7×10^{-15}	2.0×10^{-15}
SND@LHC	2.2×10^{-14}	1.5×10^{-14}	3.7×10^{-14}	9.3×10^{-15}
FASERν2	2.0×10^{-12}	1.3×10^{-12}	1.0×10^{-12}	2.4×10^{-13}
AdvSND(far)	7.7×10^{-13}	5.0×10^{-13}	1.2×10^{-12}	2.1×10^{-13}
FLArE-10	6.6×10^{-13}	3.6×10^{-13}	1.0×10^{-12}	4.6×10^{-14}
FLArE-100	6.2×10^{-12}	2.9×10^{-12}	8.5×10^{-12}	1.3×10^{-12}

Table: $\epsilon_{ij}(L^i C\gamma_\mu e)(\overline{d}\gamma^\mu u)H^j$ with a coefficient $1/\Lambda^3 \sim 1/(5\text{ TeV})^3$

- Unfortunately still more than 10 orders of magnitude below 1!
  - W-boson production rate not big enough
  - Scattering probability in general small

LLP detectors

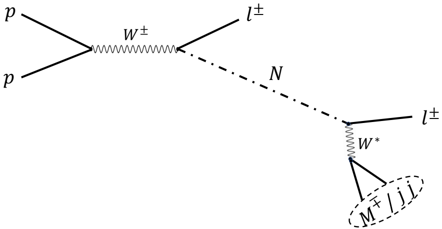
- Sterile neutrinos:

$$\mathcal{L} \quad = \quad \frac{g}{\sqrt{2}} V_{\alpha j}\ \bar{l}_\alpha \gamma^\mu P_L N_j W^-_\mu + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} V^L_{\alpha i} V^*_{\alpha j} \overline{N_j} \gamma^\mu P_L \nu_i Z_\mu + \text{h.c.}$$

- Signal process: $pp \to W^\pm \to e^\pm N,\, N \to e^\pm M^\mp$ or $e^\pm jj$

$$N_S^N = \frac{\sigma_\nu}{\mathrm{BR}(W \to e\,\nu)} \cdot \mathrm{BR}(W^\pm \to e^\pm\, N) \cdot \mathcal{L} \cdot \epsilon_{\text{trigger}} \cdot \langle P_{\text{decay}} \rangle \cdot \mathrm{BR}(N \to e^\pm jj/M^\mp)$$

- $\epsilon_{\text{trigger}} \sim 40\%$ for m_N between 0.2 and 5 GeV
- $\mathrm{BR}(N \to e^\pm jj/M^\mp)$: $20\% - 30\%$
- $\langle P_{\text{decay}} \rangle$ obtained with `Pythia8` Monte-Carlo simulation & exp. func.

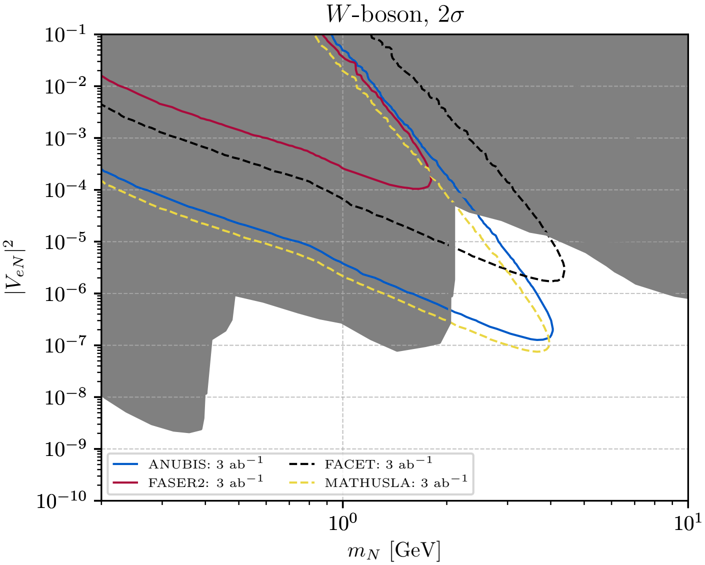


- Event correlation, measurement of leptons' charge, final-state

Discussion of LLP far detectors

- Can't do:
    - `CODEX-b`: $\eta \in [0.2, 0.6]$ while `LHCb` $\eta_l \in [2, 5]$
    - `MoEDAL-MAPP`: negative η range
    - `MATHUSLA`: > 100 thousand m^3, too large to install magnet (cost)
    - `FACET`: enclosing the beam pipe, cannot install magnets
- Maybe:
    - `ANUBIS`: no such intrinsic issues, but still a bit too large
- Should do:
    - `FASER(2)`: no such intrinsic issues and small enough
- Still need to install required hardware: money, space, engineers, . . .
- Could consider a trigger simply by a signal in `FASER(2)` or `ANUBIS`

Sensitivity results for LLP detectors (if no discovery)



Summary

- Stable or very long-lived active/sterile neutrinos cannot be used for observing LNV at LHC local detectors
- Proposed to use LHC far detectors to look for same-sign leptons
  - Neutrino detectors with active neutrino-nucleus charged-current scattering:
    hopeless because of helicity flip, low production rates of ν from W, or low scattering probability
  - LLP detectors with sterile neutrino displaced decays:
    hopeful, if upgrades can be implemented, which is hard

Thank You!

Back-up slides

Why mesons do not work?

- Mesons are light and soft at the LHC
- The prompt charged lepton is therefore also soft
- Impossible to get a hard enough prompt lepton together with a forward-traveling energetic neutrino
- Even in the forward direction, hundreds or up to thousands of tracks originate from pile-up effects, multi-parton interactions, as well as proton beam remnants ⇒ can't do event correlation

A sample UV-complete realization of the dim-7 operator

- t-channel leptoquark $\Rightarrow \nu Z$ scattering
- Leptoquarks: $S_d \sim (\mathbf{3},\mathbf{1})_{-1/3}$ and $S_Q \sim (\mathbf{3},\mathbf{2})_{1/6}$

$$\mathcal{L} \supset -\left(g_{ue}\overline{u_R}e_R^c S_d + g_{Ld}\overline{d_R}L^T\epsilon S_Q + \mu S_Q^\dagger S_d H\right) + \text{h.c.}\dots$$

$$\begin{pmatrix} \sqrt{1-\frac{v^2\mu^2}{2(m_d^2-m_Q^2)^2}} & \frac{v\mu}{\sqrt{2}(m_d^2-m_Q^2)} \\ \frac{-v\mu}{\sqrt{2}(m_d^2-m_Q^2)} & \sqrt{1-\frac{v^2\mu^2}{2(m_d^2-m_Q^2)^2}} \end{pmatrix} \equiv \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$\begin{aligned} \hat{m}_d^2 &= m_d^2 + \sin^2\theta(m_d^2 - m_Q^2) \\ \hat{m}_{Q^-}^2 &= m_Q^2 - \sin^2\theta(m_d^2 - m_Q^2) \\ \hat{m}_{Q^+}^2 &= m_Q^2 \end{aligned}$$

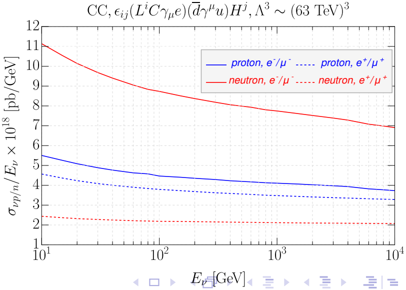
$$\epsilon_{ij}(L^i C\gamma_\mu e)(\overline{d}\gamma^\mu u)H^j \Rightarrow \frac{1}{\Lambda^3} = \frac{\mu g_{ue} g_{Ld}}{2\, m_Q^2 m_d^2}$$

Computation of $\sigma_{\nu Z}$ for the dim-7 operator

- Implement the model with `FeynRules` into UFO format (with Majorana ν)
- MadGraph5: $p\,\nu_{e/\mu} \to je^+/\mu^+$ and $p\,\nu_{e/\mu} \to je^-/\mu^-$, fixing the neutrino beam polarization to be 100% left-handed and right-handed, respectively, and setting the incoming nucleon beam at rest
- $Q^2 = 2\,x\,y\,E_\nu\,m_{p/n}$
  - $x = 0.1$ frac. of the p/n's mom. carried by the quark in the initial state
  - $y = 0.5$ frac. of the neutrino mom. transferred to the hadronic system
  - `run_card.dat`: the renormalization scale and the factorization scale of the proton/neutron target $= \sqrt{Q^2}$.
- Scan over $E_\nu \in [10\text{ GeV}, 10\text{ TeV}]$ to get the scattering cross sections

First-generation of quarks only:

- main matter content of nucleons ⇒ the largest scattering cross sections
- such dim-7 operators could induce radiatively neutrino masses, the strength of which is proportional to the masses of the fermion fields



Leptonic decay branching ratio of W

- σ_ν for $pp \to W^\pm \to l^\pm \nu$ measured at ATLAS [1603.09222]

- $\mathrm{BR}(W^\pm \to e^\pm N) = \frac{1}{\Gamma_W} \frac{G_F}{\sqrt{2}} \frac{m_W^3}{12\pi} |V_{eN}|^2 \left(2 + \frac{m_N^2}{m_W^2}\right) \cdot \left(1 - \frac{m_N^2}{m_W^2}\right)^2$