Long lived right-handed neutrinos,
oscillations and leptogenesis

Oliver Fischer

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Neutrino oscillations & the Standard Model

- No right-handed neutrinos in the Standard Model (SM).
- No mass matrix, no mixing of the neutrino flavour states.
⇒ Neutrino oscillations are evidence of physics beyond the SM.
Lowscale seesaw

Benchmark model, defined in Antusch, OF; JHEP 1505 (2015) 053
Similar to e.g.: Mohapatra, Valle (1986); Malinsky, Romao Valle (2005); Shaposhnikov (2007);

- Lowscale seesaw Lagrangian, two sterile neutrinos $N_i$ with protective symmetry:

\[ \mathcal{L}_N = -\frac{1}{2} N^1_R M (N^2_R)^c - y_{\nu \alpha} N^1_R \bar{\phi} L^\alpha + \text{H.c.} \]

- The mass matrix:

\[ M_{\nu} = \begin{pmatrix} 0 & m_D & m'_D \\ (m_D)^T & 0 & M \\ (m'_D)^T & M & \mu \end{pmatrix} , \]

- Perturbations $\Rightarrow m_{\nu}$ and HNL mass splitting ($\Delta M$)

- $m'_D$: Linear seesaw, $\Delta M^{NO} = 0.0416 \text{ eV}$, $\Delta M^{IO} = 0.000753 \text{ eV}$

- $\mu$: inverse seesaw, $\Delta M \sim \frac{m_{\nu_i}}{|\theta|^2}$. 
Lepton number violation and $\Delta M$

- $R_{\ell\ell} = \text{ratio of LNV/LNC dilepton events.}$
- $R_{\ell\ell}$ is a function of mass splitting and decay width of $N$.
- For mass splitting $\sim$ decay width, $R_{\ell\ell} \in [0, 1]$.
- Zero mass splitting $\Rightarrow$ zero LNV.
Parameter space with LNV

\[ R_{\ell\ell} = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2} \]

- Upper contour: \( R_{\ell\ell} = 0.1 \)
- Lower contour: \( R_{\ell\ell} = 0.9 \)
Observing Heavy neutrino-antineutrino oscillations
A best case scenario for LHCb

Displacements $2 \text{ cm} \leq \Delta x \leq 50 \text{ cm}$.

$\mathcal{O}(100)$ events with $\ell_\alpha (\ell_\beta + J)_{\text{displaced}}$ after run 5.
Oscillation: SS vs OS dileptons as function of displacement

- **Proper oscillation length:** \( \lambda_{\text{osc}, \text{IO}}^{\text{lin}} = 3.29 \cdot 10^{-3} \sqrt{\gamma^2 - 1} \) m
- **Proper lifetime:** \( c\tau = 0.0094 \) m

Antusch, Cazzato, Fischer; 1709.03797
Leptogenesis and the origin of neutrino masses

- Active-sterile mixing angles $\theta_\alpha$ fixed by the light neutrino data.
- Ratios of $\theta_\alpha$ measurable at FCC-ee with sub-percent accuracy.
- Test minimal type I seesaw hypothesis.
- Together with $\Delta M$ also tests the compatibility with leptogenesis.
Conclusions!