Lepton Number Violation at Colliders via Heavy Neutrino-Antineutrino Oscillations

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Cern Theory Colloquium

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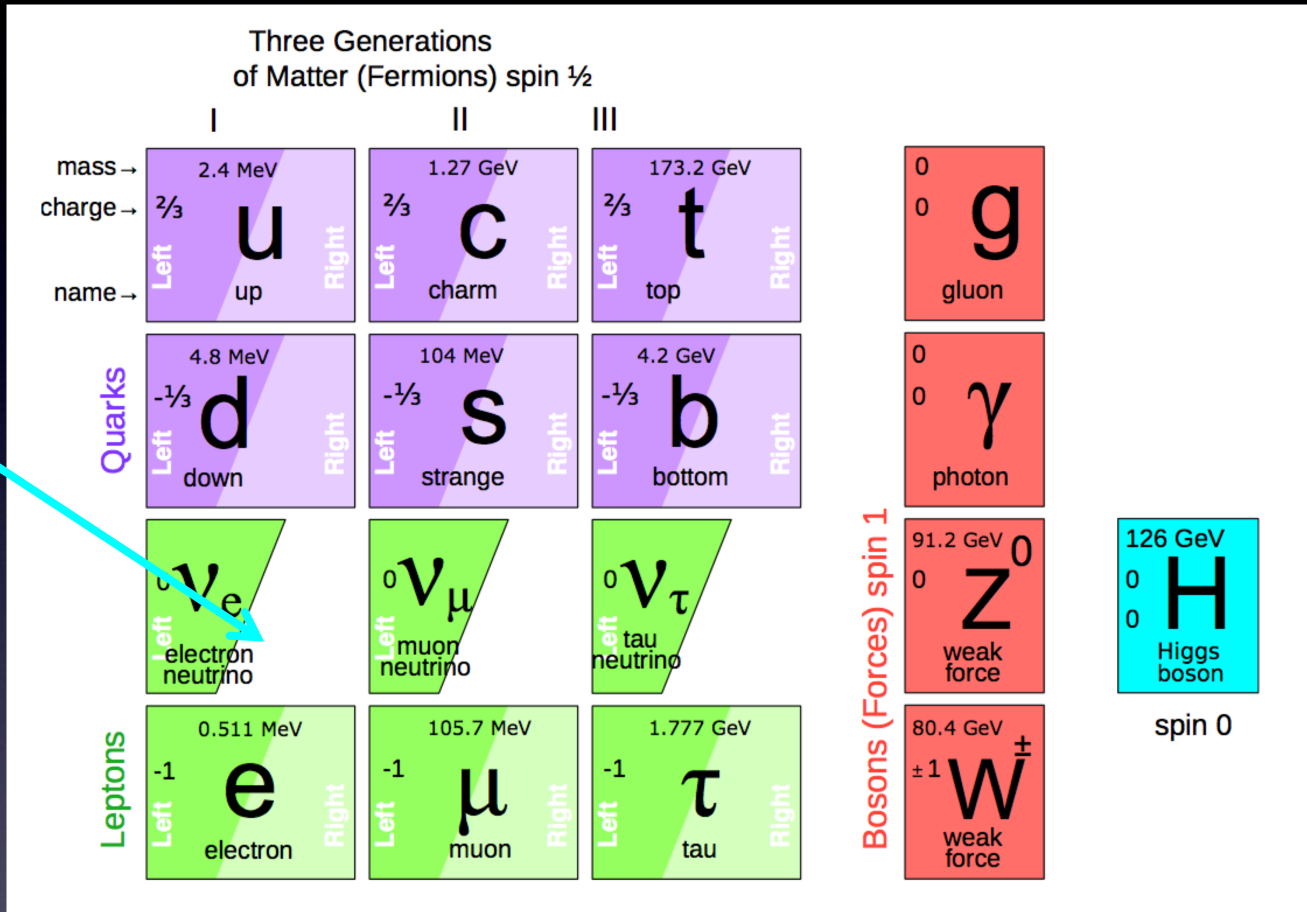
Heavy Neutral Leptons – the right SM extension to explain the light neutrino masses?

There are no right-chiral neutrino states N_{Ri} in the Standard Model

➔ N_{Ri} would be completely neutral under all SM symmetries (HNLs ↔ RH neutrinos ↔ sterile neutrinos)



Adding N_{Ri} leads to the following extra terms in the Lagrangian density:

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\overline{N_R^i} M_{ij} N_R^{cj} - (Y_\nu)_{i\alpha} N_R^i \widetilde{\phi}^\dagger L^\alpha + \text{H.c.}}$$

M: HNL mass matrix

Y_ν: neutrino Yukawa matrix (→ Dirac mass terms m_D)

Light Neutrino Masses via the "Seesaw Mechanism"

Majorana mass matrix of the (three) light neutrinos

Mass matrix of the (2+n) sterile (= right-handed) neutrinos (masses of Majorana-type)

$$\boxed{(m_\nu)_{\alpha\beta} = -\frac{v_{\mathrm{EW}}^2}{2}(Y_\nu^T M_N^{-1} Y_\nu)_{\alpha\beta}}$$

Valid for $v_{EW}\, y_\nu \ll M_R$

„Seesaw Formula"

Neutrino Yukawa matrix

From neutrino oscillation experiments and mass searches:

$|m_3^2 - m_1^2| \approx 2.5 \cdot 10^{-3}\ \mathrm{eV}^2$
$m_2^2 - m_1^2 \approx 7.4 \cdot 10^{-5}\ \mathrm{eV}^2$
all three m_α below ~ O(0.2) eV

+ measurements of the leptonic mixing angles (from neutrino osc. experiments)

P. Minkowski ('77), Mohapatra, Senjanovic, Yanagida, Gell-Mann, Ramond, Slansky, Schechter, Valle, …

Note: At least two sterile neutrinos are required
➔ generate masses for two of the light neutrinos
(necessary for realizing the two observed mass splittings)

Outline of my talk

- "Landscape of the Seesaw Mechanism" ... & region testable at colliders
- Sensitivities for HNL searches at future colliders: Displaced vertices, signatures with LFV or (?) LNV
- LFV signatures at ep colliders ↔ New (updated) results
- LNV → Can be induced by Heavy Neutrino-Antineutrino Oscillations

Minimal example: 2 RH Neutrinos (2 HNLS)

In the mass basis:

$$\boxed{\mathcal{L}_N = -(m_D^{(1)})_\alpha \overline{\nu}_{\mathrm{L}}^{\alpha} N_{\mathrm{R}}^{1} - (m_D^{(2)})_\alpha \overline{\nu}_{\mathrm{L}}^{\alpha} N_{\mathrm{R}}^{2} - \frac{1}{2} M_1 \overline{N_{\mathrm{R}}^{1}} N_{\mathrm{R}}^{c1} - \frac{1}{2} M_2 \overline{N_{\mathrm{R}}^{2}} N_{\mathrm{R}}^{c2} + \mathrm{H.c.}}$$

where $(m_D^{(i)})_\alpha = \frac{v_{\mathrm{EW}}}{\sqrt{2}} (Y_\nu)_{i\alpha}$

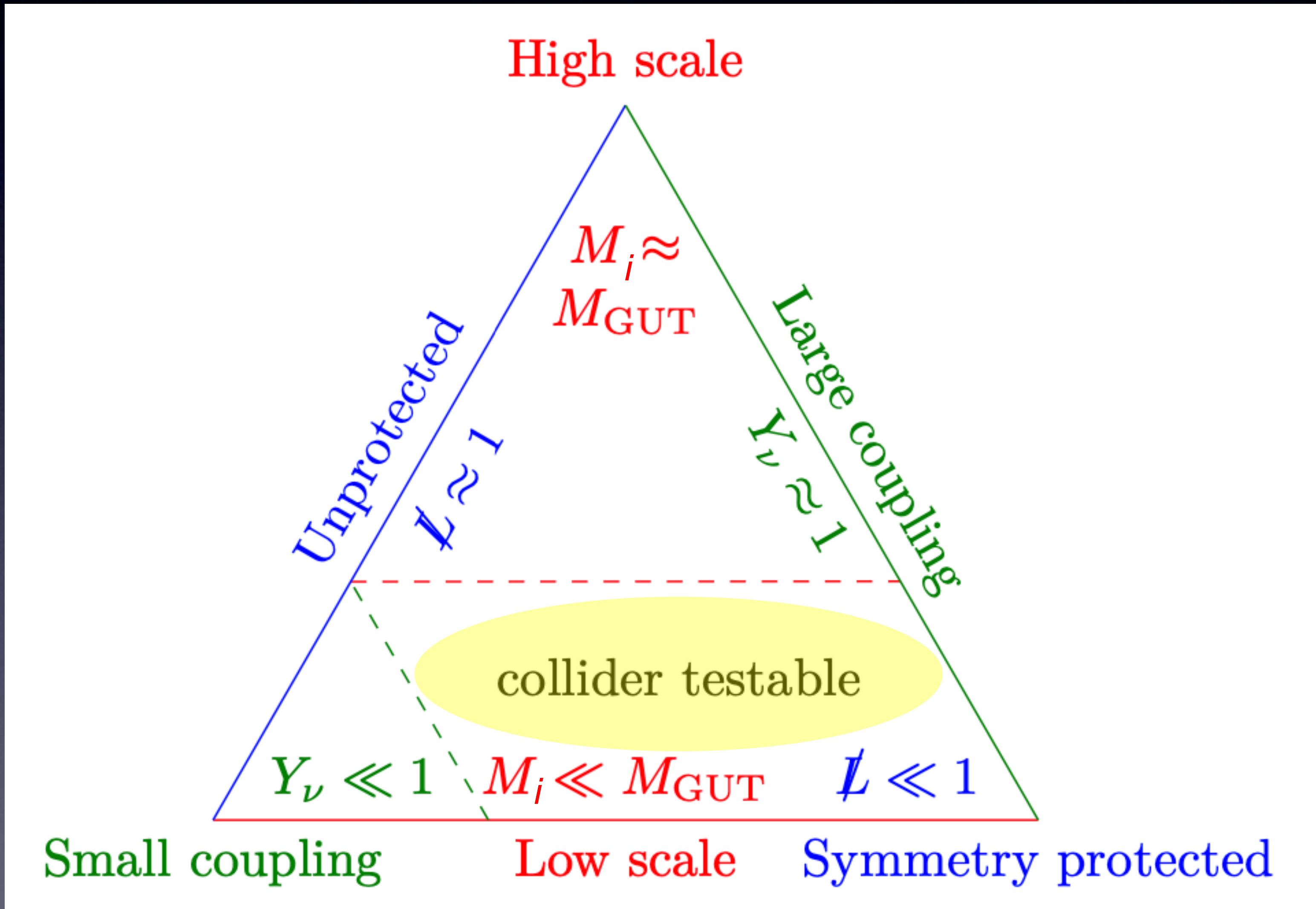
$\downarrow$ **„Seesaw Formula“**

$$\boxed{(m_\nu)_{\alpha\beta} = \frac{(m_D^{(1)})_\alpha (m_D^{(1)})_\beta}{M_1} + \frac{(m_D^{(2)})_\alpha (m_D^{(2)})_\beta}{M_2}}$$

Landscape of the Seesaw Mechanism

$$\boxed{(m_\nu)_{\alpha\beta} = \frac{(m_D^{(1)})_\alpha (m_D^{(1)})_\beta}{M_1} + \frac{(m_D^{(2)})_\alpha (m_D^{(2)})_\beta}{M_2}}$$

↔ Smallness of observed $m_{\nu\alpha}$?



Low Scale Seesaw with "Symmetry protection"

Example for protective "lepton number"-like symmetry (case of 2HNLs):

	L_α	N_{R1}	N_{R2}
"Lepton-#"	+1	+1	-1

→ With 2 HNLs (min # to explain m_ν) and exact symmetry

$$\mathscr{L}_N = - \overline{N_R}^1 M N_R^{c\,2} - y_\alpha \overline{N_R}^1 \tilde{\phi}^\dagger L^\alpha + \mathrm{H.c.}$$

In the symmetry limit: $m_{\nu\alpha} = 0$

with basis $\Psi = (\nu_L, (N_R^1)^c, (N_R^2)^c)$

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ (m_D)^T & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

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From general 2 HNL seesaw to "symmetry limit"

For comparison: most general seesaw with 2 HNLs:

$$M_\nu^{\text{general}} = \begin{pmatrix} 0 & m_D & m_D' \\ (m_D)^T & M' & M \\ (m_D')^T & M & M'' \end{pmatrix}$$

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→

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Note: "Symmetry protection" → right-chiral neutrinos form "pseudo-Dirac pair"!

In the symmetry limit: $m_{\nu\alpha} = 0$

with basis $\Psi = (\nu_L, (N_R^1)^c, (N_R^2)^c)$

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ (m_D)^T & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

From general 2 HNL seesaw to "symmetry limit"

For comparison: most general seesaw with 2 HNLs:

$$M_\nu^{\text{general}} = \begin{pmatrix} 0 & m_D & m_D' \\ (m_D)^T & M' & M \\ (m_D')^T & M & M'' \end{pmatrix}$$

To generate the light neutrino masses → approximate symmetry

$$M_\nu^{\text{L broken}} = \begin{pmatrix} 0 & m_D & \varepsilon \\ (m_D)^T & \varepsilon' & M \\ \varepsilon^T & M & \varepsilon'' \end{pmatrix}$$

when ε-terms "get larger"

Low Scale Seesaw with "Symmetry protection"

$\rightarrow$ Light neutrino masses induced from small breaking of the "L-like" symmetry (m_ν ~ ε)

$$\mathscr{L}_N = - \overline{N_R}^1 M \; N_R^{c\,2} - y_\alpha \overline{N_R}^1 \widetilde{\phi}^\dagger L^\alpha + \mathrm{H.c.}$$

+ symmetry breaking terms O(ε)

"Linear" seesaw:*

$$M_\nu = \begin{pmatrix} 0 & m_D & \varepsilon \\ (m_D)^T & 0 & M \\ \varepsilon^T & M & 0 \end{pmatrix}$$

$$\rightarrow m_\nu \sim \frac{\epsilon^T m_D}{M}$$

In "Minimal linear seesaw" (2 HNLs):

$$\Delta M^{\mathrm{lin}}_{\mathrm{NH}} = m_{\nu_3} - m_{\nu_2} \overset{m_{\nu_1}=0}{=} 0.042 \text{ eV}$$

$$\Delta M^{\mathrm{lin}}_{\mathrm{IH}} = m_{\nu_2} - m_{\nu_1} \overset{m_{\nu_3}=0}{=} 0.00075 \text{ eV}$$

cf. S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

"Inverse" seesaw:*

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ (m_D)^T & 0 & M \\ 0 & M & \varepsilon \end{pmatrix}$$

$$\rightarrow m_\nu \sim \epsilon \frac{m_D^T m_D}{M^2}$$

Estimate for induced HNL mass splitting ΔM in "inverse" seesaw:

$$\Delta M^{\mathrm{inv}} = \frac{m_{\nu_\alpha}}{|\theta^2|}$$

(Note: Here only one ν_α gets mass)

also: ... no tree-level m_ν

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ (m_D)^T & \varepsilon & M \\ 0 & M & 0 \end{pmatrix}$$

*) Note: names "inverse" and "linear" seesaw used here to indicate the position of the ε-term in M_ν

For low scale seesaw models and discussions, see e.g.: D. Wyler, L. Wolfenstein ('83), R. N. Mohapatra, J. W. F. Valle ('86), M. Shaposhnikov (`07), J. Kersten, A. Y. Smirnov ('07), M. B. Gavela, T. Hambye, D. Hernandez, P. Hernandez ('09), M. Malinsky, J. C. Romao, J. W. F. Valle ('05), S.A., Hohl, King, Susic: arXiv:1712.05366) …

Benchmark scenario: The SPSS
(= Symmetry Protected Seesaw Scenario)

... captures the phenomenology of a dominant "pseudo-Dirac"-like HNL pair at colliders
... without the constraints of a restricted pure 2HNL model (↔ correlations between $y_{\nu\alpha}$)

$$
\boxed{Y_\nu = \begin{pmatrix} y_{\nu_e} & 0 & \\ y_{\nu_\mu} & 0 & \cdots \\ y_{\nu_\tau} & 0 & \end{pmatrix}, \quad M_N = \begin{pmatrix} 0 & M & & 0 \\ M & 0 & & \\ & & \cdots & \\ 0 & & & \cdots \end{pmatrix}}
$$

+ O(ε) perturbations to generate the light neutrino masss
(which we can often neglect for collider studies)

Additional sterile neutrinos can exist, but assumed to have no effects at colliders (which can be realised easily, e.g. by giving lepton number = 0 to them).

For details on the SPSS, see:
S.A., O. Fischer (arXiv:1502.05915)
S.A., E. Cazzato, O. Fischer (arXiv:1612:02728)

The SPSS in the "symmetry limit"

We consider the SPSS (Symmetry Protected Seesaw Scenario)

In the symmetry limit:

$$\boxed{\begin{aligned}\mathscr{L}_N = &- \overline{N_R}^{1} M \, N_R^{c\,2} - y_\alpha \overline{N_R}^{1} \widetilde{\phi}^\dagger L^\alpha + \mathrm{H.c.} \\ &+ \ldots \text{ (terms from additional sterile vs)}\end{aligned}}$$

We consider the SPSS (Symmetry Protected Seesaw Scenario)

In the symmetry limit:

$$\mathscr{L}_N = - \quad \overline{N_R}^1 M \quad N_R^{c\,2} - y_\alpha \overline{N_R}^1 \tilde{\phi}^\dagger L^\alpha + \mathrm{H.c.}$$

$+$ … (terms from additional sterile νs)

4 Parameters: M, y_α (α=e,μ,τ)

We consider the SPSS (Symmetry Protected Seesaw Scenario)

In the symmetry limit:

$$\mathscr{L}_N = - \overline{N_R}^1 M N_R^{c\,2} - y_\alpha \overline{N_R}^1 \tilde{\phi}^\dagger L^\alpha + \text{H.c.}$$
$$+ \ \ldots \text{ (terms from additional sterile vs)}$$

After EW symmetry breaking, we diagonalize the 5x5 mass matrix:

Mass eigenstates:

$$\tilde{n}_j = (\nu_1, \nu_2, \nu_3, N_4, N_5)_j^T = U_{j\alpha}^\dagger n_\alpha$$

"**light**" and "**heavy**" neutrinos

with:

$$n = \left(\nu_{e_L}, \nu_{\mu_L}, \nu_{\tau_L}, (N_R^1)^c, (N_R^2)^c\right)^T$$

"**active**" and "**sterile**" neutrinos

This defines the 5x5 mixing matrix U.

We consider the SPSS: Instead of the y_α, we use the active sterile mixing angles θ_α, (α=e,μ,τ)

In the symmetry limit:

$$\mathscr{L}_N = - \overline{N_R}^{1} M \, N_R^{c\,2} - y_\alpha \overline{N_R}^{1} \tilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

$$+ \; \ldots \text{ (terms from additional sterile } \nu\text{s)}$$

- The leptonic mixing matrix to leading order in the active-sterile mixing parameters:

$$U_{5x5} = \begin{pmatrix} \mathcal{N}_{1e} & \mathcal{N}_{1\mu} & \mathcal{N}_{1\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{2e} & \mathcal{N}_{2\mu} & \mathcal{N}_{2\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{3e} & \mathcal{N}_{3\mu} & \mathcal{N}_{3\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & \frac{-\mathrm{i}}{\sqrt{2}}(1-\frac{1}{2}\theta^2) & \frac{1}{\sqrt{2}}(1-\frac{1}{2}\theta^2) \end{pmatrix}$$

Parameters:
M, y_α (α=e,μ,τ)
or equivalently
M, θ_α (α=e,μ,τ)

Active-sterile neutrino mixing parameters:

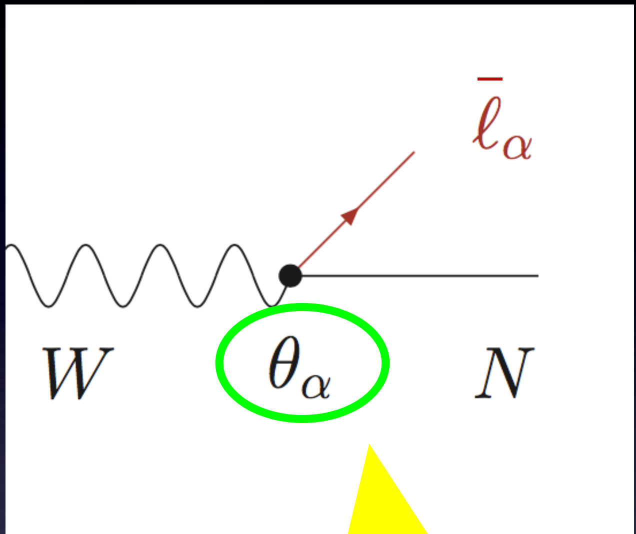
$$\theta_\alpha = \frac{y_\alpha^*}{\sqrt{2}} \frac{v_{\mathrm{EW}}}{M}, \qquad \alpha = e, \mu, \tau$$

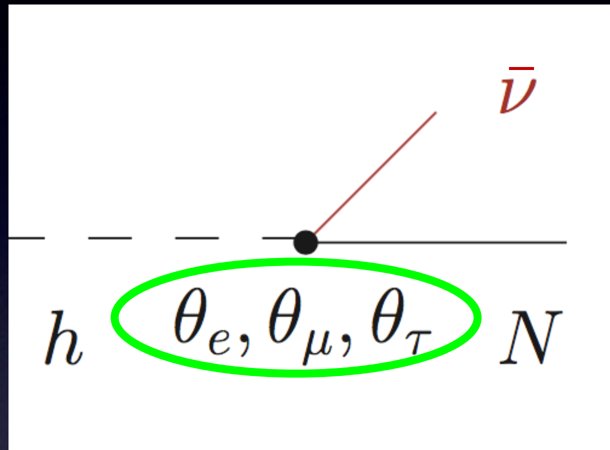
Sterile neutrinos mix with the active ones

$$U = \begin{pmatrix} \mathcal{N}_{1e} & \mathcal{N}_{1\mu} & \mathcal{N}_{1\tau} & \boxed{-\frac{\mathrm{i}}{\sqrt{2}}\theta_e} & \boxed{\frac{1}{\sqrt{2}}\theta_e} \\ \mathcal{N}_{2e} & \mathcal{N}_{2\mu} & \mathcal{N}_{2\tau} & \boxed{-\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu} & \boxed{\frac{1}{\sqrt{2}}\theta_\mu} \\ \mathcal{N}_{3e} & \mathcal{N}_{3\mu} & \mathcal{N}_{3\tau} & \boxed{-\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau} & \boxed{\frac{1}{\sqrt{2}}\theta_\tau} \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & \frac{-\mathrm{i}}{\sqrt{2}}(1-\frac{1}{2}\theta^2) & \frac{1}{\sqrt{2}}(1-\frac{1}{2}\theta^2) \end{pmatrix}$$

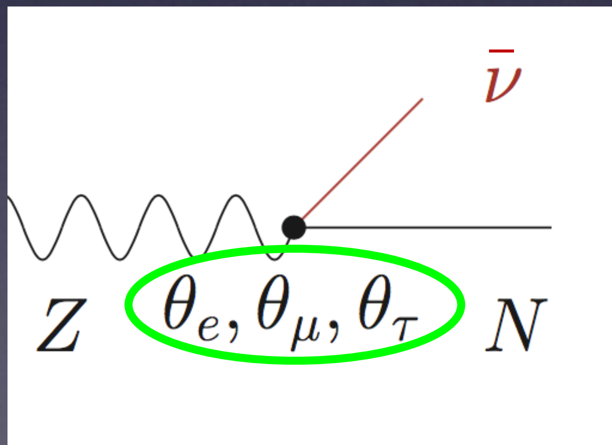
$\Rightarrow$ heavy neutrinos can get produced in weak interaction processes!

Heavy neutrino interactions



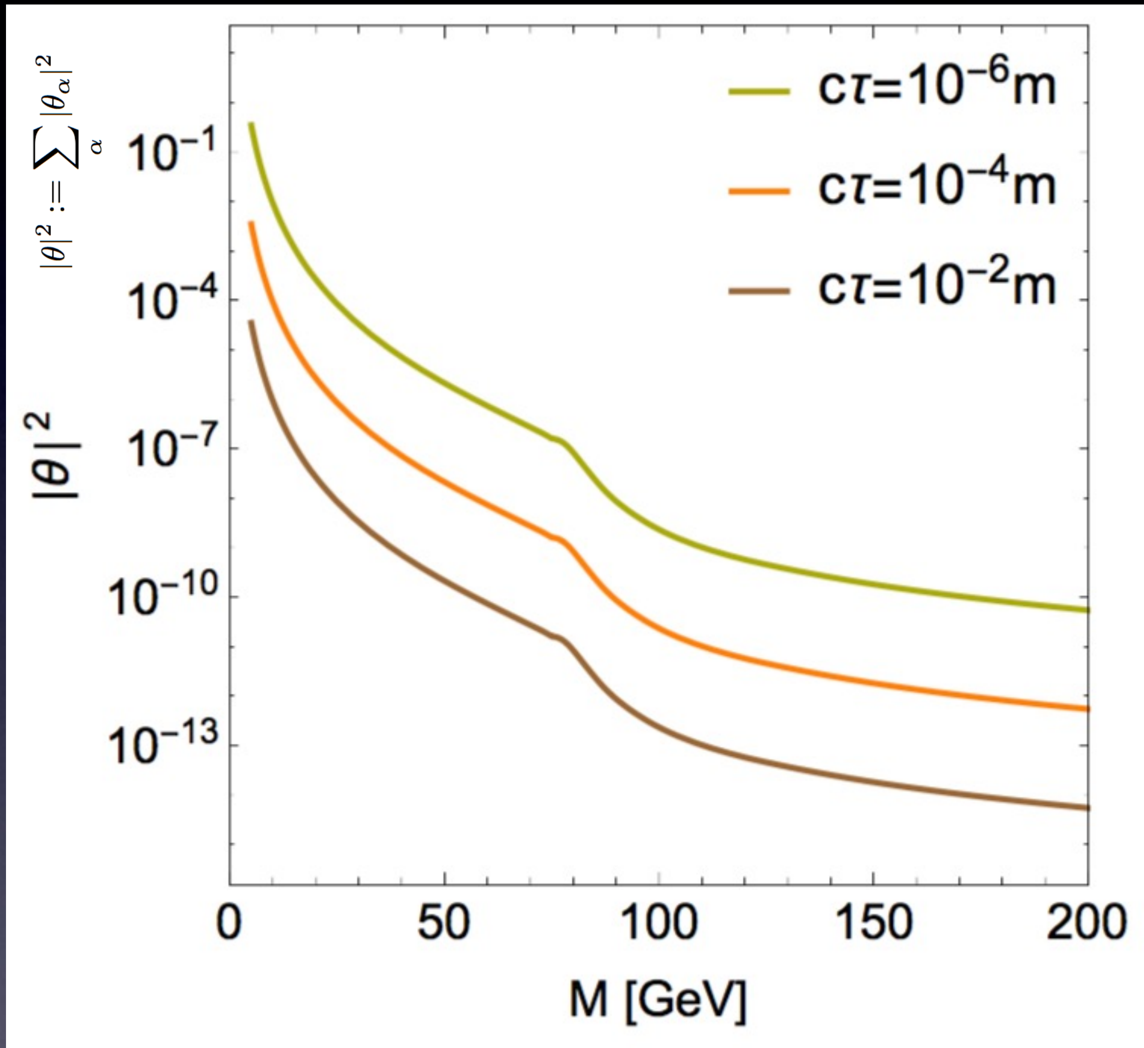


When W bosons are involved, there is a possible sensitivity to the flavour-dependent θ_α



... vertices for production and for decay ...

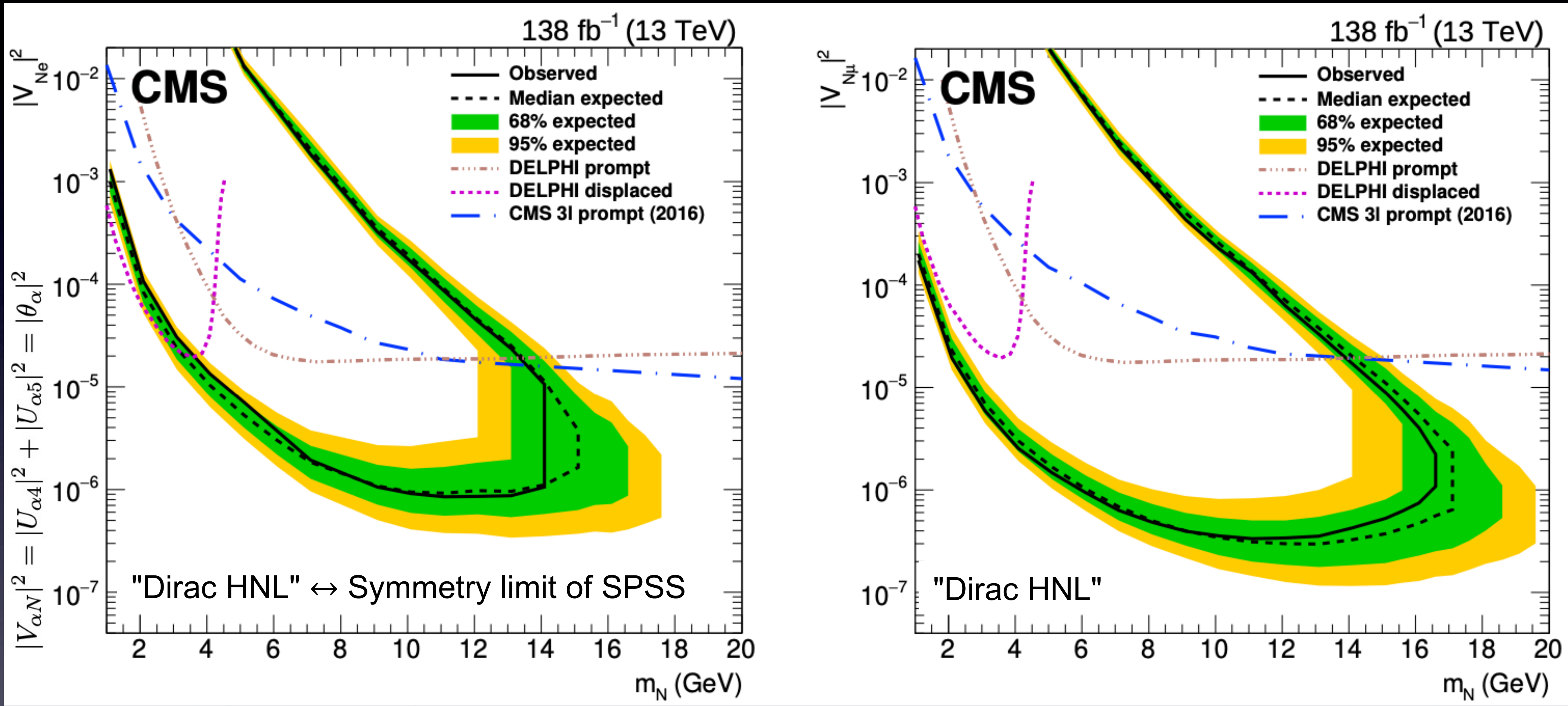
Lifetime and decay length of heavy neutrinos: For M < m_W, they can be long-lived!



cf. S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

Note: Decay length in the laboratory frame is: $c\tau\sqrt{\gamma^2 - 1}$

Current bounds for $M < M_W$ from displaced vertex searches

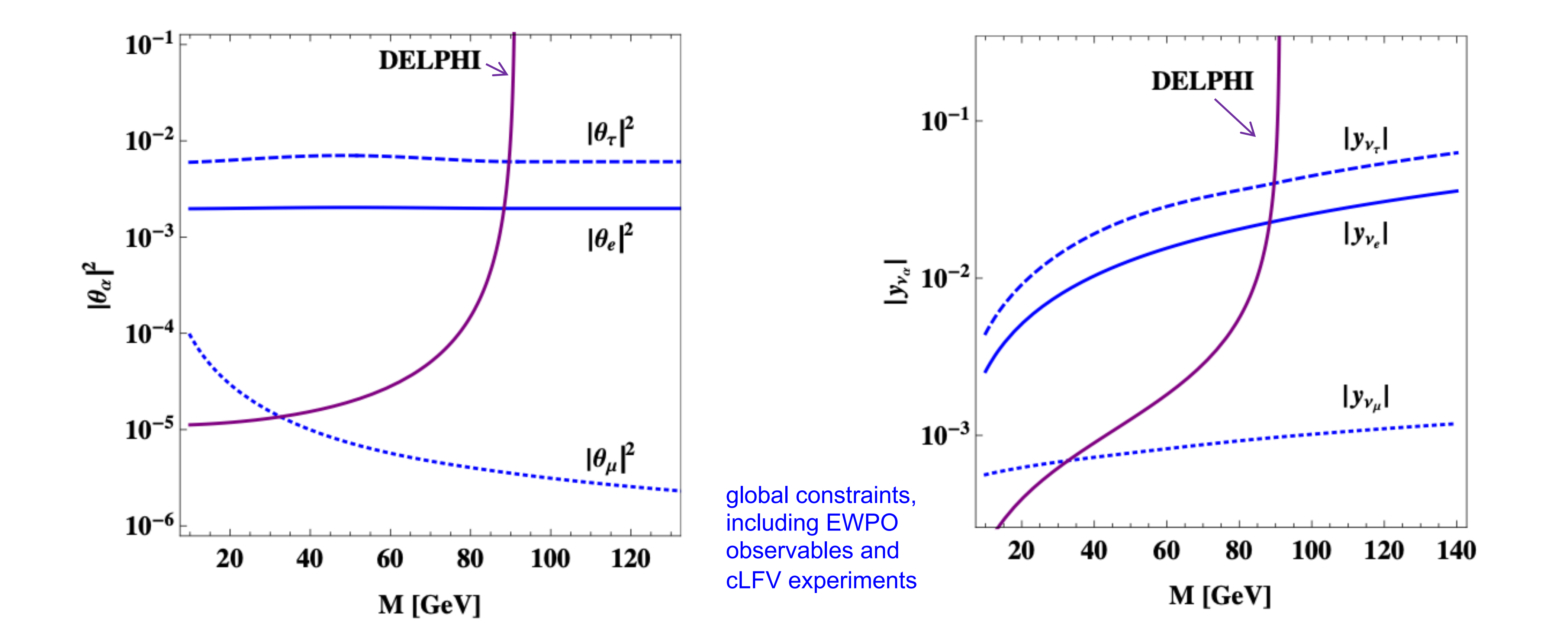


CMS Collaboration
arXiv: 2201.05578

See also bounds from ATLAS: arXiv:1905.09787

... and LHCb analysis arXiv:1612.00945 interpreted for HNLs in: S. A., E. Cazzato, O. Fischer, arXiv:1706.05990

In addition: Constraints from precision experiments (EWPO, cLFV, ...) – also apply to higher M

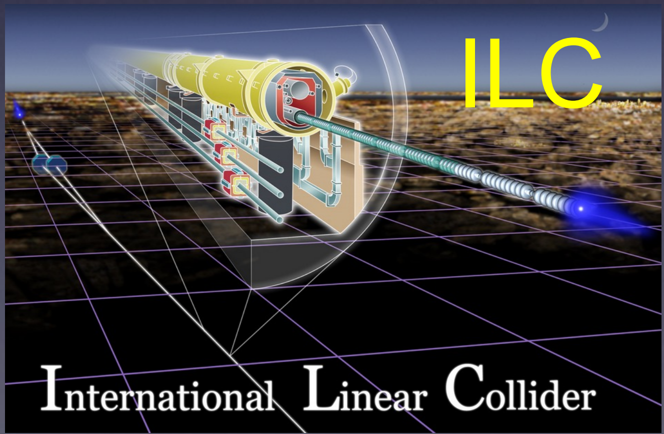


Constraints from global fit (M > 10 GeV): S.A., O. Fischer (arXiv:1502.05915)
For a similar study, see also: E. Fernandez-Martinez, J .Hernandez-Garcia, J. Lopez-Pavon (arXiv:1605.08774)
Constraints for smaller M, see e.g.: M. Drewes, B. Garbrecht (arXiv:1502.00477)

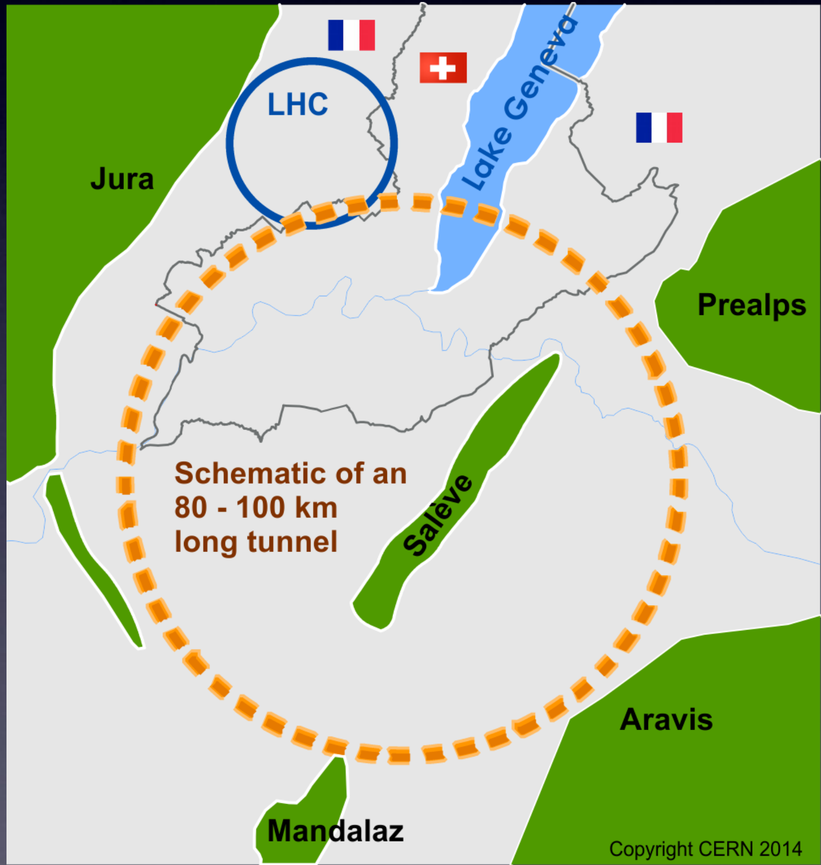
What are the sensitivities for probing HNLs at future collider experiments?

Note: I will consider the SPSS as a benchmark scenario and restrict myself to M > 10 GeV

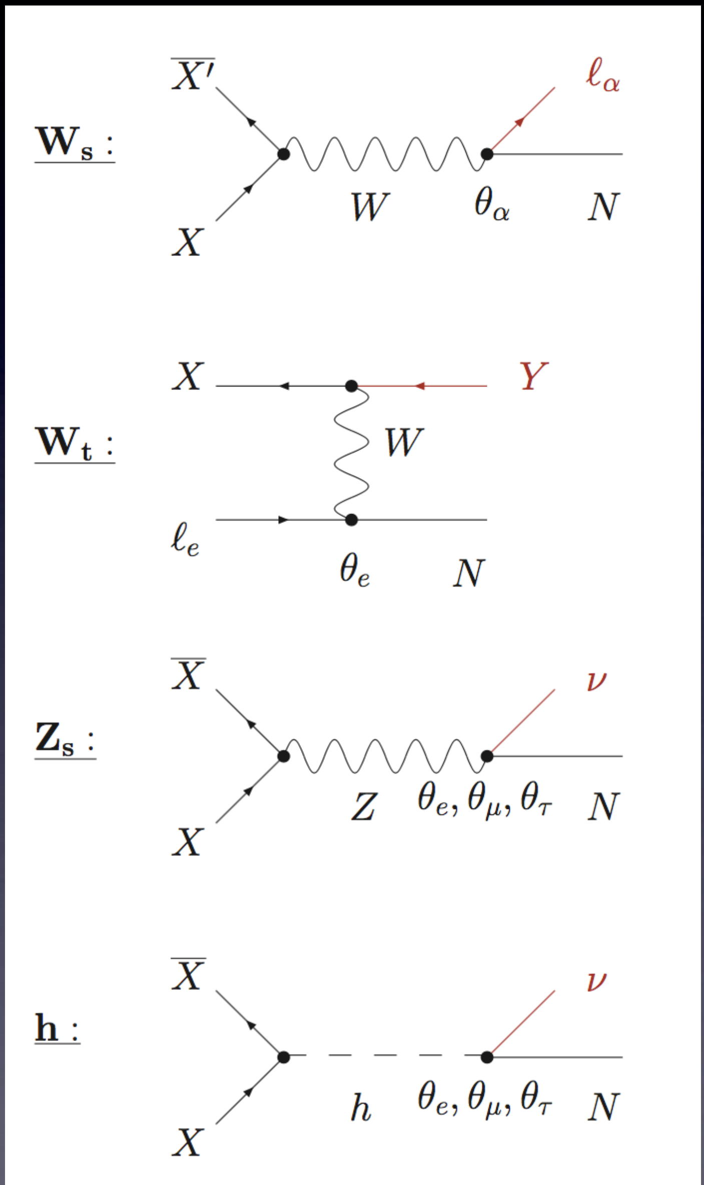
Ambitious concepts for future colliders …
... different collider types: e^+e^-, pp, ep



FCC (-ee, -hh, -eh)



Systematic assessment of HNL signatures at the various collider types



S.A., E. Cazzato, O. Fischer (arXiv:1612.02728),
See also many other works by many authors ...

Different collider types feature different production channels …

(at LO)

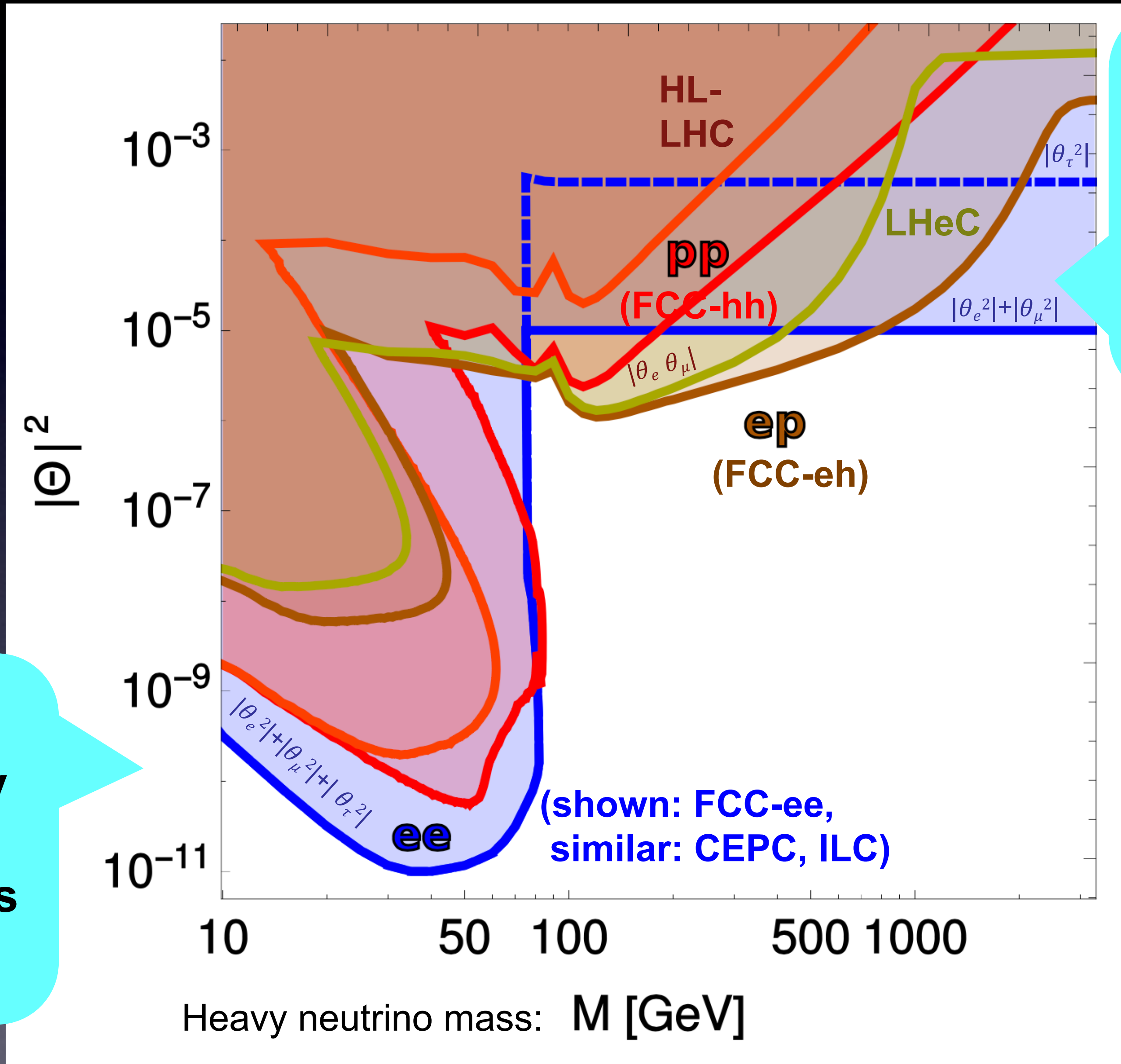
	e^-e^+ *	pp	e^-p
$\mathbf{W_s}$	$\times$	$\checkmark$+LNV/LFV	$\times$
$\mathbf{W_t}$	$\checkmark$	$\times$	$\checkmark$ +LNV/LFV *
$\mathbf{Z_s}$	$\checkmark$	$\checkmark$	$\times$
$\mathbf{h}$	$(\checkmark)$	$(\checkmark)$	$(\checkmark)$

... helps a lot to suppress SM background!

*) unambiguous (i.e. clear from final state), no SM background at parton level (but of course background with e.g. extra neutrinos)

**) LNV signatures also possible at e+e- colliders, but there only show up in final state angular distributions

Summary: Estimated sensitivities at future ee, pp and ep colliders



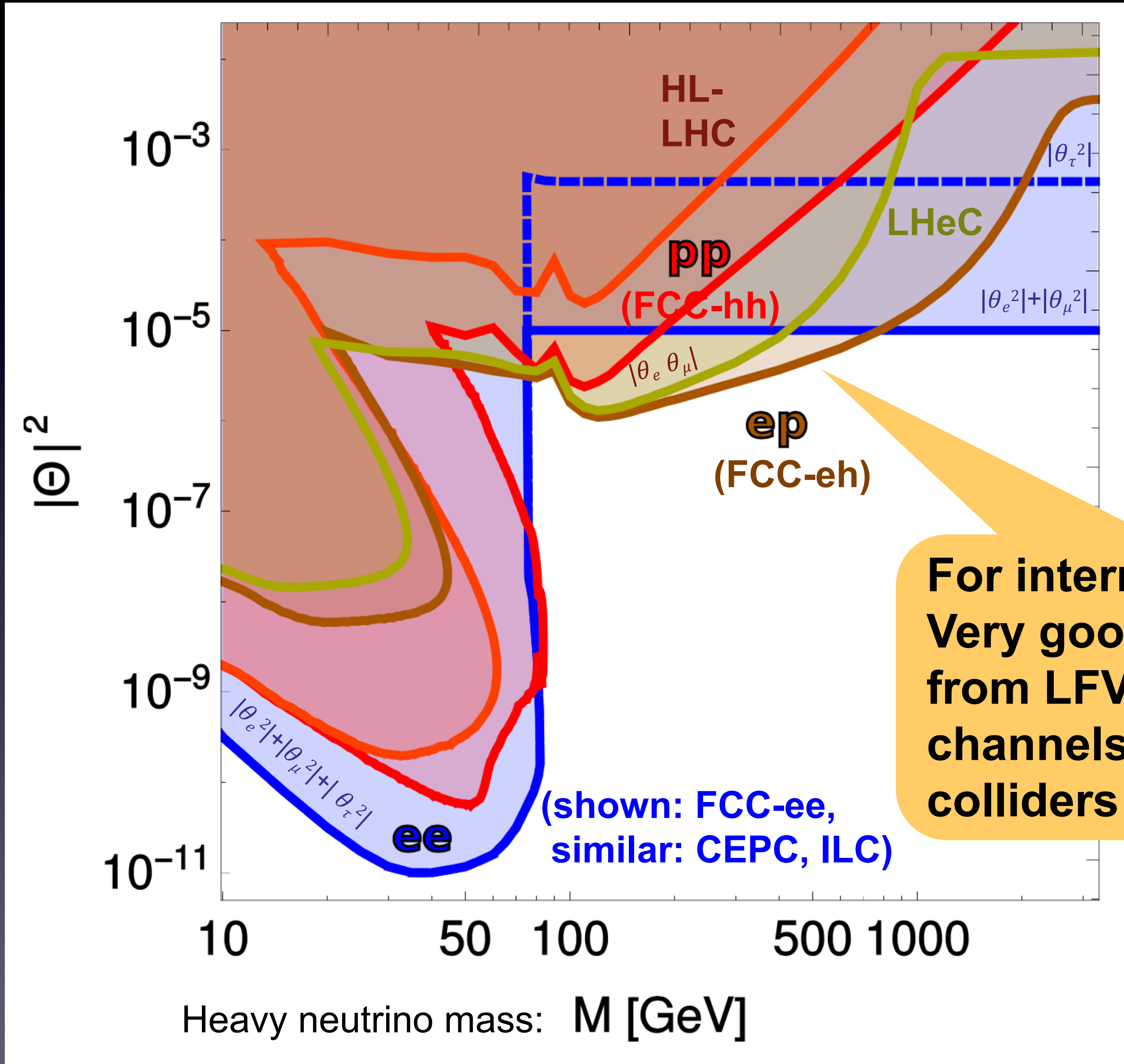
For M >> O(TeV): Very good sensitivity from EWPO measurements at FCC-ee

For M < m_W: Best sensitivity from displaced vertex searches at FCC-ee

Also, future exp. on: $\mu \to e\gamma, \mu \to 3e$, $\mu - e$ conversion in nuclei very sensitive!

Plot from: S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

Summary: Estimated sensitivities at future ee, pp and ep colliders



Note: Sensitivity to different combinations of active-sterile mixing angles!

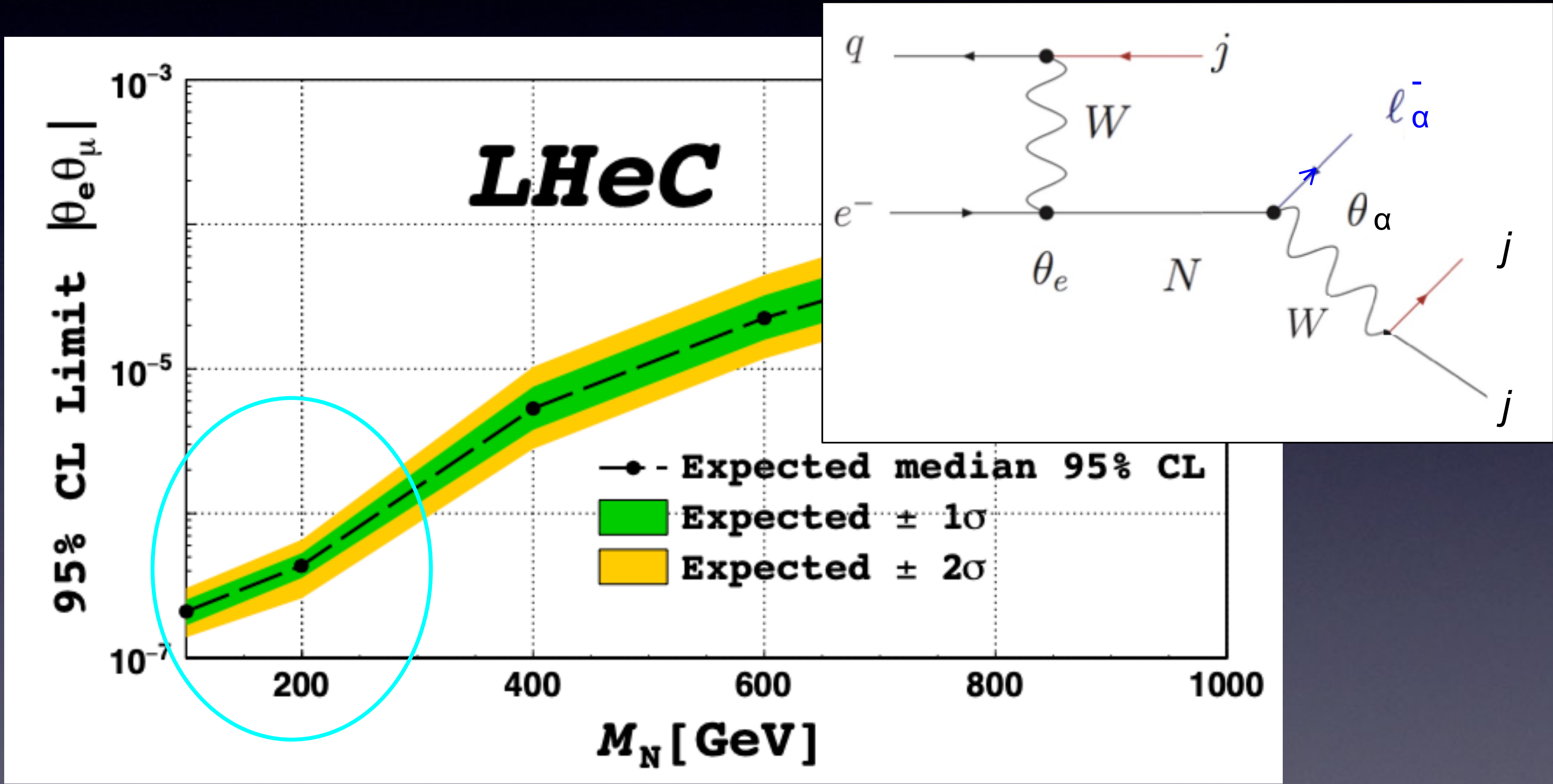
Plot from: S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

Sensitivity of lepton-trijet searches at ep colliders

update!

LFV lepton-trijet signature at LHeC and FCC-eh:
Sensitivity from analysis at the reconstructed level

"lepton-trijet" signature at ep colliders (LHeC, FCC-eh) $l_\alpha^- jjj$ with e.g. $\alpha = \tau^-$ or μ^-



Extremely sensitive!

LHeC with 1 ab^{-1}

S.A., A. Hammad, O. Fischer (arXiv:1908.02852)

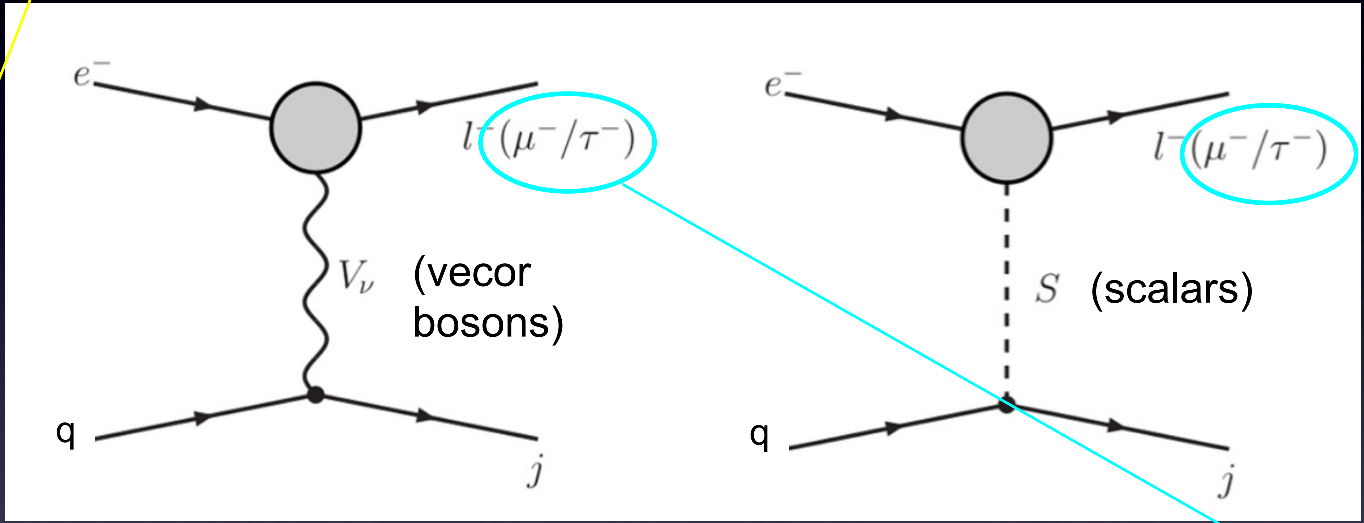
In addition, as we found out recently:
LFV at ep colliders can also probe HNLs with much larger masses!

Novel signature: cLFV from effective e-μ and e-τ conversion operators at LHeC/FCC-eh

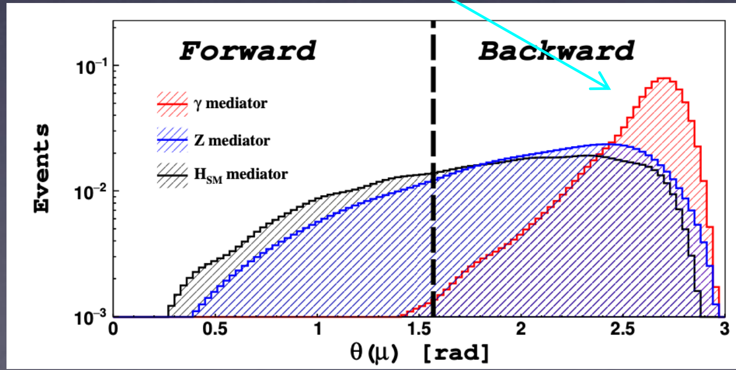
cLFV searches via e-μ and e-τ conversion at ep colliders

S.A., A. Hammad, A. Rashed (arXiv:2010.08907)

Effective description:



Scattered dominantly in backward direction of the detector!



Effective operators:

$$\mathcal{L}_{\rm eff}^{\rm scalar} = \bar{\ell}_\alpha P_{L,R} \ell_\beta S\ N_{L,R}$$

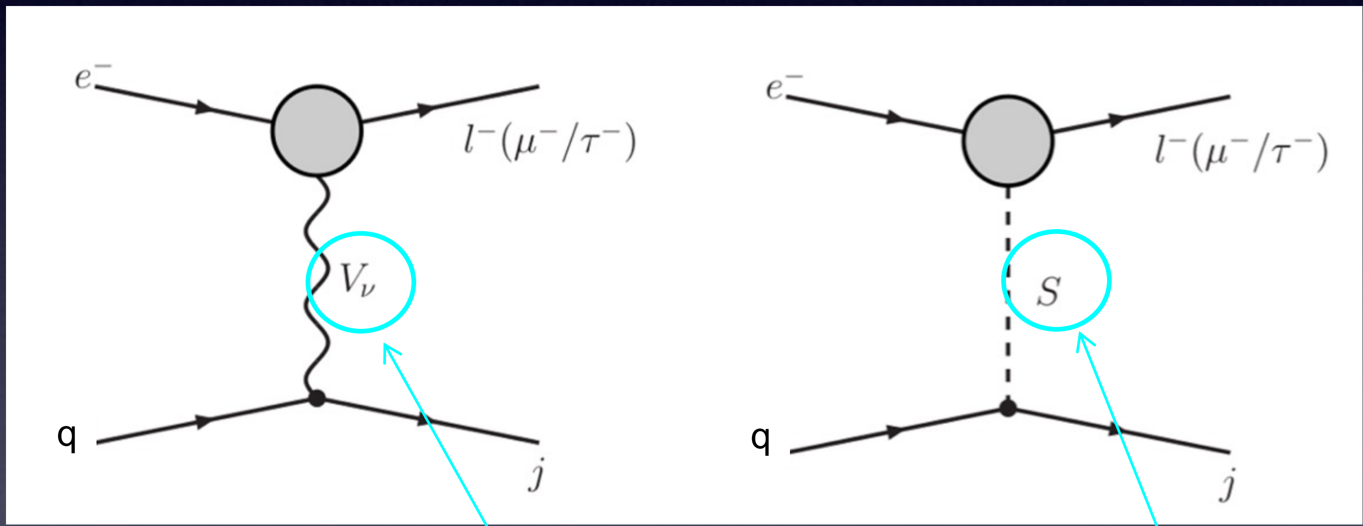
$$\mathcal{L}_{\rm eff}^{\rm monopole} = \bar{\ell}_\alpha \gamma_\mu P_{L,R} \ell_\beta \left[A_{L,R}\ g^{\mu\nu} + B_{L,R}(g^{\mu\nu} q^2 - q^\mu q^\nu) \right] V_\nu$$

$$\mathcal{L}_{\rm eff}^{\rm dipole} = \bar{\ell}_\alpha \sigma^{\mu\nu} P_{L,R} \ell_\beta\ q_\mu V_\nu\ D_{L,R},$$

cLFV searches via e-μ and e-τ conversion at ep colliders

S.A., A. Hammad, A. Rashed (arXiv:2010.08907)

Effective description:



Can probe new vector bosons (e.g. LFV via Z') or scalars ...

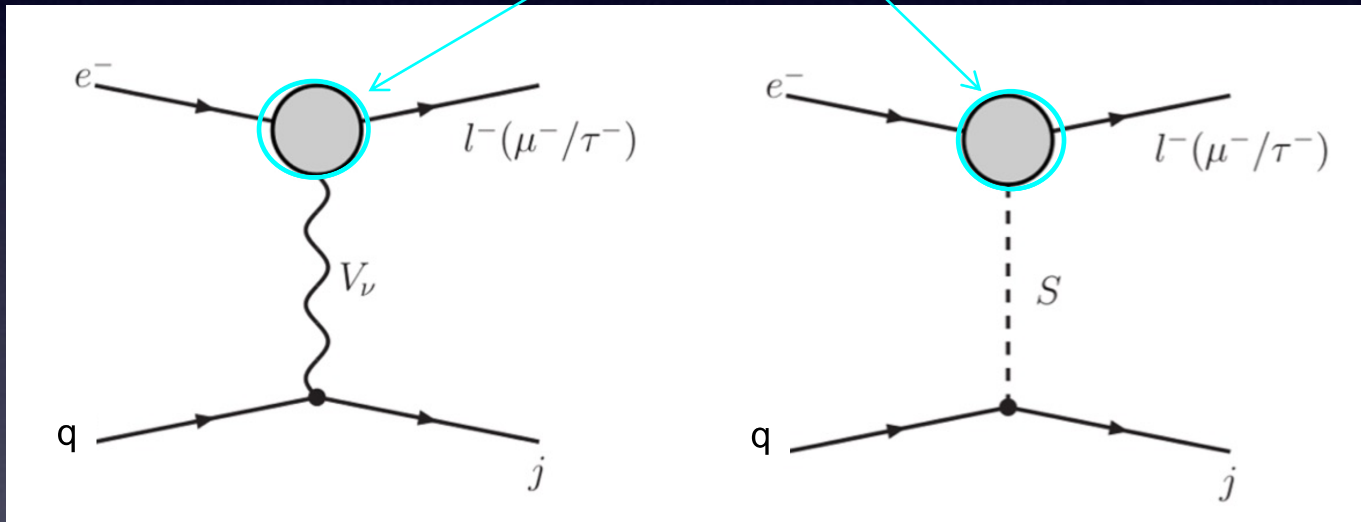
S.A., A. Hammad, A. Rashed (arXiv:2003.11091)

cLFV searches via e-μ and e-τ conversion at ep colliders

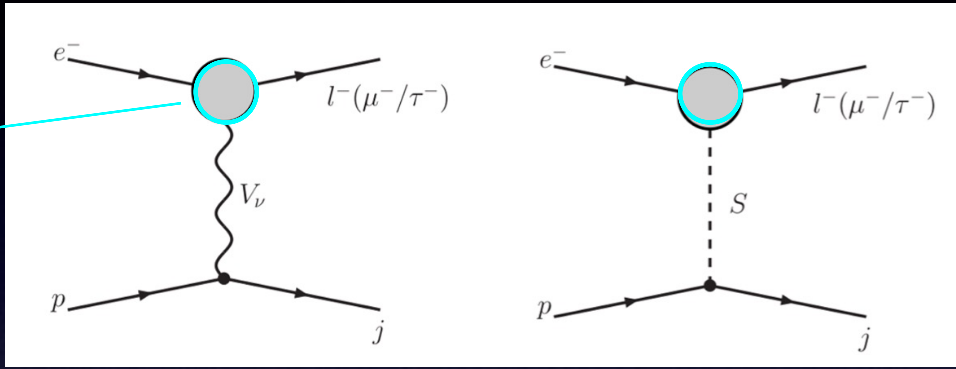
S.A., A. Hammad, A. Rashed (arXiv:2010.08907)

Can probe effective FCNC vertices (here V = γ,Z, S = h)

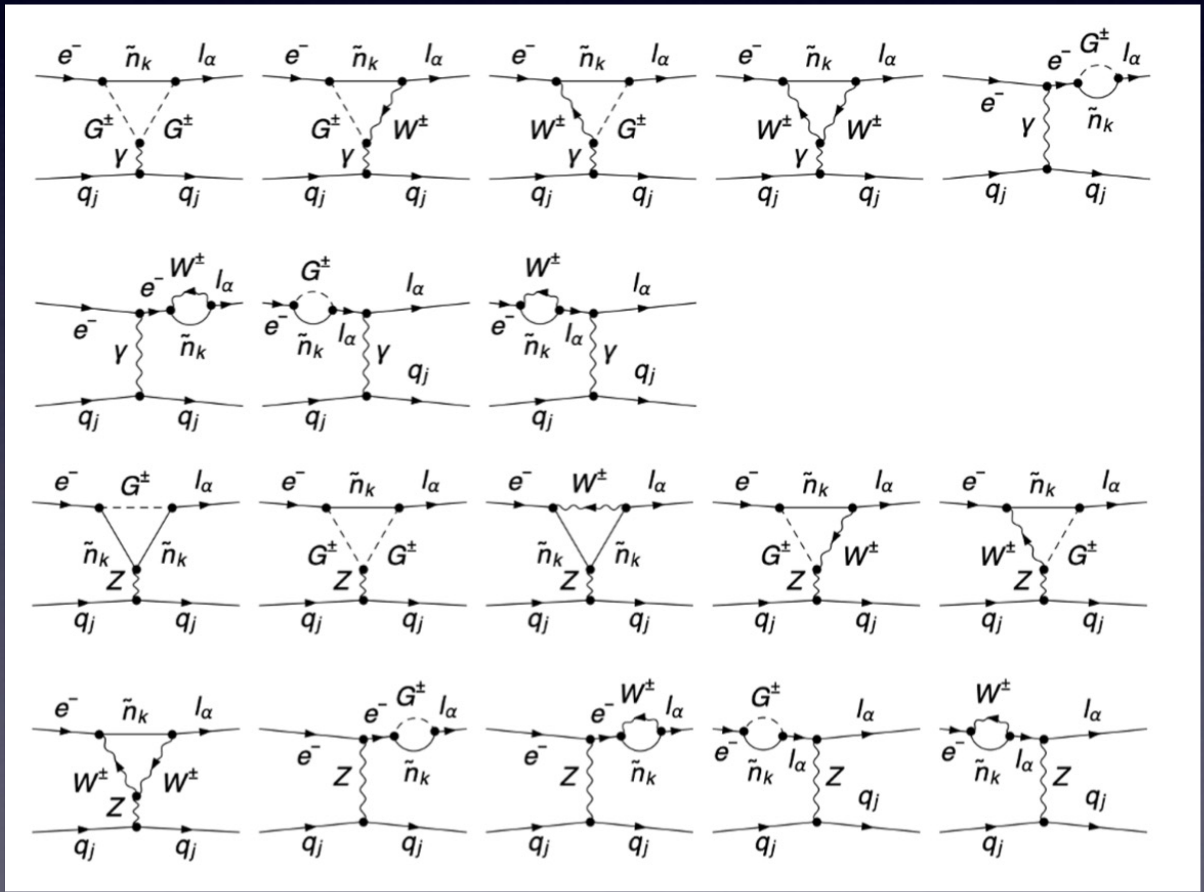
Effective description:



cLFV searches via e-μ and e-τ conversion at ep colliders

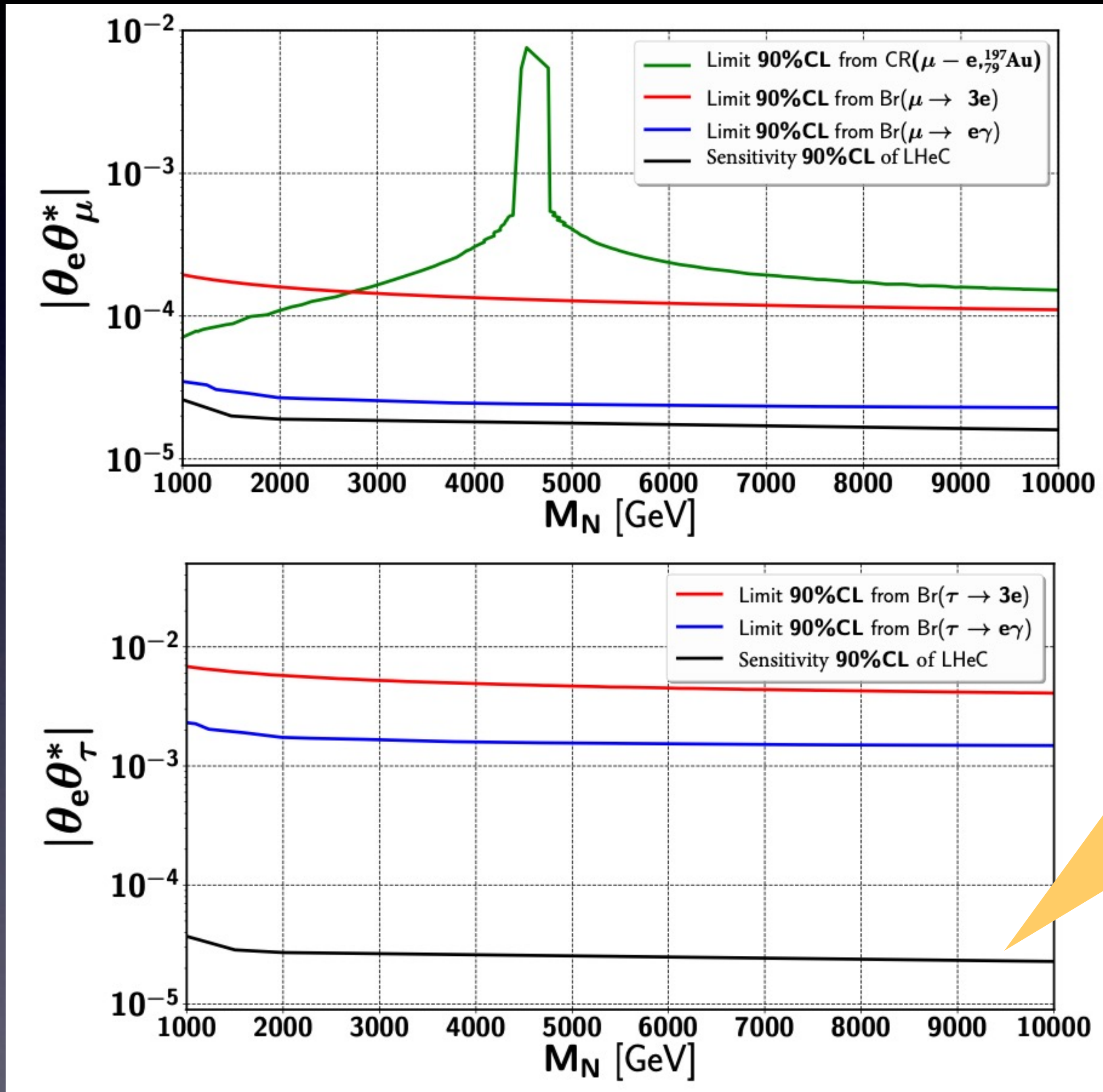


In the SM extended by HNLs:



S.A., A. Hammad, A. Rashed (arXiv:2010.08907)

Sensitivity at LHeC for HNLs with masses far above M_W via e-μ and e-τ conversion



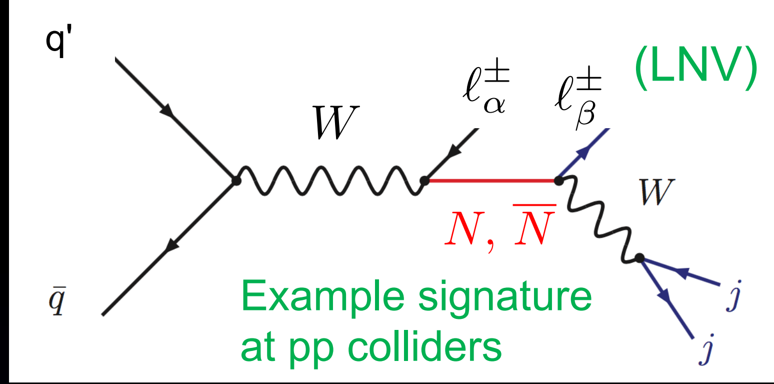
LHeC with 3 ab^{-1}

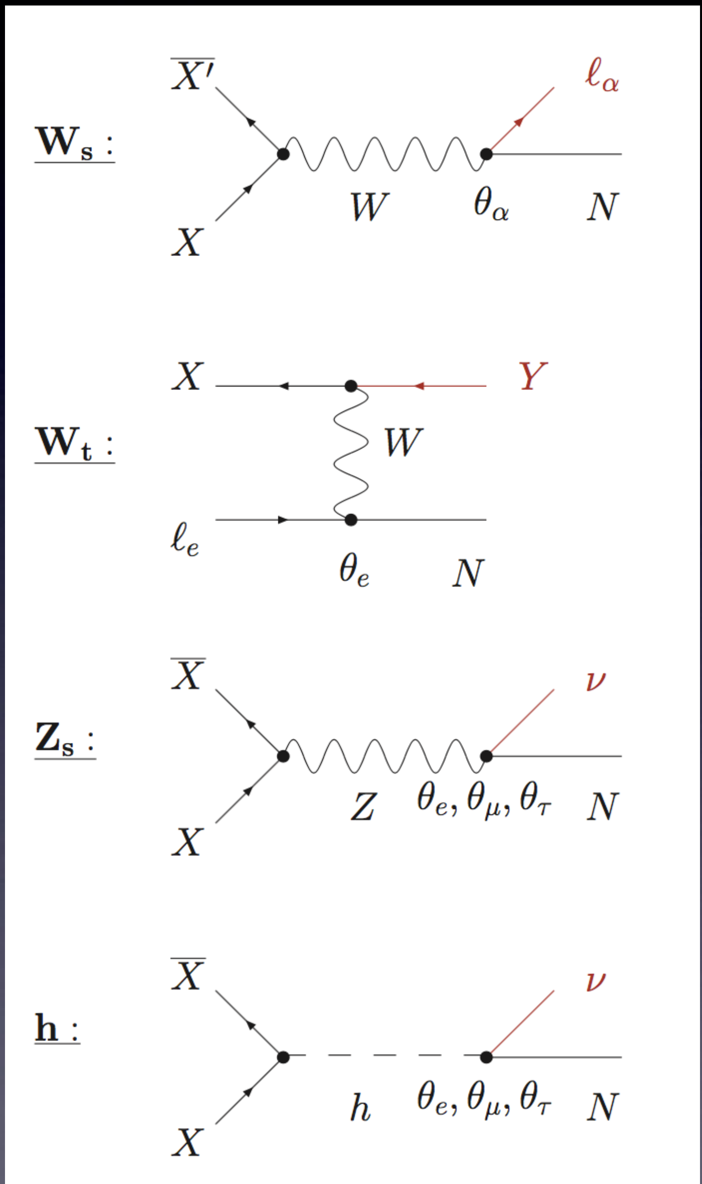
To my knowledge, this search channel could yield the best sensitivity to e-τ cLFV (among the currenlty envisioned experiments)!

S.A., A. Hammad, A. Rashed (arXiv:2010.08907)

Beyond the "L-like"-symmetry limit:
Can we observe LNV from the HNLs
(required to generate light m_ν)?

LNV signatures?





**) LNV signatures also possible, but only show up in final state angular distributions

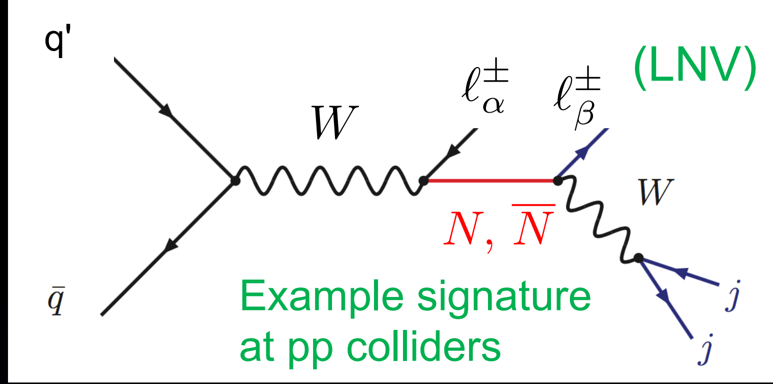
	e^-e^+ *	pp	e^-p
$\mathbf{W_s}$	$\times$	$\checkmark$ +LNV/LFV	$\times$
$\mathbf{W_t}$	$\checkmark$	$\times$	$\checkmark$ +LNV/LFV
$\mathbf{Z_s}$	$\checkmark$	$\checkmark$	$\times$
$\mathbf{h}$	$(\checkmark)$	$(\checkmark)$	$(\checkmark)$

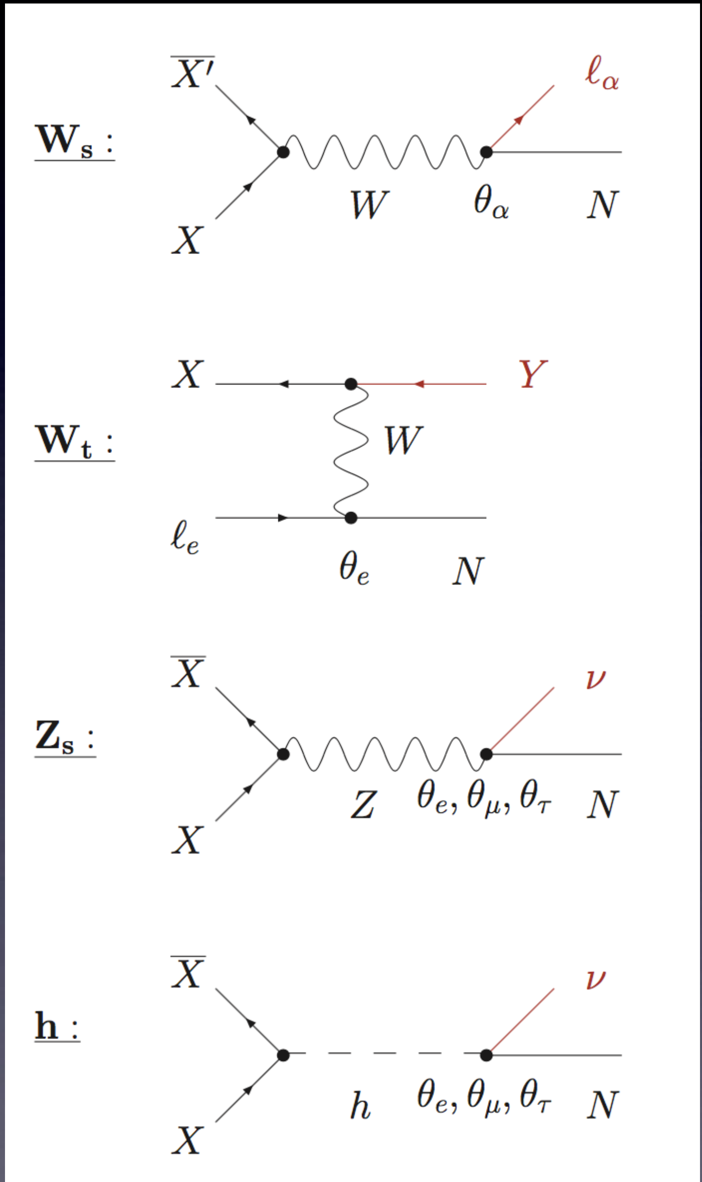
(at LO)

<u>Lepton-number violating (LNV) signatures</u> possible (with no SM background at parton level) <u>but expected to be strongly suppressed</u> by the (approximate) protective "lepton number"-like symmetry!

See e.g. discussion in Kersten, Smirnov (2007)
→ LNV from neutrino mass generation not observable at LHC

LNV signatures





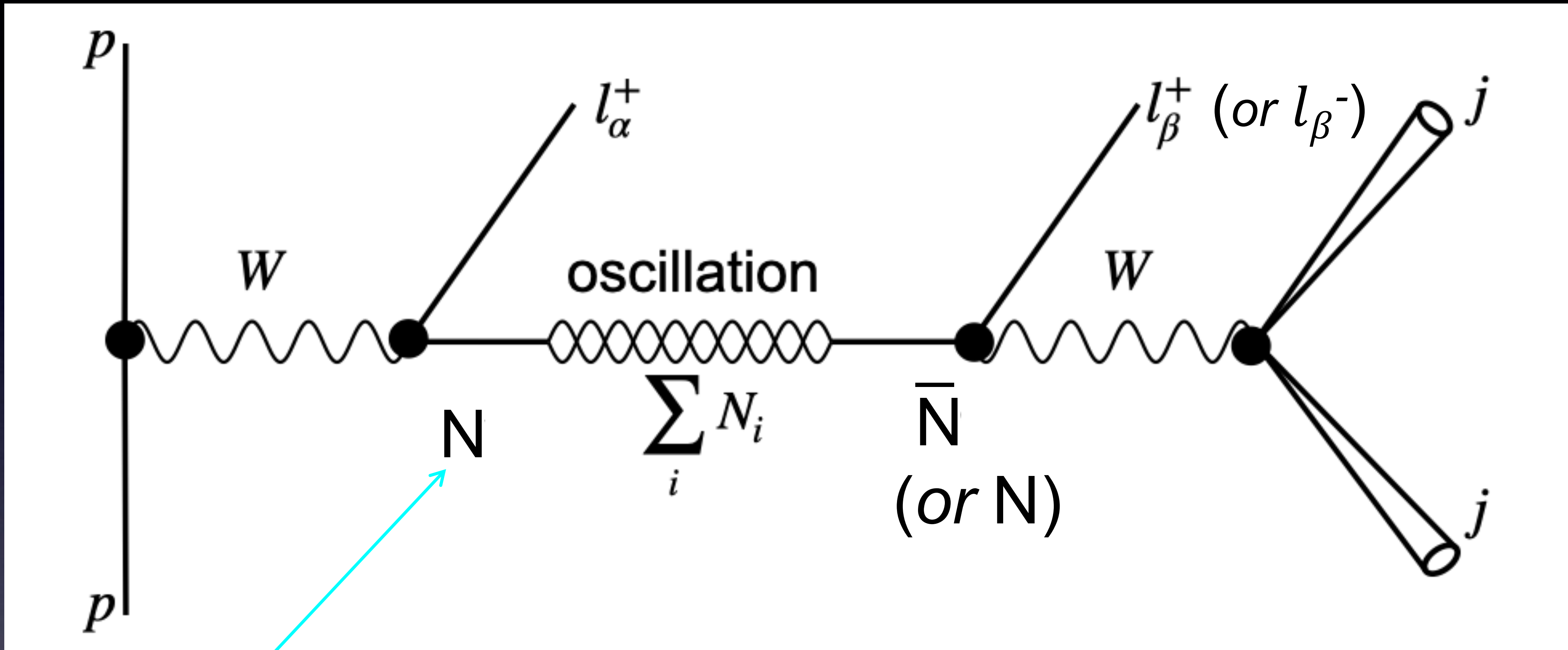
**) LNV also possible, but requires measuring final state distributions

	e^-e^+ *	pp	e^-p
$\mathbf{W_s}$	$\times$	$\checkmark$+LNV/LFV	$\times$
$\mathbf{W_t}$	$\checkmark$	$\times$	$\checkmark$+LNV/LFV
$\mathbf{Z_s}$	$\checkmark$	$\checkmark$	$\times$
$\mathbf{h}$	($\checkmark$)	($\checkmark$)	($\checkmark$)

(at LO)

Statement not entirely valid when one takes into account the possibility of <u>Heavy Neutrino-Antineutrino Oscillations!</u>

Heavy Neutrino-Antineutrino Oscillations

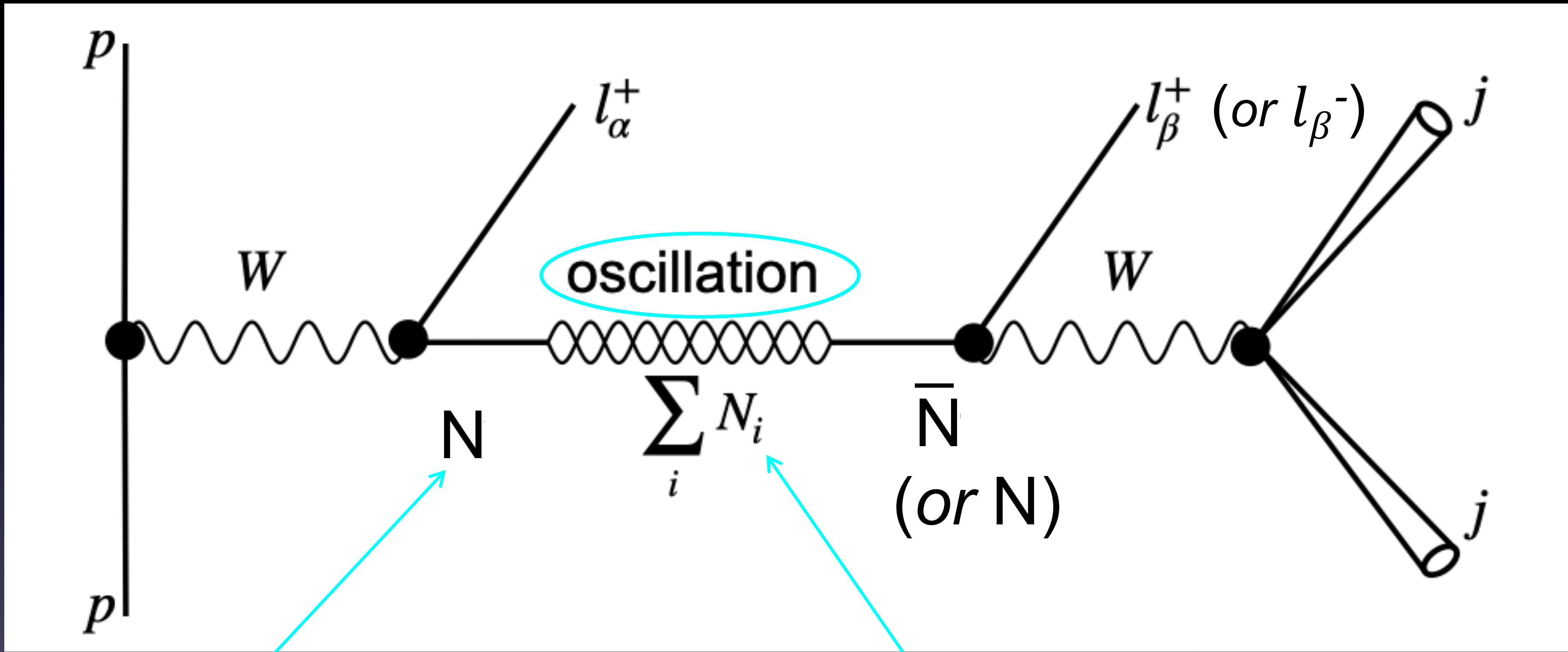


Interaction states: Produced from W decay
- "Heavy Neutrinos N" (together with l_α^+)
- "Heavy Antineutrinos $\overline{\text{N}}$" (together with l_α^-)

They are superpositions of the mass eigenstates:

$$\overline{N} = 1/\sqrt{2}(iN_4 + N_5) \quad N = 1/\sqrt{2}(-iN_4 + N_5)$$

Heavy Neutrino-Antineutrino Oscillations



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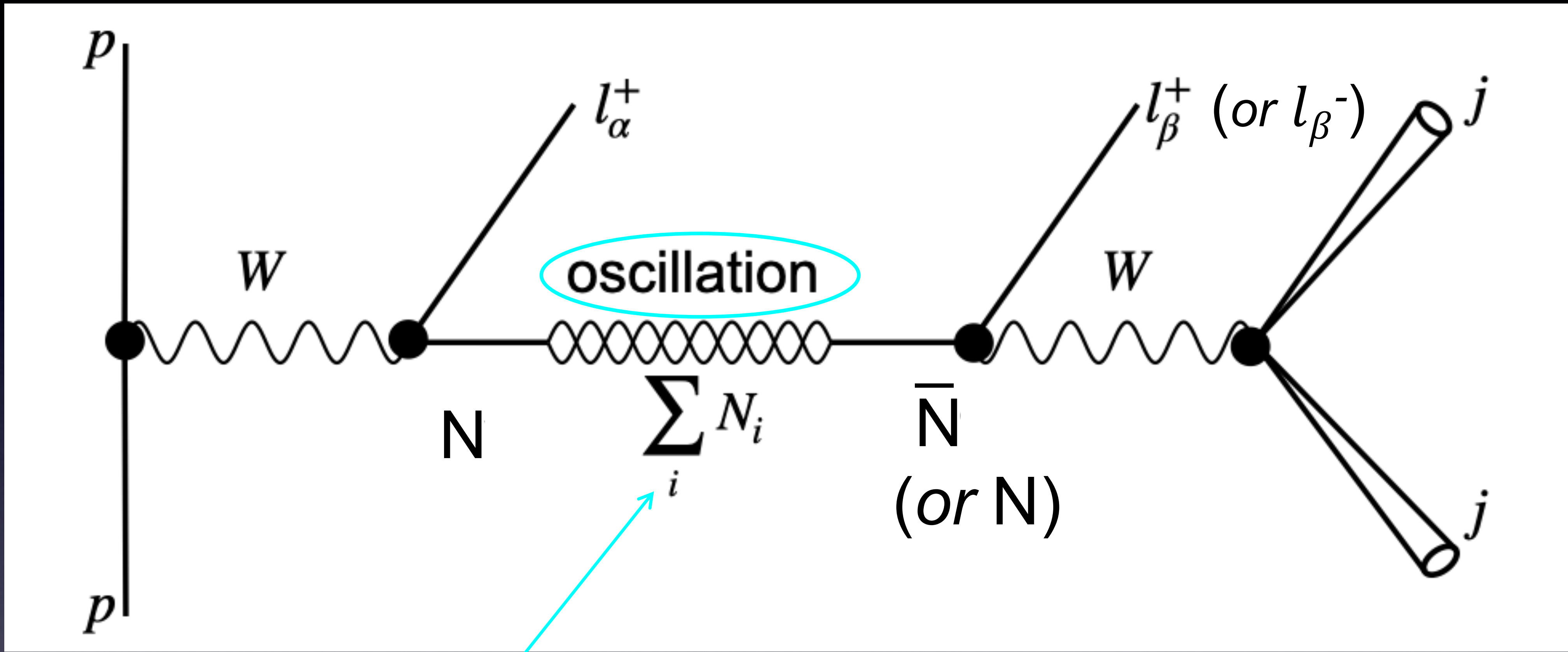
Due to the O(ε) perturbations to generate the light neutrino masses: → **mass splitting ΔM** between the heavy mass eigenstates N_4 and N_5
→ propagation of interfering mass eigenstates induces oscillations between $\overline{\text{N}}$ and N

Heavy Neutrino-Antineutrino Oscillations

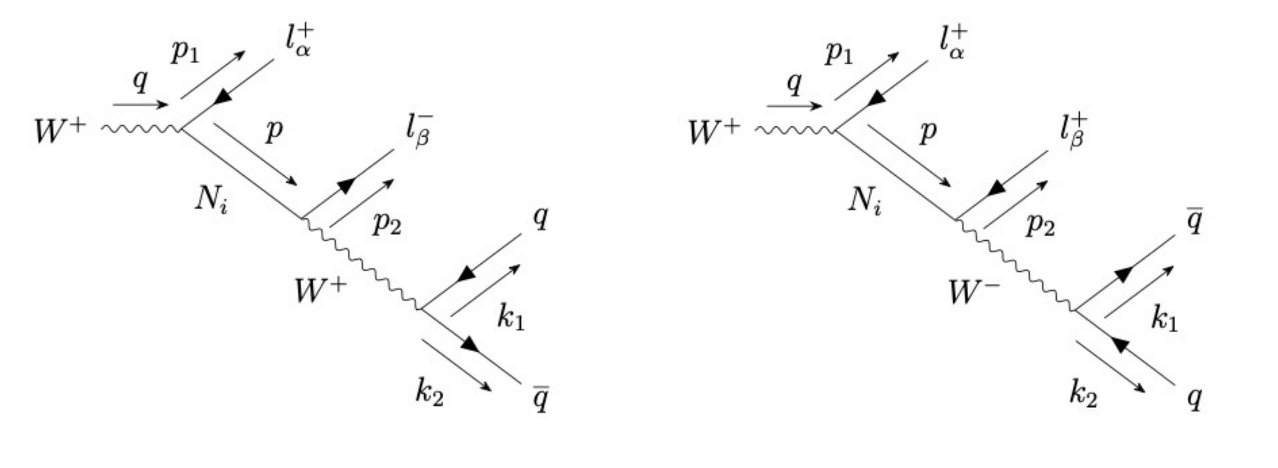


Due to the O(ε) perturbations to generate the light neutrino masses: → **mass splitting ΔM** between the heavy mass eigenstates N_4 and N_5 → propagating mass eigenstates induce **oscillations between N and $\bar{\text{N}}$**

Since an N decays into a l_α^- and a $\bar{\text{N}}$ into a l_α^+, the Heavy Neutrino-Antineutrino Oscillations lead to an **oscillation between LNC and LNV final states**, as a function of the oscillation time (or travelled distance)

We recently studied the Heavy Neutrino-Antineutrino Oscillations in QFT ...

Study in QFT (using the formlism of external wave packets [cf. Beuthe 2001])



(a) Feynman diagram for the LNC process (b) Feynman diagram for the LNV process

$$\mathcal{A} = \langle f | \hat{T}\left(\exp\left(-i \int \mathrm{d}^4x \, \mathcal{H}_I \right) \right) - \mathbf{1} \, | i \rangle$$

→ Full oscillation formulae

Oscillation formulae in the SPSS (with ε-perturbations, in an expansion):

Oscillation probability

$$P_{\alpha\beta}^{LNV}(L) = \frac{1}{2\sum_\beta |\theta_\alpha|^2|\theta_\beta|^2} \Big(|\theta_\alpha|^2|\theta_\beta|^2(1-\cos(\phi_{45}L)) \quad \leftarrow \text{LO}$$

$$- 2(I_\beta|\theta_\alpha|^2 + I_\alpha|\theta_\beta|^2)\sin(\phi_{45}L) \Big) , \quad \leftarrow \text{NLO}$$

Survival probability

$$P_{\alpha\beta}^{LNC}(L) = \frac{1}{2\sum_\beta |\theta_\alpha|^2|\theta_\beta|^2} \Big(|\theta_\alpha|^2|\theta_\beta|^2(1+\cos(\phi_{45}L)) \quad \leftarrow \text{LO}$$

$$- 2(I_\beta|\theta_\alpha|^2 - I_\alpha|\theta_\beta|^2)\sin(\phi_{45}L) \Big) . \quad \leftarrow \text{NLO}$$

where

$$I_\beta := \mathrm{Im}(\theta_\beta^* \theta'_\beta \exp(-2i\Phi)) ,$$

$$\phi_{ij} := -\frac{2\pi}{L_{ij}^{osc}} = -\frac{M_i^2 - M_j^2}{2|\mathbf{p}_0|} ,$$

$$\Phi := \frac{1}{2}\mathrm{Arg}\left(\vec{\theta}' \cdot \vec{\theta}^* \right) .$$

S.A., J. Rosskopp (arXiv:2012.05763)

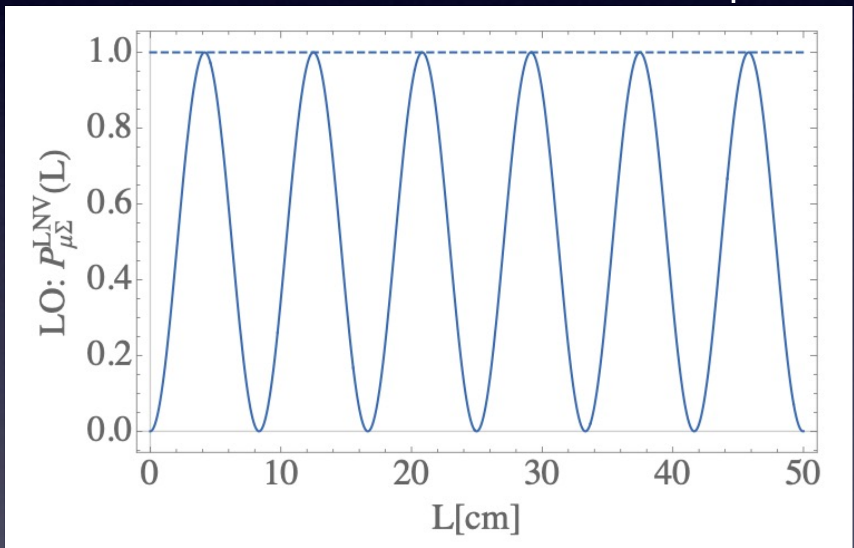
We recently studied the Heavy Neutrino-Antineutrino Oscillations in QFT ...

$$P^{LNV}_{\alpha\beta}(L) = \frac{1}{2\sum_\beta |\theta_\alpha|^2|\theta_\beta|^2}\Big(|\theta_\alpha|^2|\theta_\beta|^2(1-\cos(\phi_{45}L)) - 2(I_\beta|\theta_\alpha|^2 + I_\alpha|\theta_\beta|^2)\sin(\phi_{45}L)\Big)\,,$$

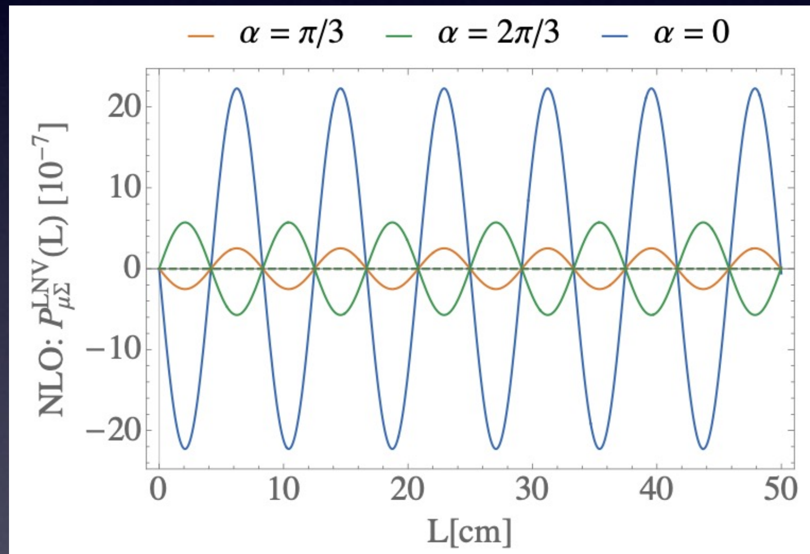
$$P^{LNC}_{\alpha\beta}(L) = \frac{1}{2\sum_\beta |\theta_\alpha|^2|\theta_\beta|^2}\Big(|\theta_\alpha|^2|\theta_\beta|^2(1+\cos(\phi_{45}L)) - 2(I_\beta|\theta_\alpha|^2 - I_\alpha|\theta_\beta|^2)\sin(\phi_{45}L)\Big)\,.$$

(*) "Minimal linear seesaw" with IH, M = 7 GeV, $|\theta^2|$ = 10^{-5}, γ = 50 (fixed)

LO: ... for some chosen benchmark point*



NLO:



NLO effects are "flavour oscillations" ... oscillations remain when summing LNC+LNV

... they go to 0 when *additionally* summing over all outgoing flavours

$$P^{LNC}_{\alpha\beta}(L) + P^{LNV}_{\alpha\beta}(L) = \frac{1}{\sum_\beta |\theta_\alpha|^2|\theta_\beta|^2}\Big(|\theta_\alpha|^2|\theta_\beta|^2 - 2I_\beta|\theta_\alpha|^2\sin(\phi_{45}L)\Big)$$

S.A., J. Rosskopp (arXiv:2012.05763)

We recently studied the Heavy Neutrino-Antineutrino Oscillations in QFT ...

In summary:

- We confirmed the LO formulae used in previous works.
  See e.g.: G. Anamiati, M. Hirsch and E. Nardi (2016), G. Cvetic, C. S. Kim, R. Kogerler and J. Zamora-Saa (2015), ... (see also Refs in arXiv:2012.05763 for other works)

- We showed that in the SPSS + ε-terms, only ΔM (in addition to θ_α and M) is relevant for describing the oscillations at LO
  → Proposal of the SPSSΔM (i.e. the SPSS plus only ΔM as additional parameter) as suitable benchmark scenario

- We carefully discussed how the "observability conditions" can be checked (such as e.g. if coherence is maintained, etc.)
  → satisfied for the considered parameter point

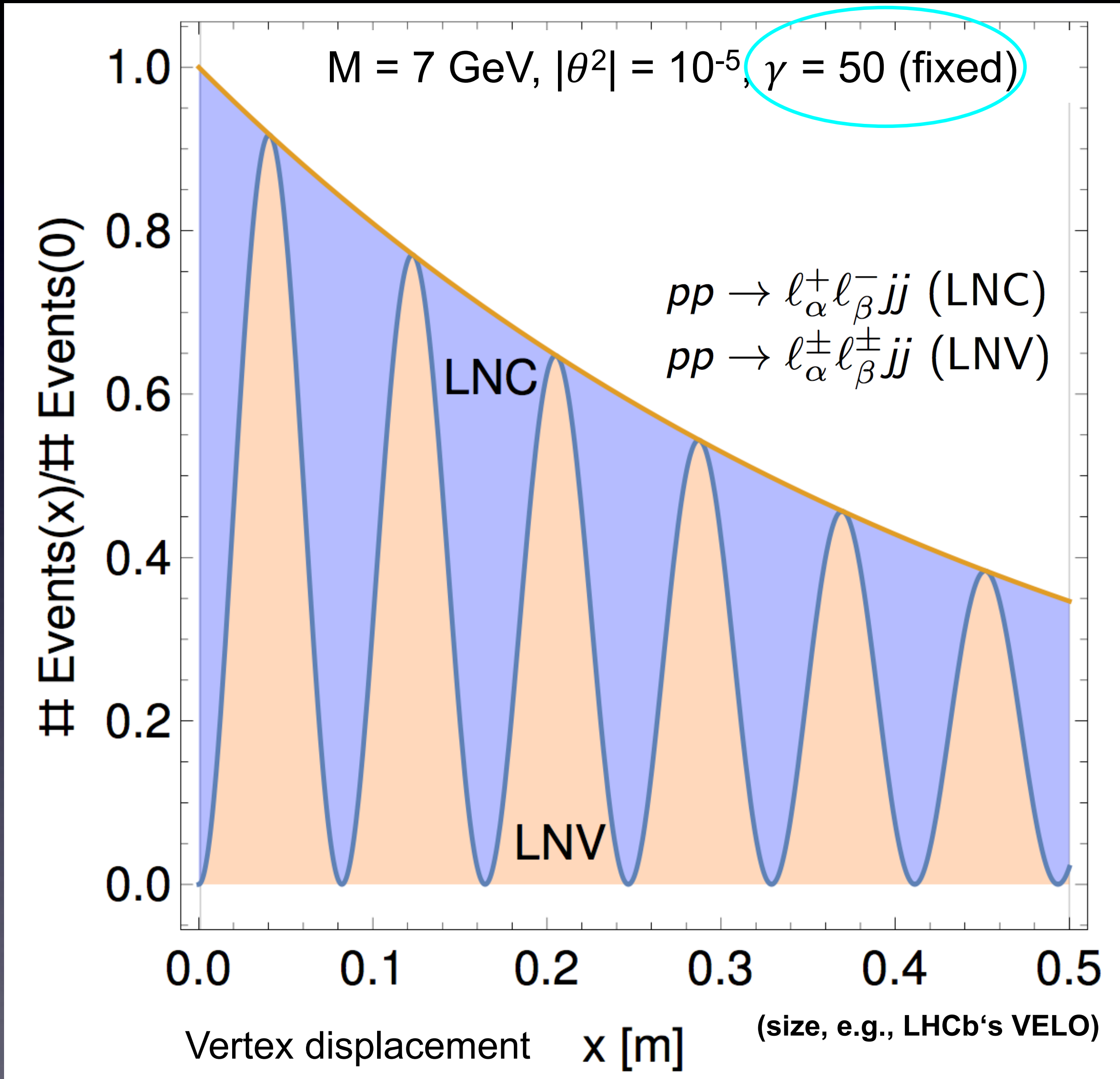
- We discussed the NLO effects (i.e. the flavour oscillations) and showed that for the considered benchmark point they are tiny.

S.A., J. Rosskopp (arXiv:2012.05763)

Signal: Oscillating fraction of LNV / LNC decays with lifetime (→ displacement)

Example:

→ using the prediction for ΔM in the "Minimal linear seesaw" model with inverse neutrino mass hierarchy (IH)

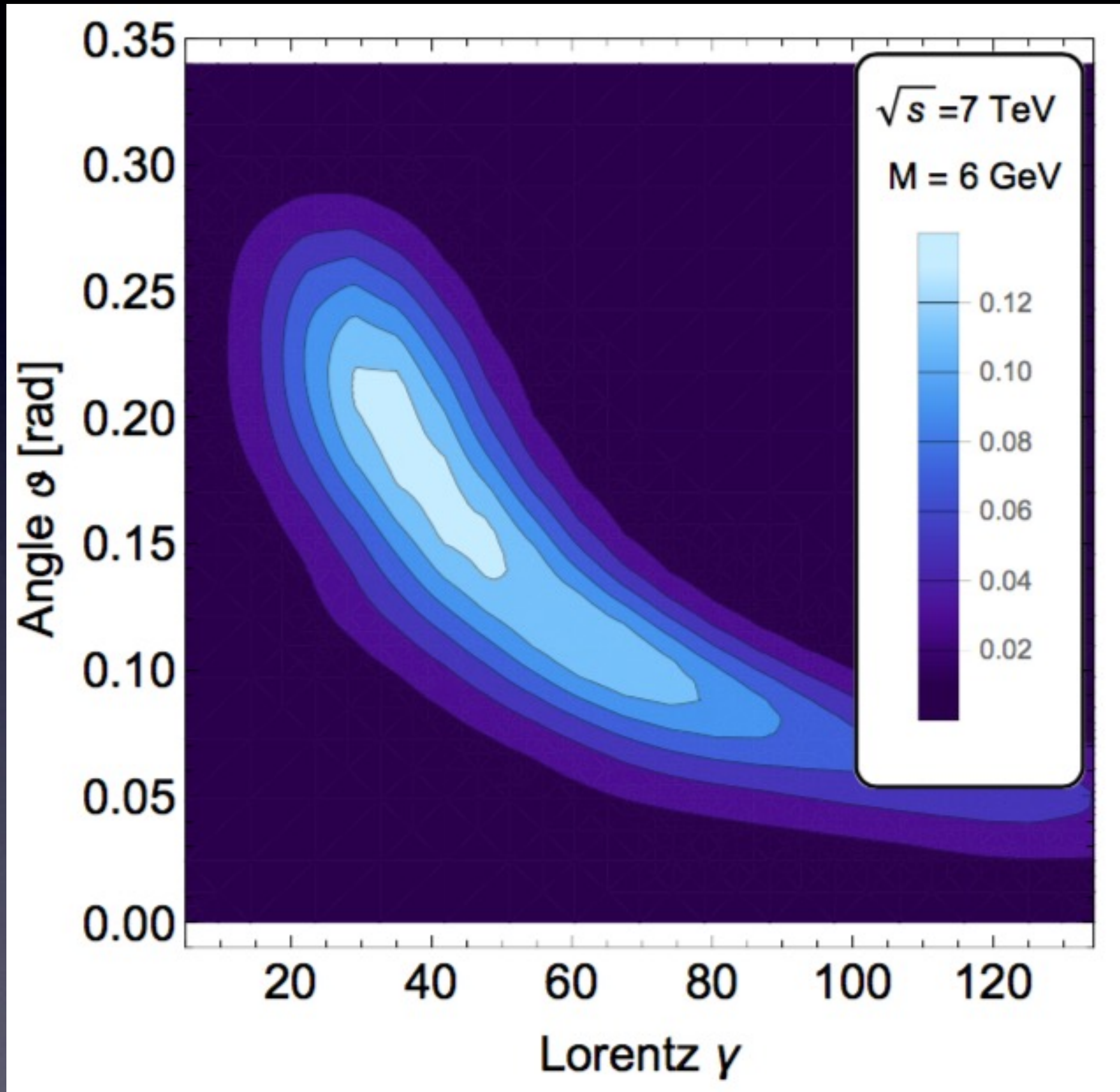


For this plot: fixed γ factor (instead of distribution), no uncertainties yet.

S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

Typical distribution of the γ-factor of HNLs at LHCb

after cuts:

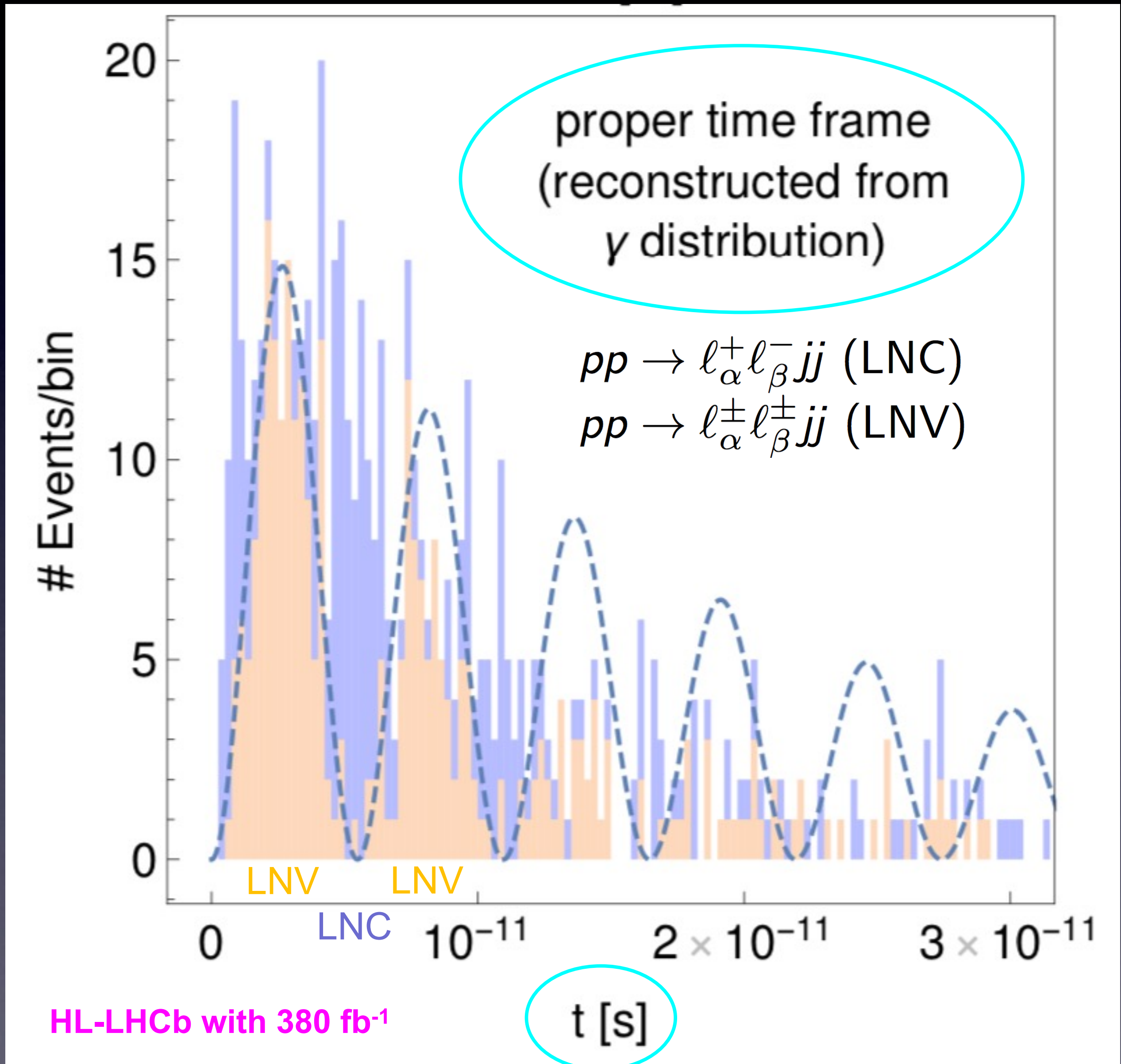


S. A., E. Cazzato, O. Fischer; arXiv:1706.05990

Estimate: Simulated signal including uncertainties in proper time frame ...

Example:

→ using the prediction for ΔM in the "Minimal linear seesaw" model with inverse neutrino mass hierarchy (IH)



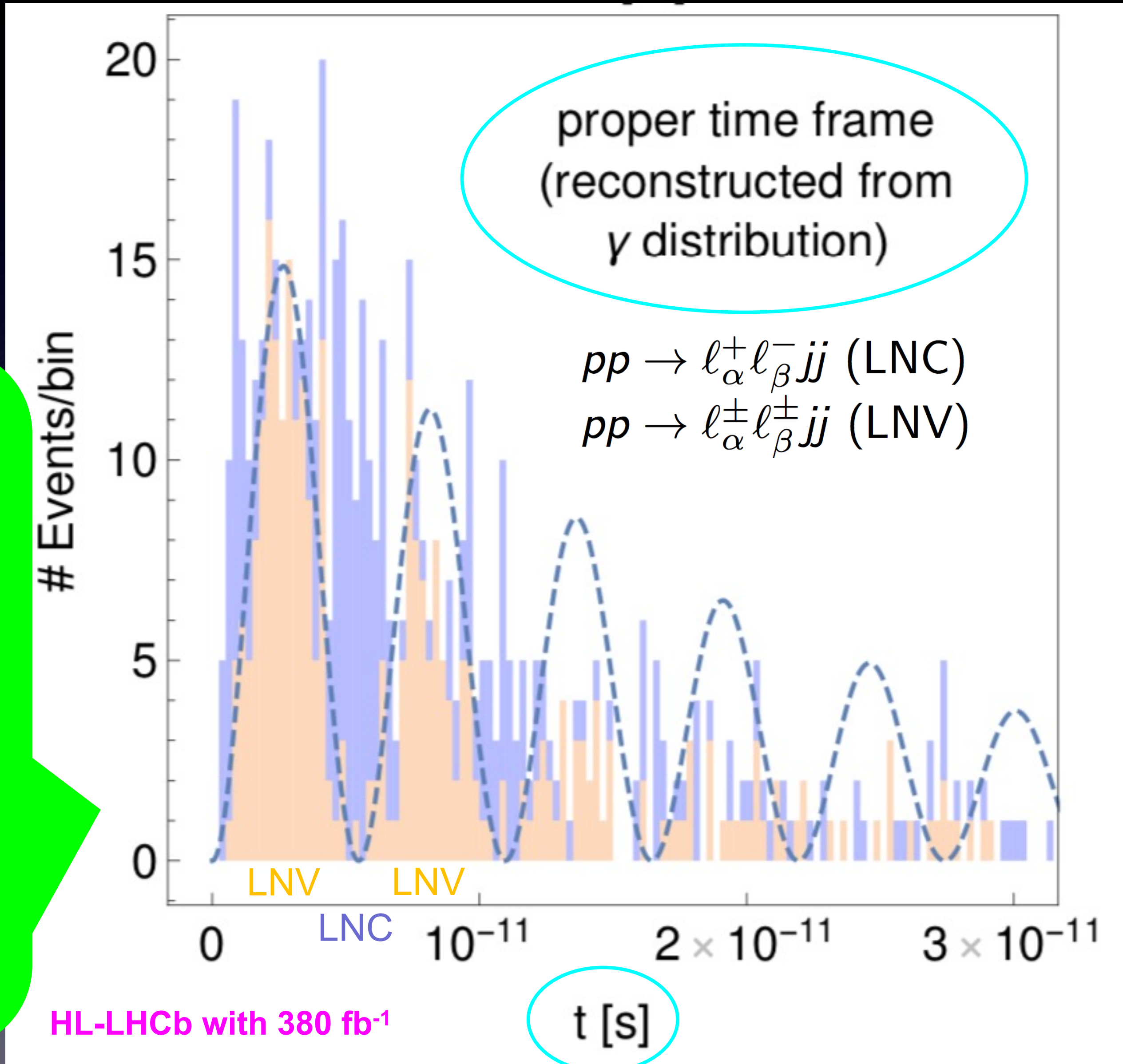
Distribution of γ factors included → one has to reconstruct signal as function of lifetime (not displacement)

S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

Estimate: Simulated signal including uncertainties in proper time frame ...

Example:

Analysis at the reconstructed level in preparation ... plus Madgraph "patch" for simulating the oscillations, and SPSSΔM model file (with Johannes Rosskopp and Jan Hajer)



Distribution of γ factors included → one has to reconstruct signal as function of lifetime (not displacement)

S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

For which parameters is LNV induced? Even if not resolvable → "integrated effect" (R_{ll} ratio)

Ratio of LNV over LNC events between t_1 and t_2:

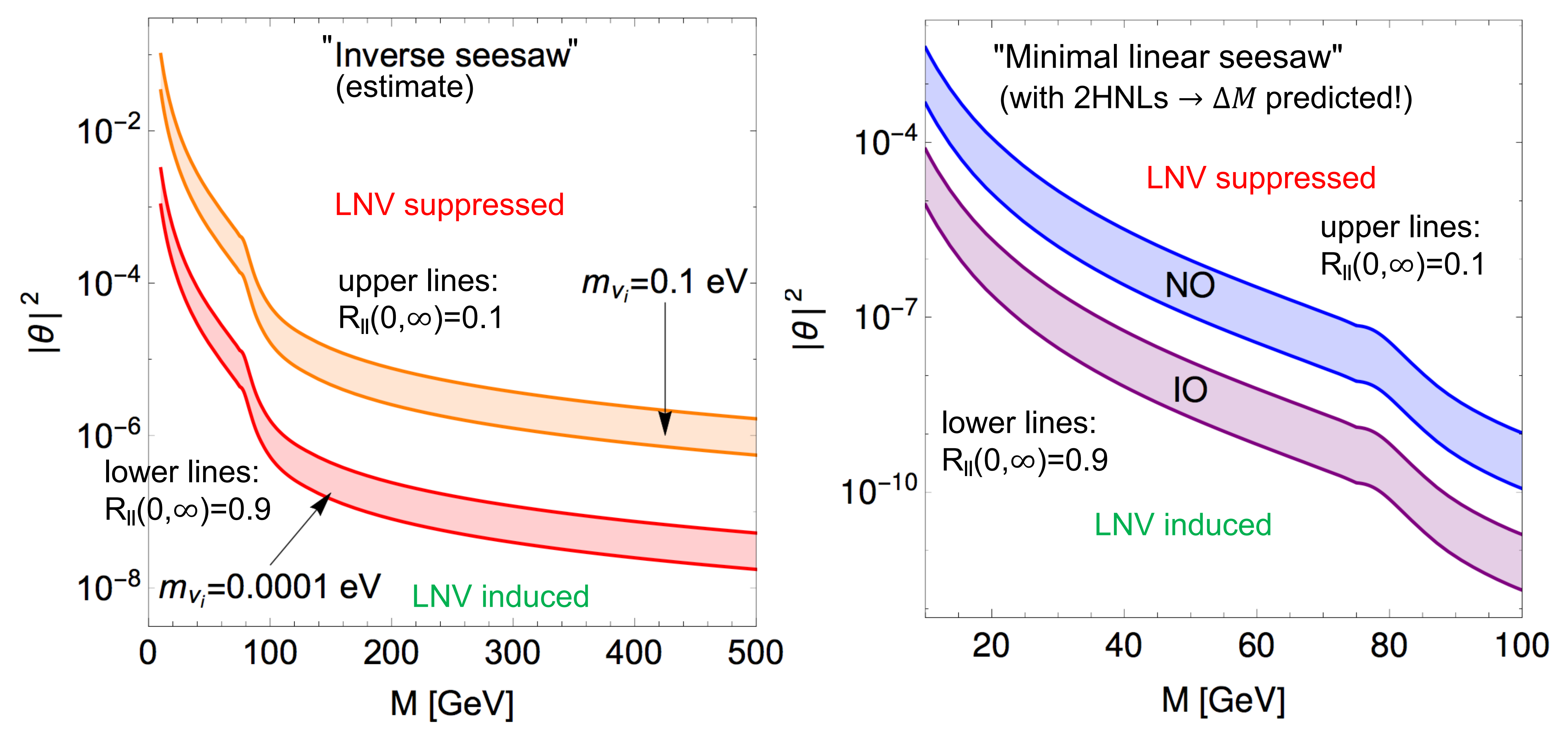
(*) using LO formulae and when the "observability conditions" are satisfied

$$R_{\ell\ell}(t_1, t_2) = \frac{\#(\ell^+\ell^+) + \#(\ell^-\ell^-)}{\#(\ell^+\ell^-)} \xrightarrow{*} R_{ll}(0,\infty) = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2}$$

cf. G. Anamiati, M. Hirsch and E. Nardi, hep-ph/1607.05641

$$\Rightarrow \boxed{R_{ll}(0,\infty) = \frac{N_{\mathrm{LNV}}}{N_{\mathrm{LNC}}} = \frac{\Delta M^2}{\Delta M^2 + 2\Gamma^2} = \begin{cases} \approx 0 & \text{No LNV induced by oscillations} \\ > 0 & \text{LNV can be induced by oscillations} \end{cases}}$$

For which parameters is LNV induced? Even if not resolvable → "integrated effect"



Plot from S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

... a little remark on LNV, and the recent discussion about testing "Dirac HNL" vs. "Majorana HNL"

... given the various potentially observable phenomena, including LNV

→ SPSSΔM (i.e. the SPSS with ΔM as additional parameter), appears to be a useful benchmark scenario (can capture all of the effects discussed in my talk ☺)*

→ ... effects cannot be described by
- 1 Majorana HNL (LNV/LNC ratio always 50%- no oscillations, for observable effects too large $m_{\nu\alpha}$, need at least 2 to describe m_ν ☹)
- 1 Dirac HNL (no LNV – no oscillations, no contribution to m_ν ☹)

**) or alternatively of course a full 2+n HNL model*

Summary

- With protective "lepton number"-like symmetry, the small observed m_ν can be explained with "large Y_ν" and ~ EW/TeV scale M_N. Low scale Seesaw: HNLs testable at present and future colliders
- → Benchmark scenario: SPSS (or SPSSΔM)
- LFV (but LNC) signatures can be very sensitive, especially at future ep colliders.
- LNV, although (apparently) suppressed by the "lepton number"-like symmetry, can be observable at colliders. It can be induced by Heavy Neutrino-Antineutrino Oscillations
- Opens up possibilities for testing neutrino mass generation at colliders ...
- In summary: Fascinating prospects for probing HNLs at future colliders!

Thanks for your attention!