Heavy Neutral Leptons at Colliders: LFV, LNV and Heavy Neutrino-Antineutrino Oscillations

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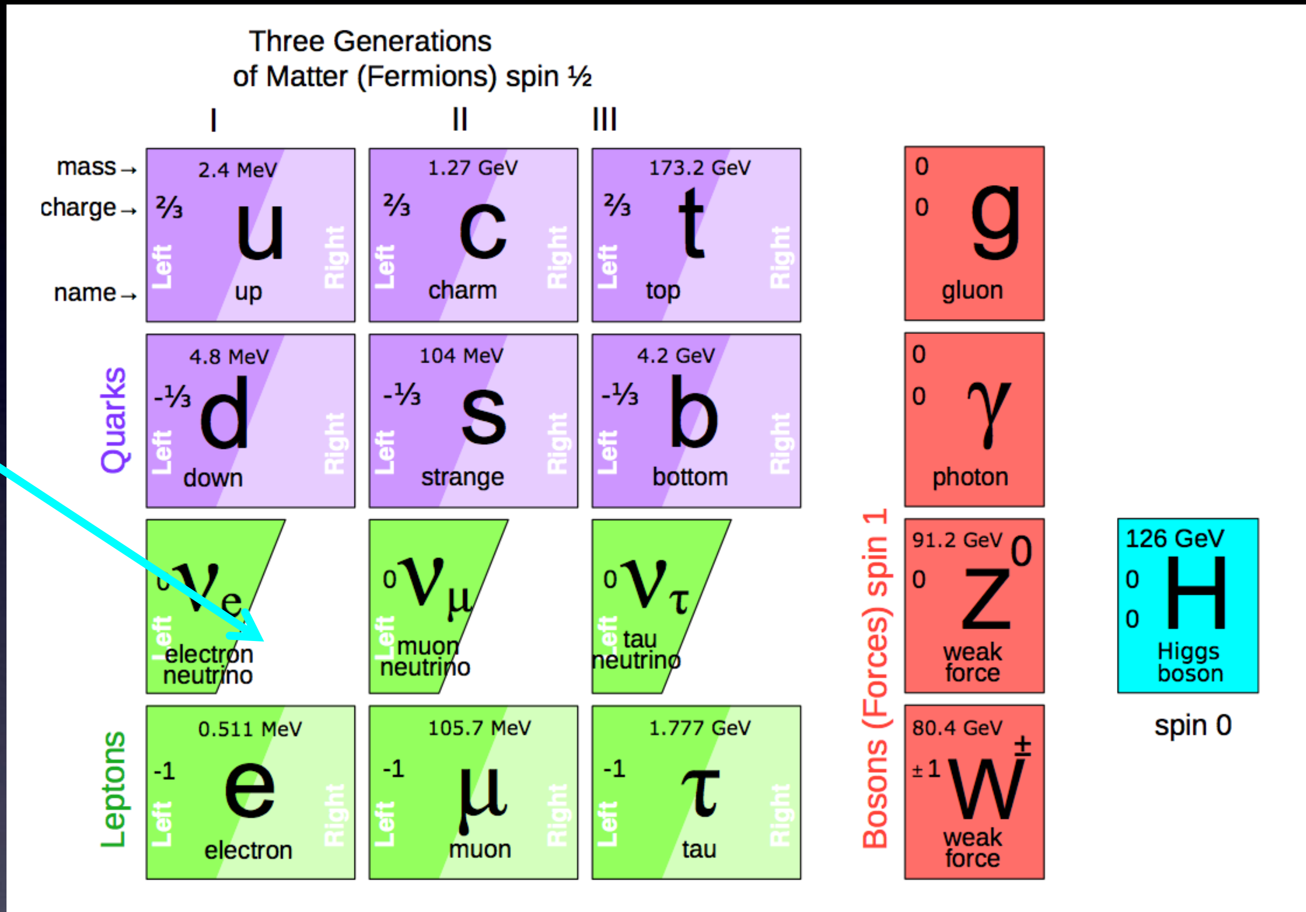
Heavy Neutral Leptons – the right SM extension to explain the light neutrino masses?

There are no right-chiral neutrino states (ν_{Ri}) in the Standard Model

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



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

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} - \frac{1}{2}\overline{\nu_{\mathrm{R}}^{I}} M^{N}_{IJ} \nu_{\mathrm{R}}^{cJ} - (Y_N)_{I\alpha}\overline{\nu_{\mathrm{R}}^{I}}\tilde{\phi}^{\dagger} L^{\alpha} + \mathrm{H.c.}$$

M^N: sterile ν mass matrix

Y_N: neutrino Yukawa matrix (→ Dirac mass terms)

High Scale vs. Low Scale Seesaw

Smallness of light neutrino masses may be a consequence of:

→ Large RH neutrino masses

→ Approximate "Lepton-number"-like symmetry

"High Scale Seesaw"

"Low Scale Seesaw"

... can well operate at EW/TeV energies accessible to colliders, with potentially "unsuppressed" Yukawa couplings → testable at colliders!

Low Scale Seesaw with "Symmetry protection"

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

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

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

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

→ Note: "Symmetry protection" requires pairs of sterile (right-handed) neutrinos ... which form "pseudo-Dirac pairs"!

In the symmetry limit

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

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

For comparison: most general seesaw with 2 HNLs:

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

From general 2 HNL seesaw to "symmetry limit" →

from symmetry to approximate symmetry

Approximate symmetry (with "small" ε-terms breaking it):

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

when ε-terms "get larger"

Low Scale Seesaw with "Symmetry protection"

→ **Light neutrino masses induced from small breaking of the "L-like" symmetry ($m_\nu \sim \varepsilon$)**

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

+ symmetry breaking terms O(ε)

"Inverse" seesaw:*

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

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

"Linear" seesaw:*

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

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

also: ... no tree-level m_ν

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

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

$$\Delta M^{\text{inv}} = \frac{m_{\nu_i}}{|\theta^2|}$$

In "minimal linear seesaw" (2 HNLs):

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

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

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

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

For low scale seesaw models, 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 (in SO(10) with low scale Z', 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_α)

$$Y_\nu = \begin{pmatrix} y_{\nu_e} & 0 & \\ y_{\nu_\mu} & 0 & \cdots \\ y_{\nu_\tau} & 0 & \end{pmatrix}, \quad M = \left(\begin{array}{cc|ccc} 0 & M_R & & & \\ M_R & 0 & & 0 & \\ \hline & & * & * & \cdots \\ & 0 & * & * & \\ & & & \vdots & \ddots \end{array}\right)$$

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

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

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).

The SPSS in the "symmetry limit"

We consider the SPSS (Symmetry Protected Seesaw Scenario)

In the symmetry limit:

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

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$+$ … (terms from additional sterile νs)

4 Parameters:
M, y_α, (α=e,μ,τ)

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+ … (terms from additional sterile νs)

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

Mass eigenstates:

$$\tilde{n}_j = (\nu_1, \nu_2, \nu_3, N_4, N_5)^T_j = U^\dagger_{j\alpha} n_\alpha$$

"**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, $(\alpha=e,\mu,\tau)$

In the symmetry limit:

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

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

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

- Active-sterile neutrino mixing parameters:

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

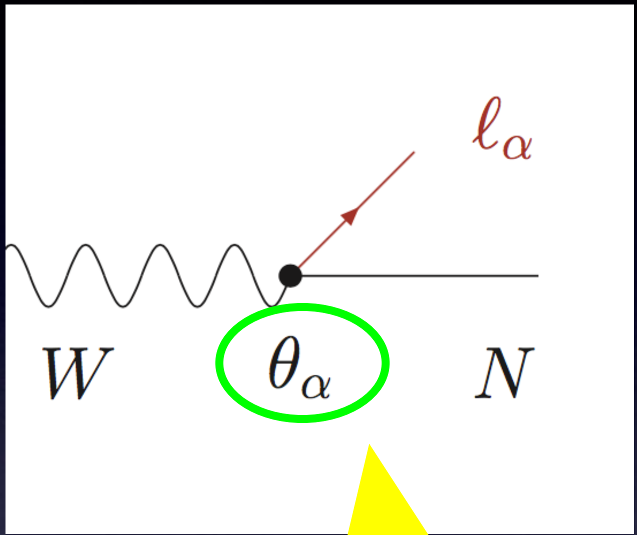
Parameters:
M, y_α, $(\alpha=e,\mu,\tau)$
or equivalently
M, θ_α, $(\alpha=e,\mu,\tau)$

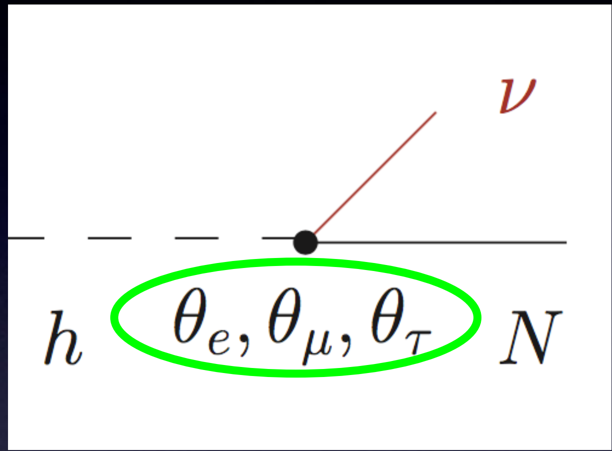
Sterile neutrinos mix with the active ones ➔ the heavy neutrinos (= mass eigenstates) participate in weak interactions!

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

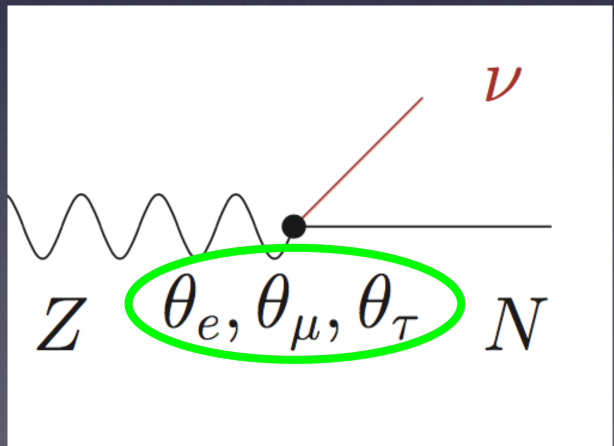
⇒ heavy neutrinos can get produced also in weak interaction processes!

Heavy neutrino interactions



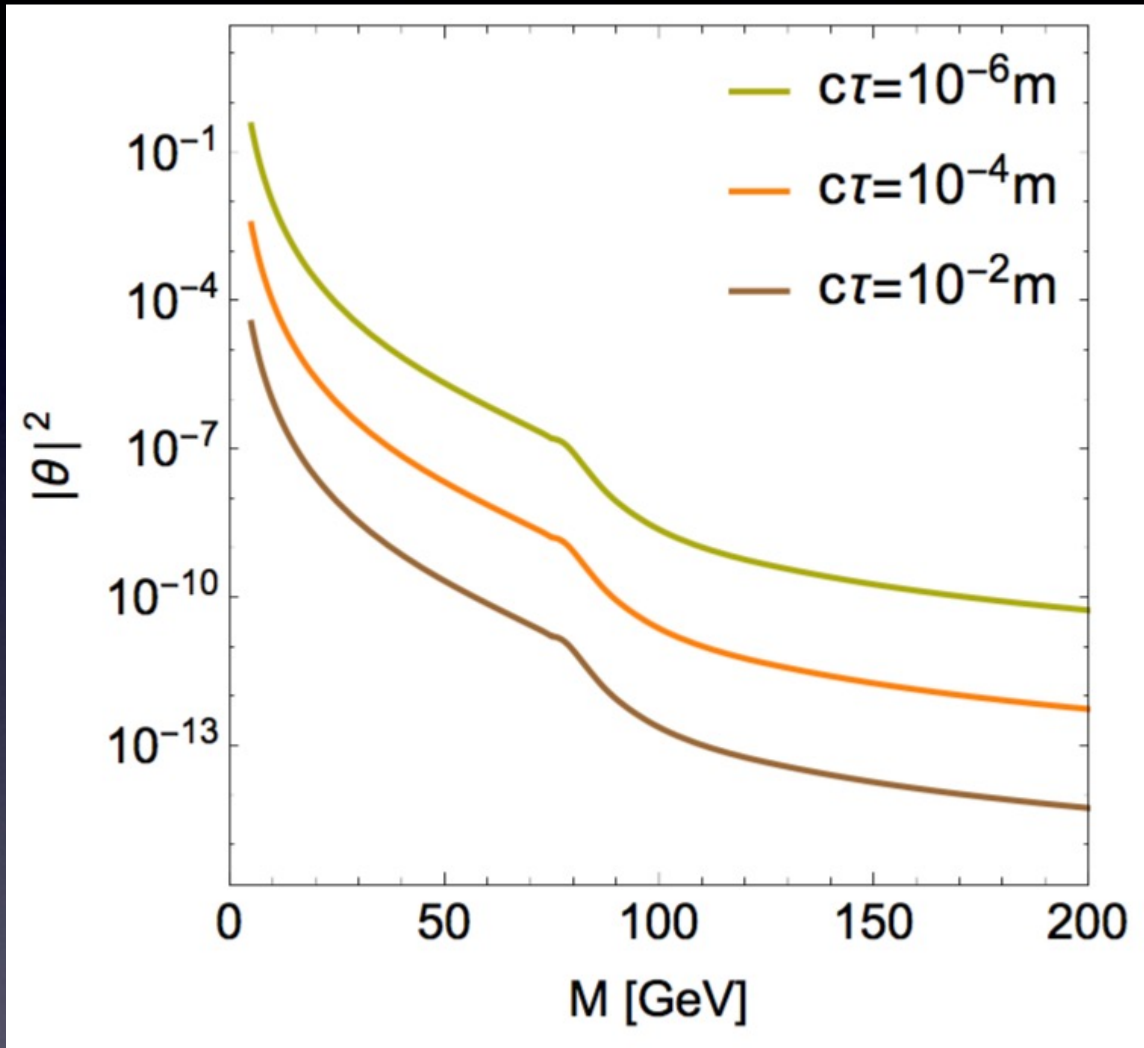


When W bosons are involved, there is a possible sensitivity to the flavour-dependent θ_α



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

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



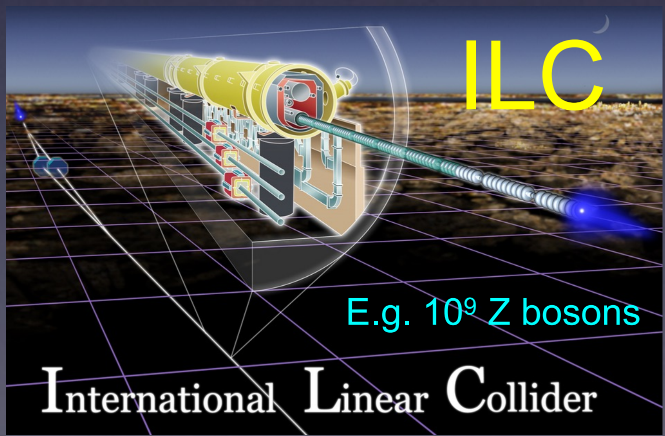
cf. S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

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

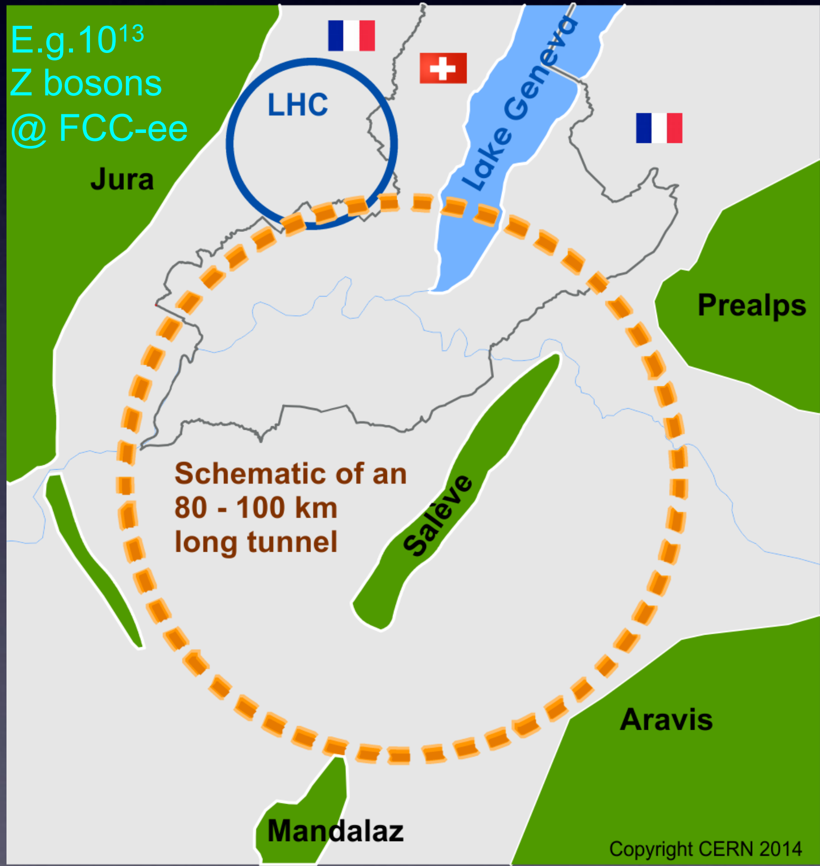
What are the sensitivities for probing HNLs at future collider experiments?

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

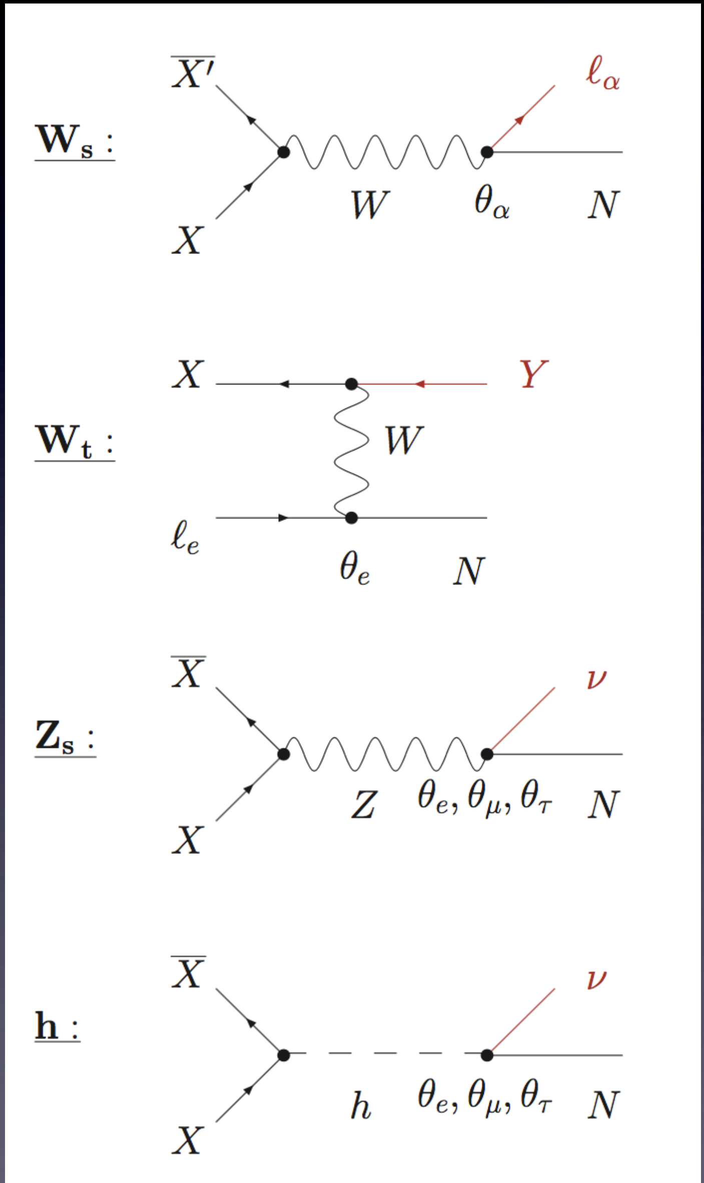
Ambitious plans for future colliders …
… different collider types: e^+e^-, pp, ep



FCC (-ee, -hh, -eh)



Systematic assessment of signatures of sterile neutrinos at colliders



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

Different collider types feature different production channels …

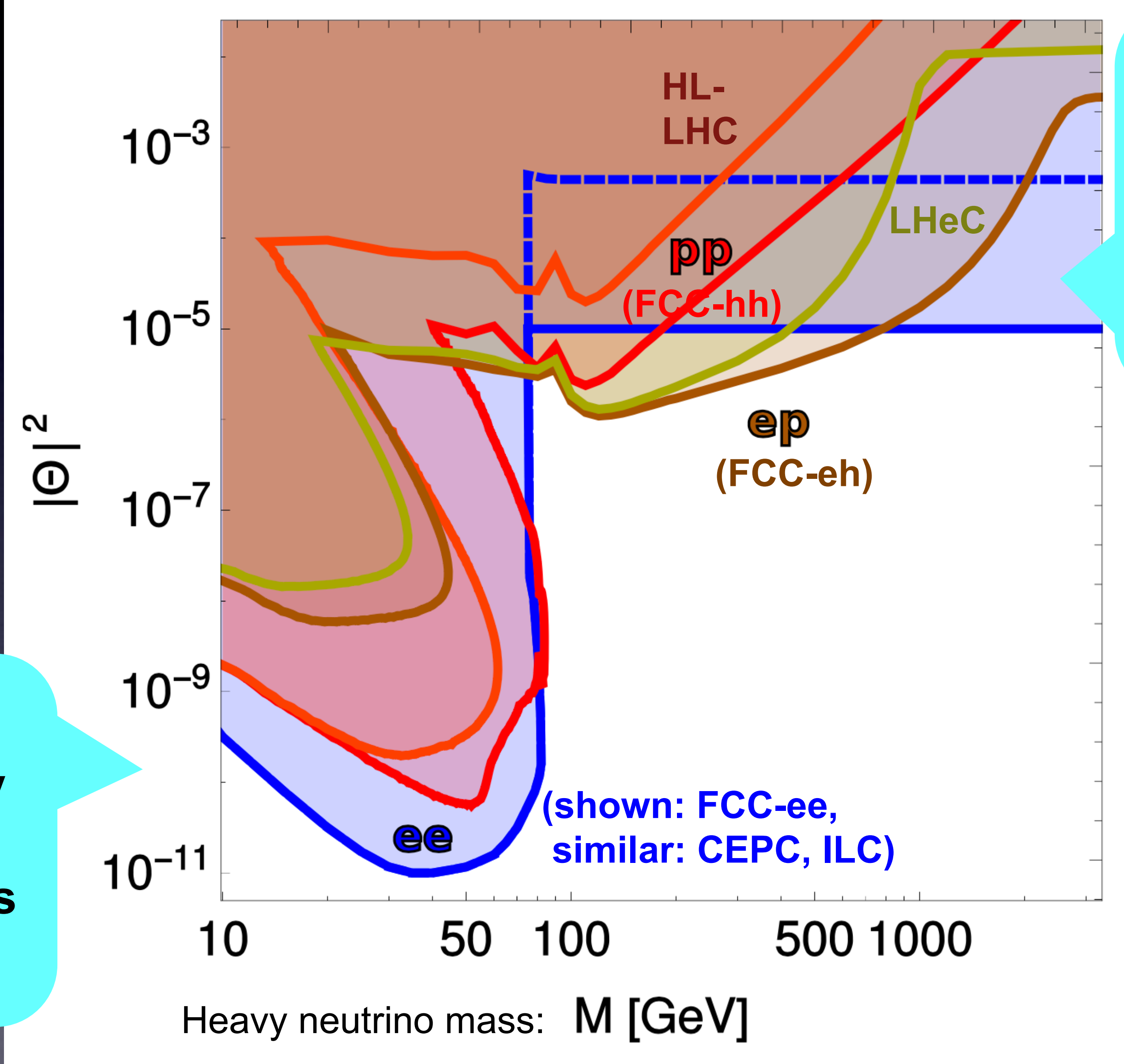
(at LO)

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

... helps a lot to suppress SM background!

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

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



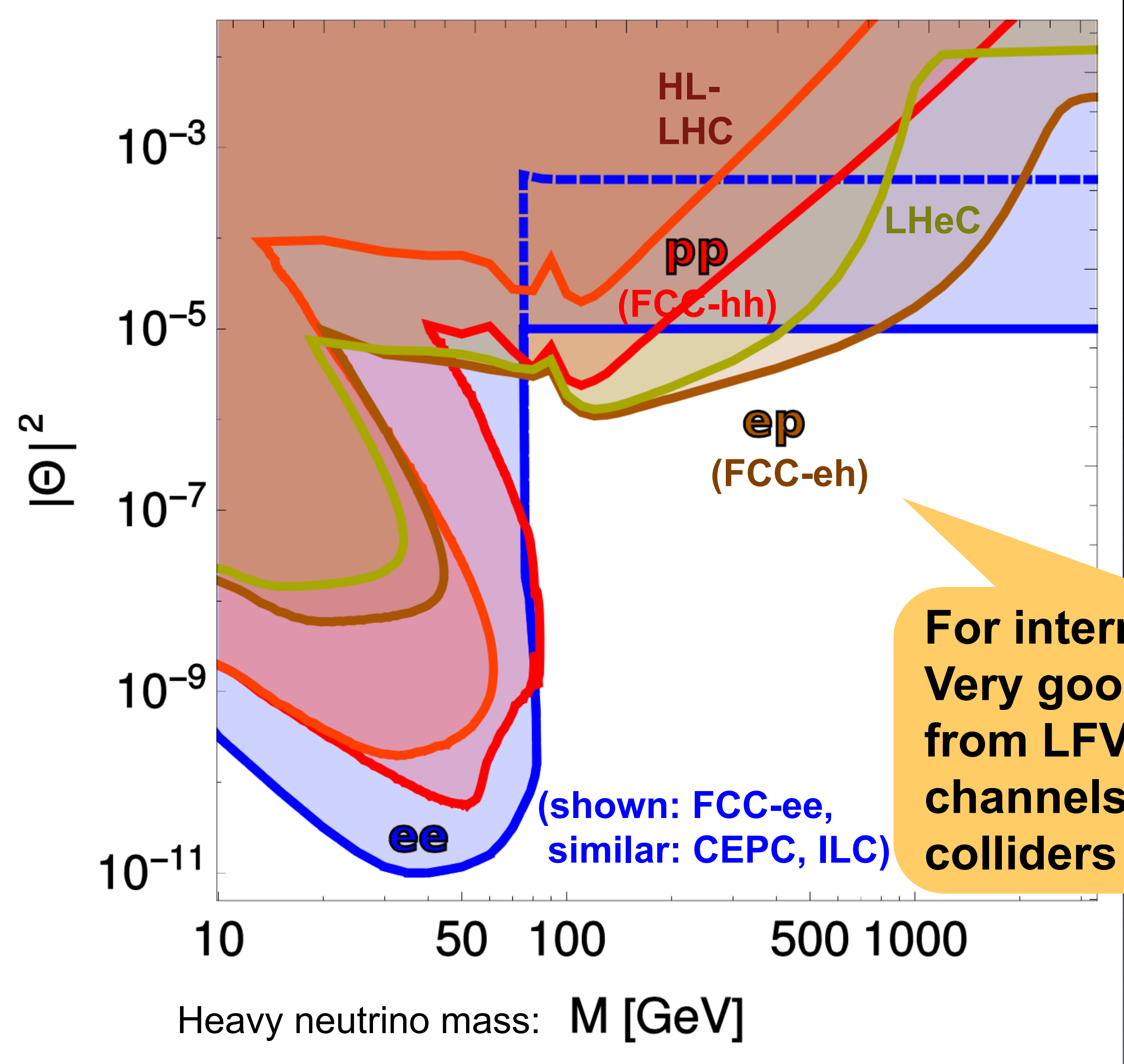
For M >> O(TeV): Very good sensitivity from EWPO measurements at FCC-ee

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



For intermediate M: Very good sensitivities from LFV (but LNC) channels at pp and ep colliders (FCC-hh & -eh)

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

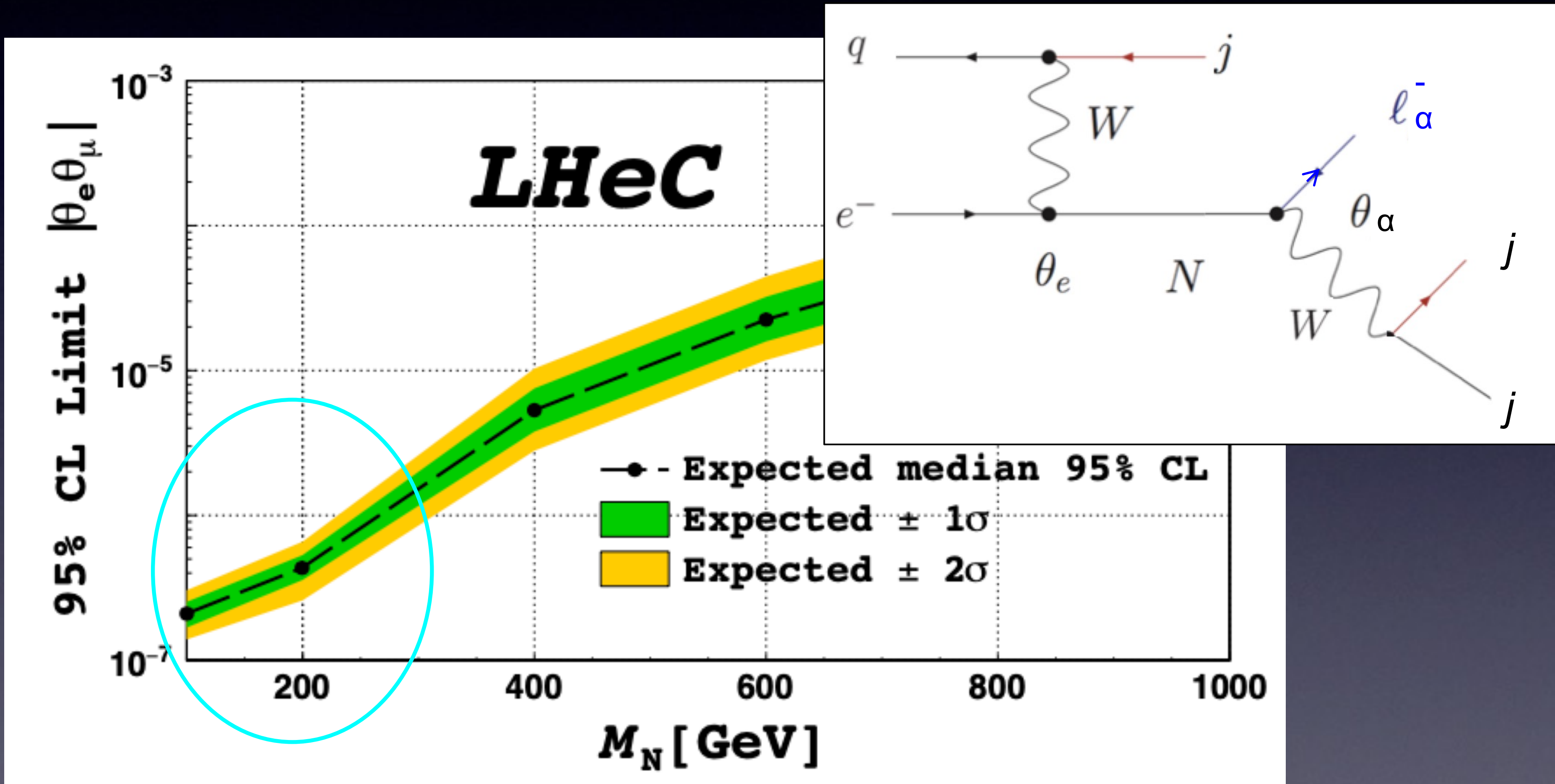
Plot from: S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

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_α^- 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:

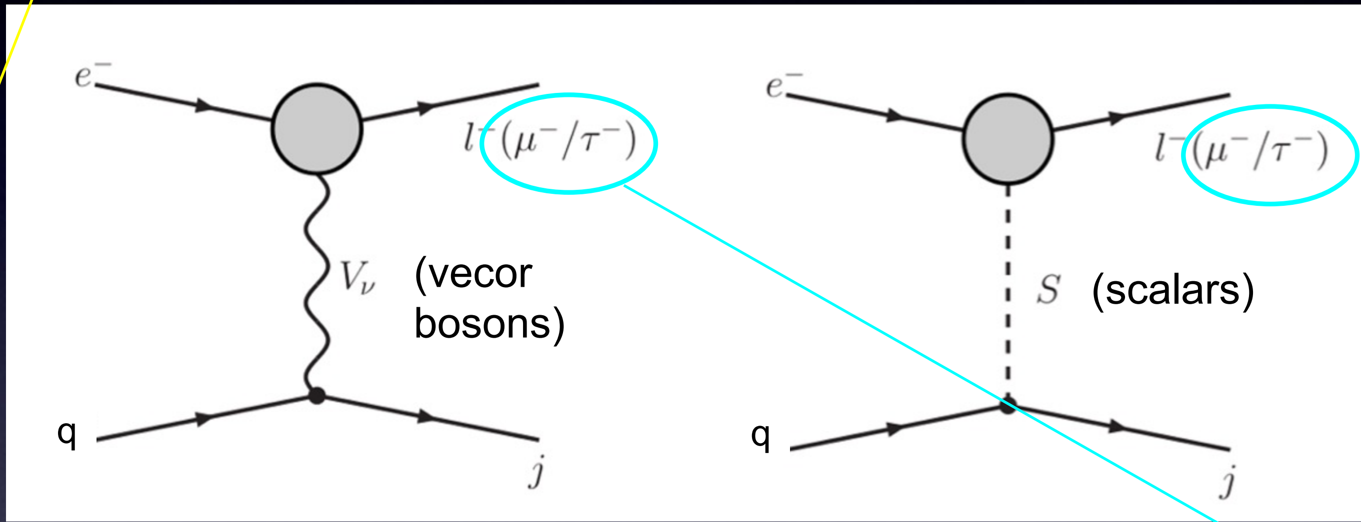
LFV at ep colliders can also probe HNLs with much larger masses!

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

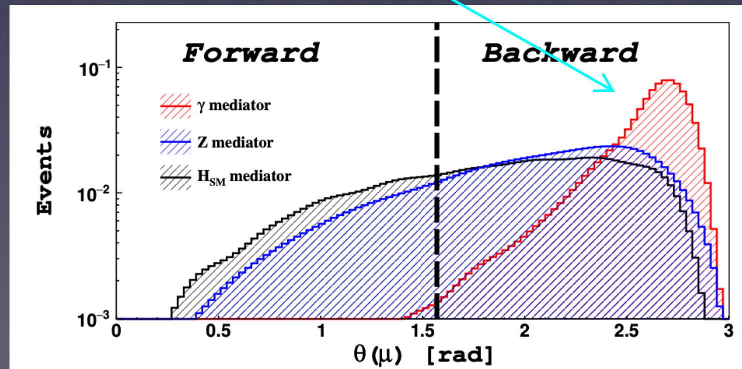
cLFV searches via e-μ and e-τ conversion at ep colliders

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

Effective description:



Scattered dominantly in backward direction of the detector!



Effective operators:

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

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

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

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

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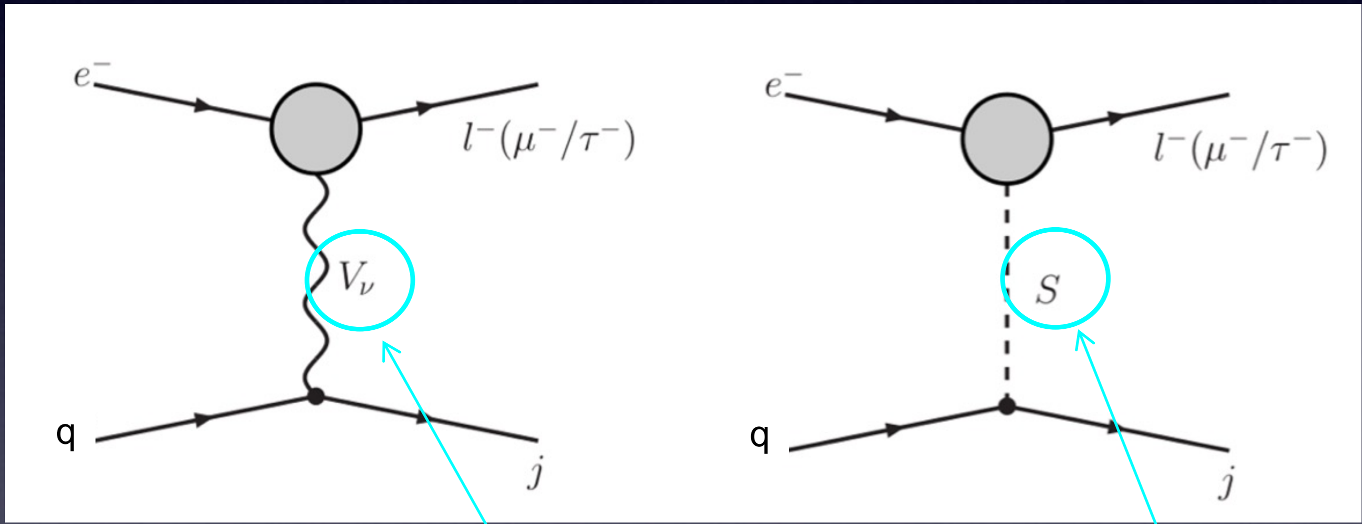


Can probe new vector bosons (e.g. LFV via Z') or scalars ...

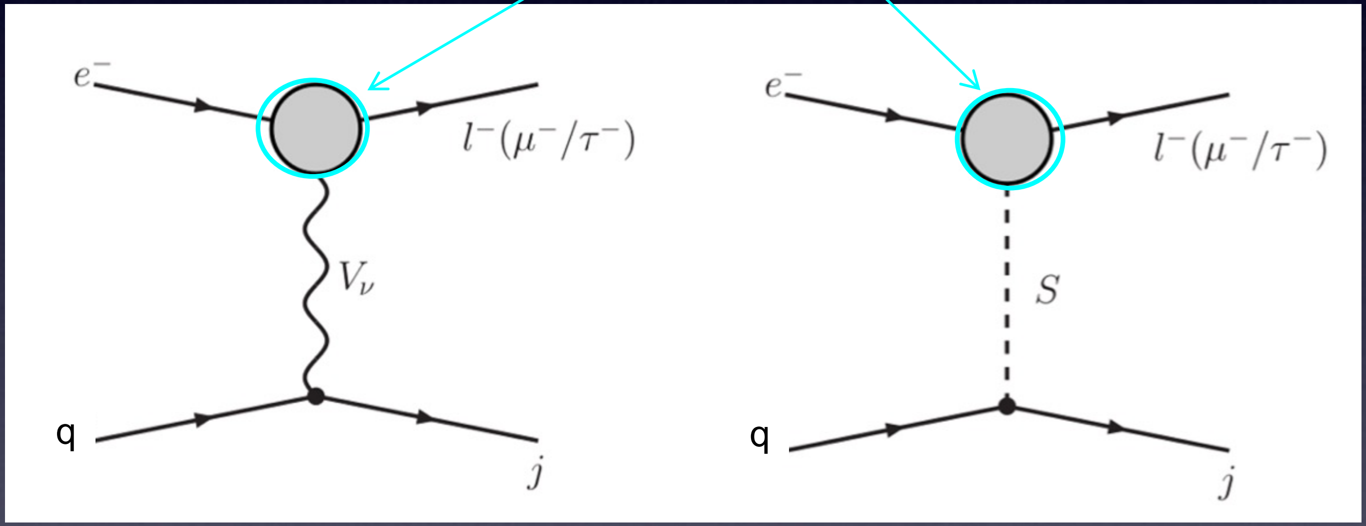
S.A., A. Hammad, A. Rashed (arXiv:2003.11091)

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

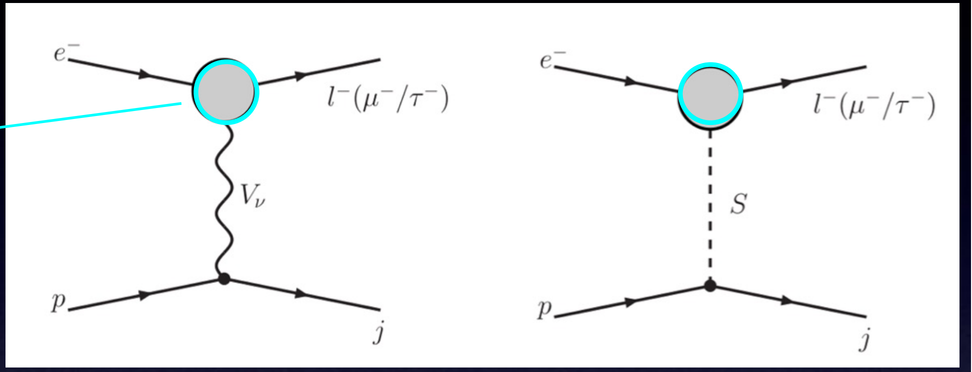
S.A., A. Hammad, A. Rashed (arXiv:2010.08907)

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

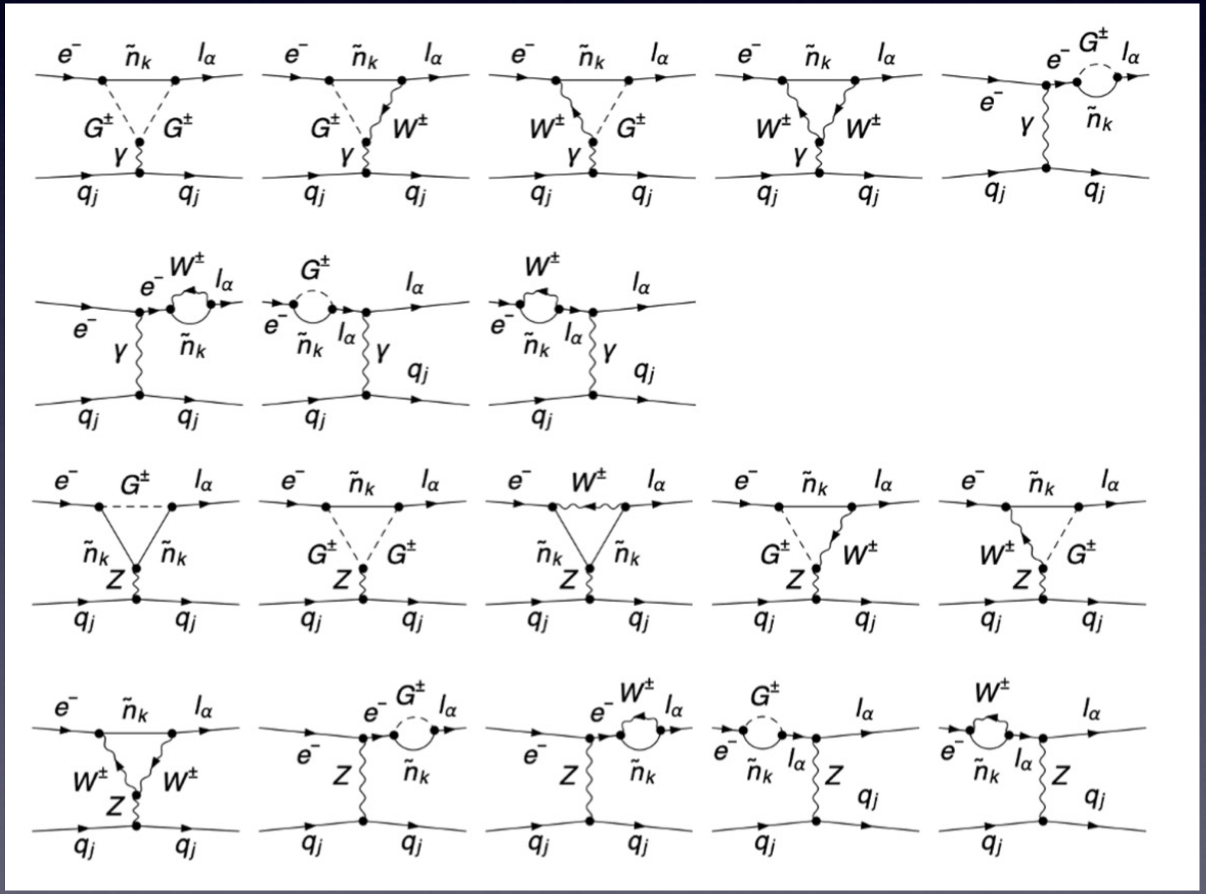
Effective description:



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

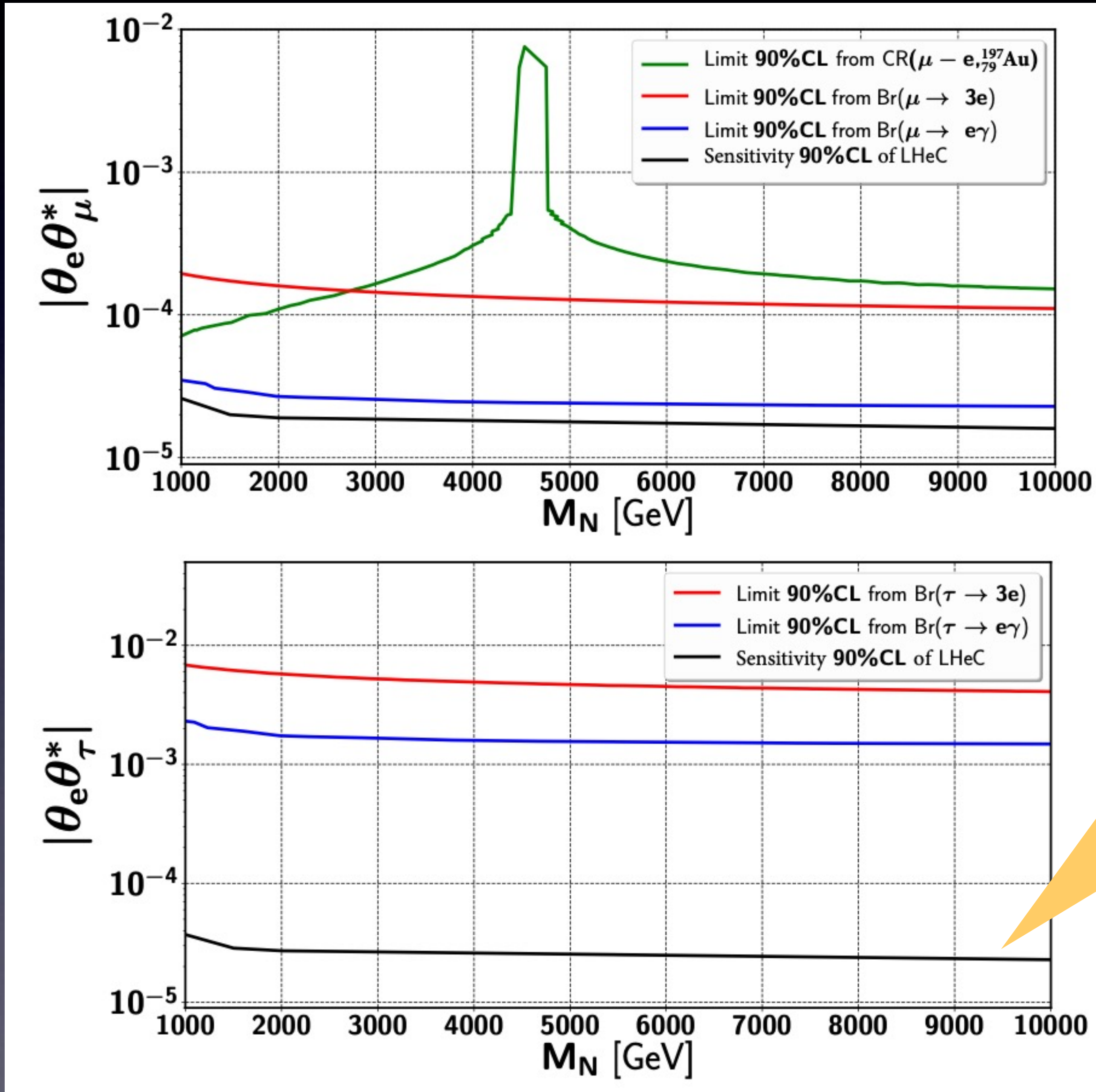


In the SM extended by HNLs:



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}

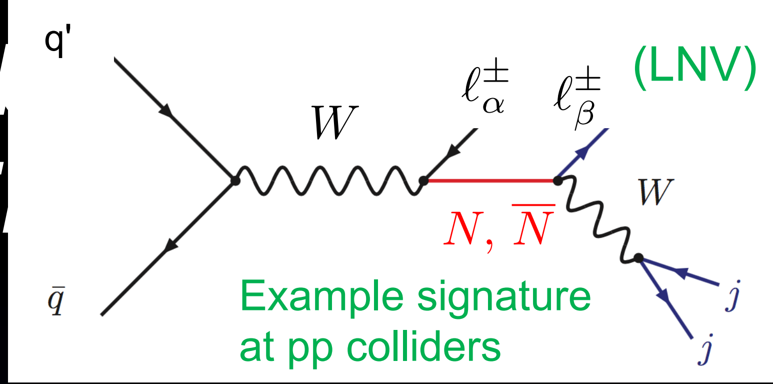
To my knowledge, this search channel could yield the best sensitivity to e-τ cLFV (among the currenlty envisioned experiments)!

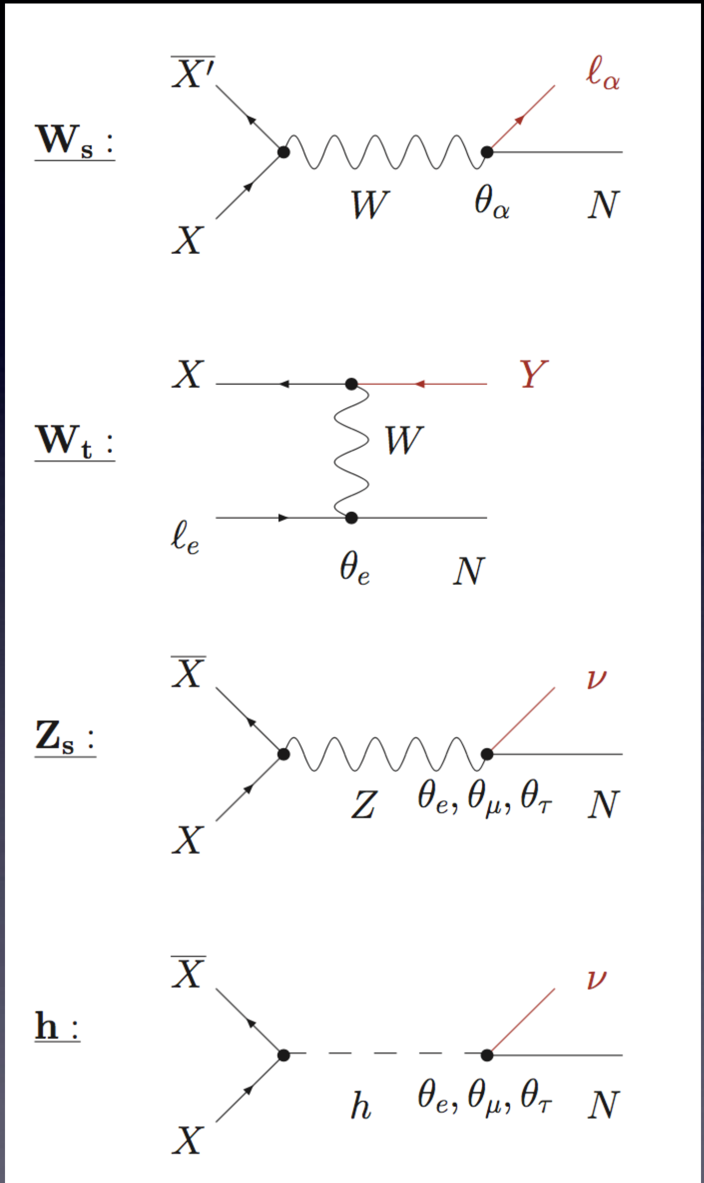
S.A., A. Hammad, A. Rashed (arXiv:2010.08907)

Beyond the "L-like"-symmetry limit:

Can we observe LNV from the HNLs (required to generate light m_ν)?

Signatures for lepton numb… from sterile neutri…





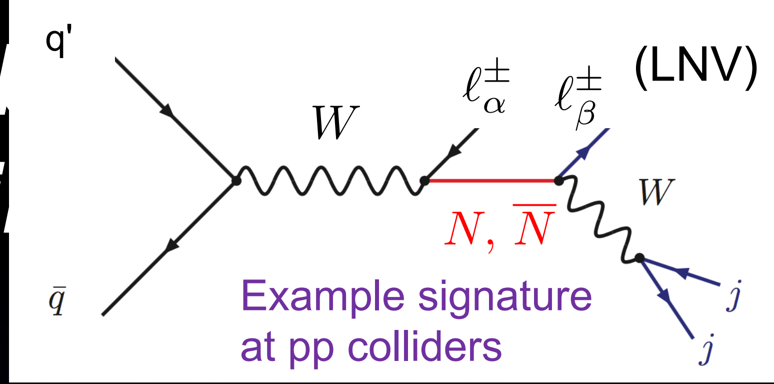
	e^-e^+	pp	e^-p
$\mathbf{W_s}$	×	✓ +LNV/LFV	×
$\mathbf{W_t}$	✓	×	✓ +LNV/LFV
$\mathbf{Z_s}$	✓	✓	×
$\mathbf{h}$	(✓)	(✓)	(✓)

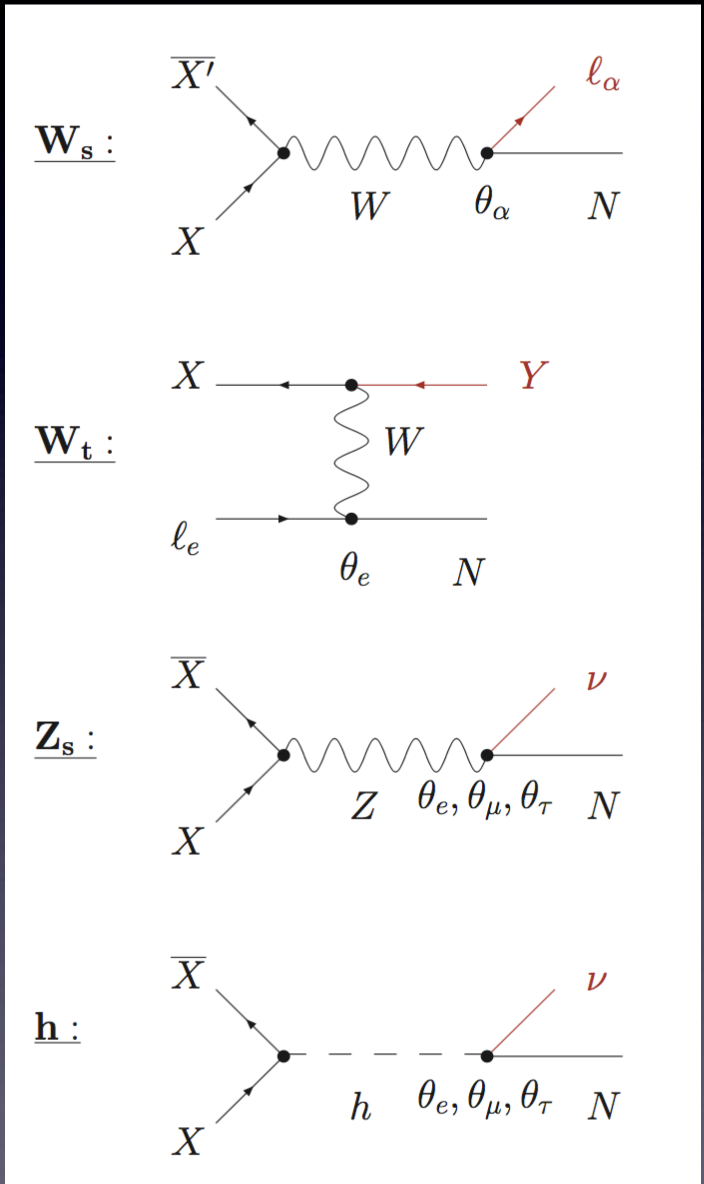
Lepton-number violating (LNV) signatures possible (with no SM background at parton level) but expected to be strongly suppressed by the (approximate) protective "lepton number"-like symmetry!

See e.g. discussion in Kersten, Smirnov (2007)

→ LNV from neutrino mass generation not observable at LHC

Signatures for lepton num
from sterile neutri

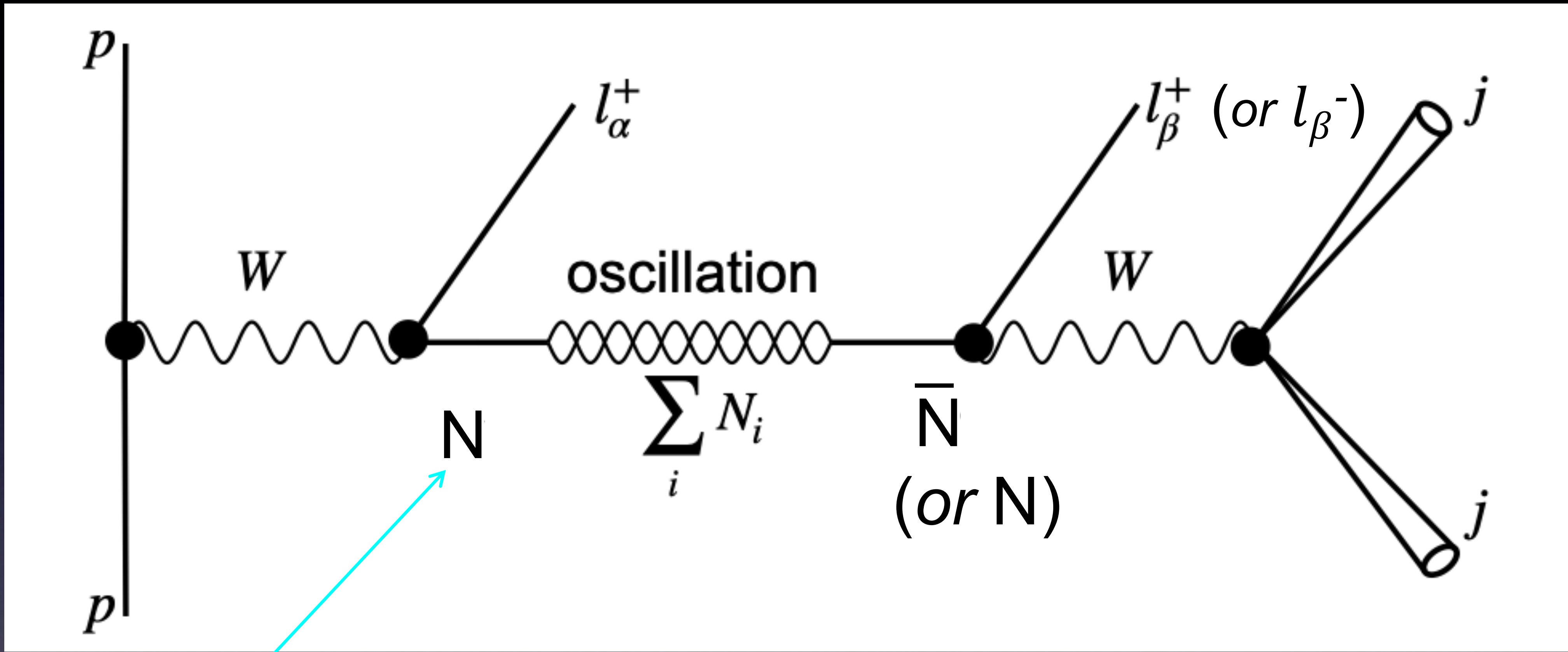




	e^-e^+	pp	e^-p
$\mathbf{W_s}$	×	✓ +LNV/LFV	×
$\mathbf{W_t}$	✓	×	✓ +LNV/LFV
$\mathbf{Z_s}$	✓	✓	×
$\mathbf{h}$	(✓)	(✓)	(✓)

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

Heavy Neutrino-Antineutrino Oscillations

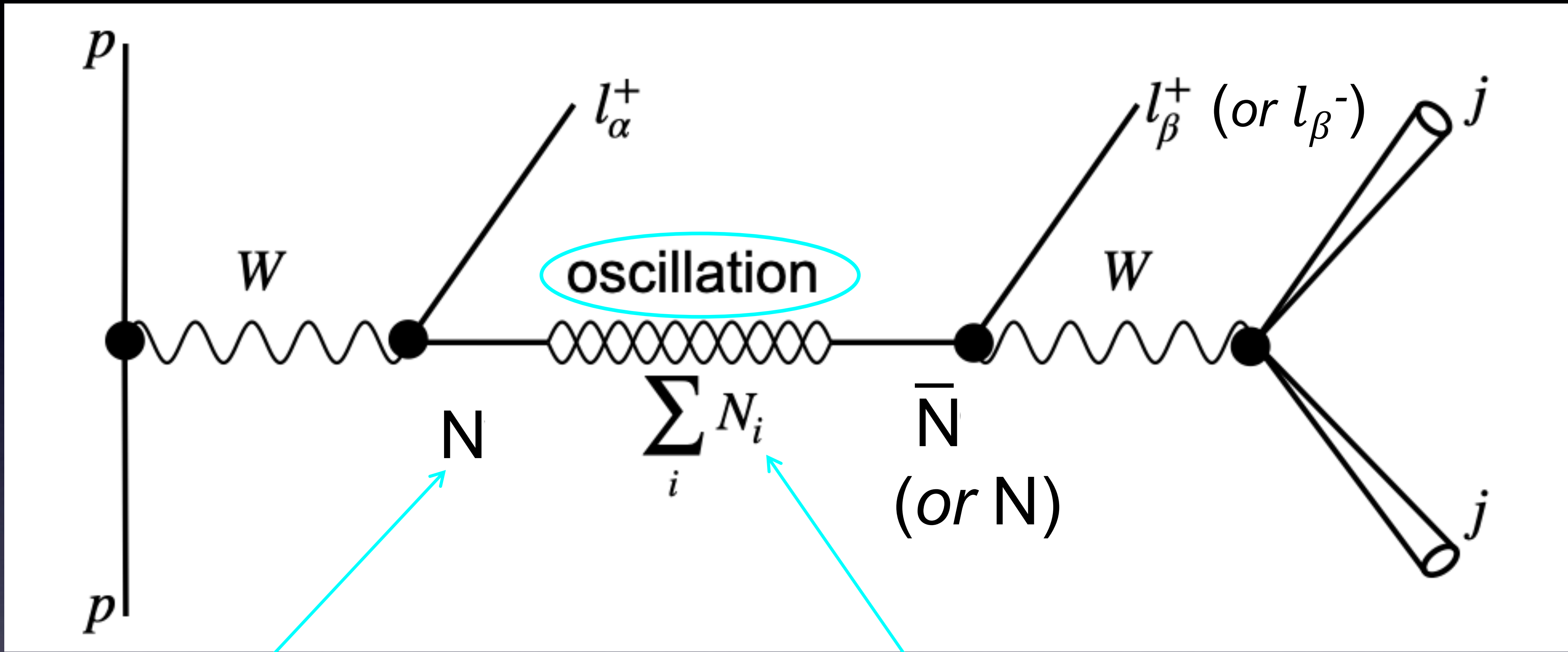


Interaction states: Produced from W decay
- "Heavy Neutrinos N" (together with l_α^+)
- "Heavy Antineutrinos $\overline{\text{N}}$" (together with l_α^-)

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



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

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 $\bar{N}$ and N

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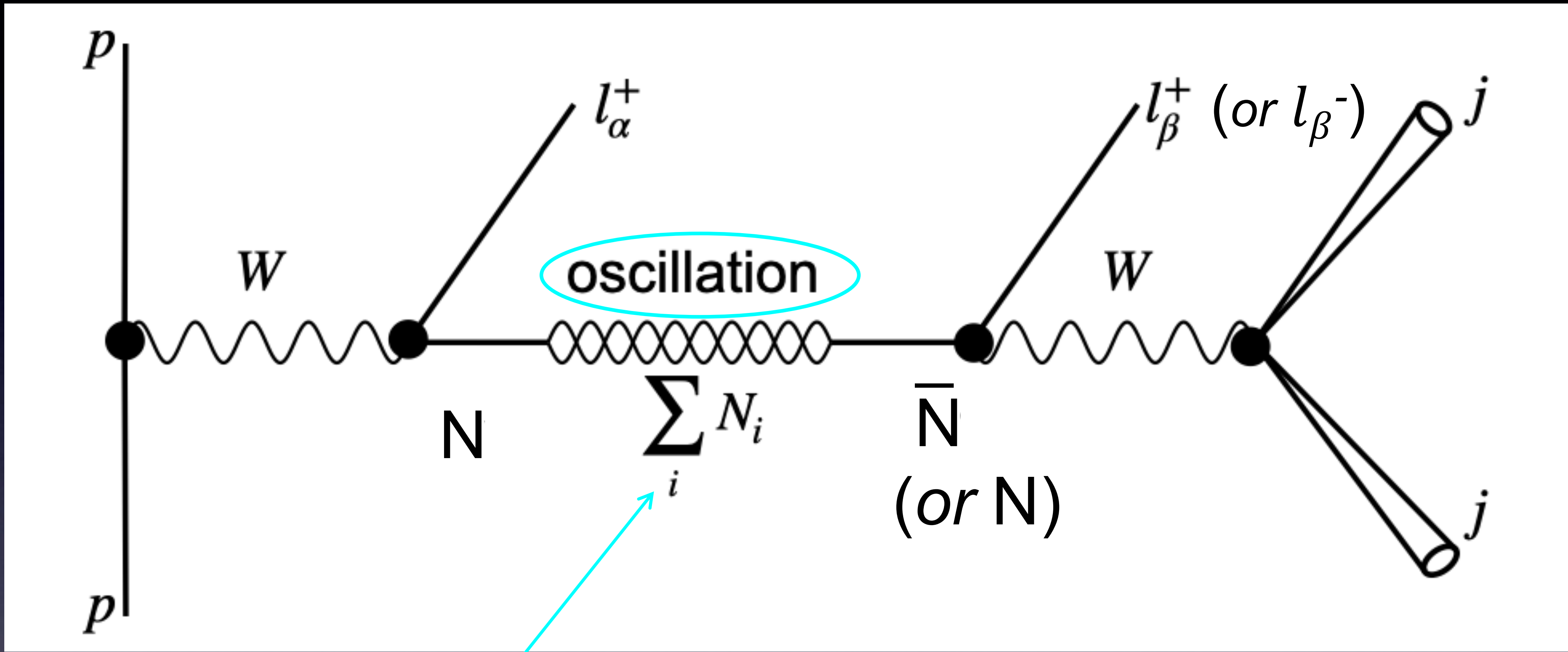
$$\overline{N} = 1/\sqrt{2}(iN_4 + N_5) \qquad N = 1/\sqrt{2}(-iN_4 + N_5)$$

Heavy Neutrino-Antineutrino Oscillations

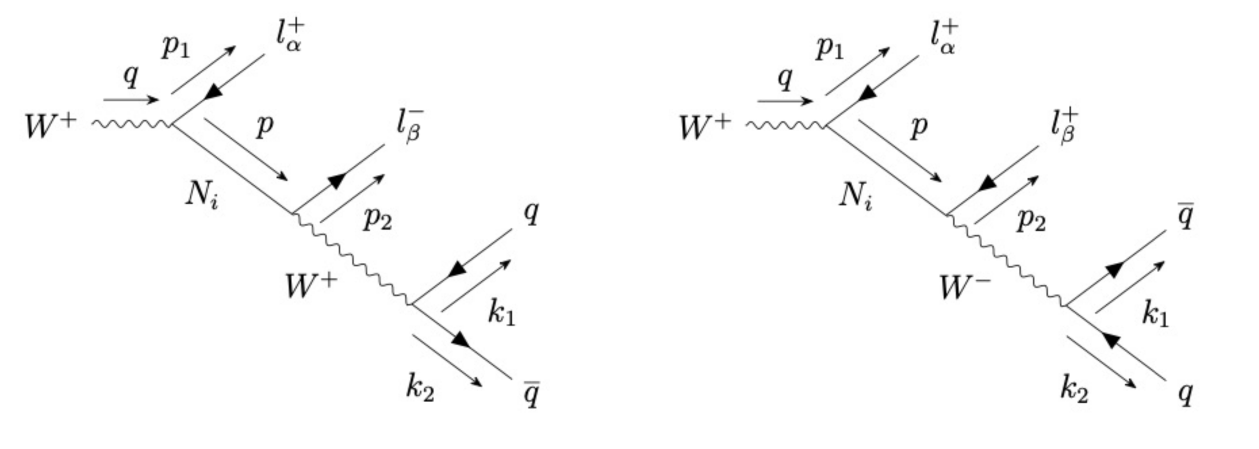


Due to the O(ε) perturbations to generate the light neutrino masses: → **mass splitting ΔM** between the heavy mass eigenstates N_4 and N_5 → propagating mass eigenstates induce **oscillations between N and $\bar{N}$**

Since an N decays into a l_α^- and a $\bar{N}$ 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

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

→ 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

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

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

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

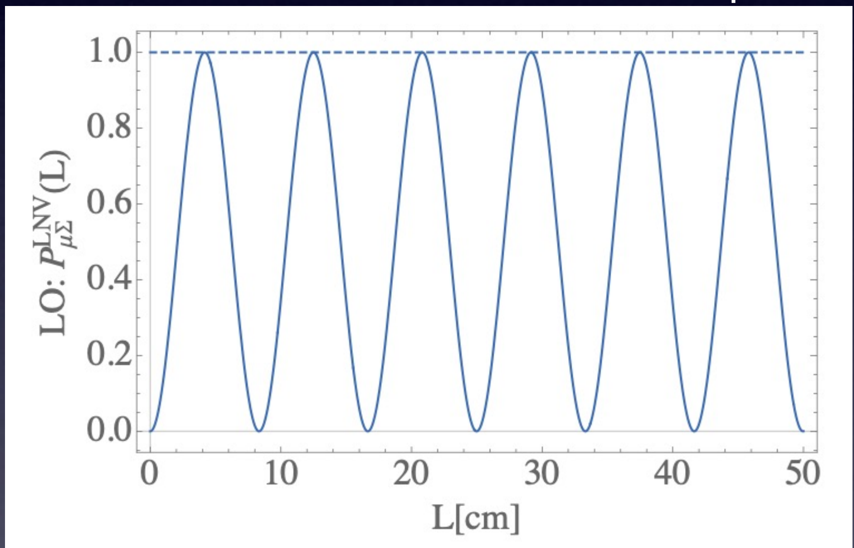
S.A., J. Rosskopp (arXiv:2012.05763)

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

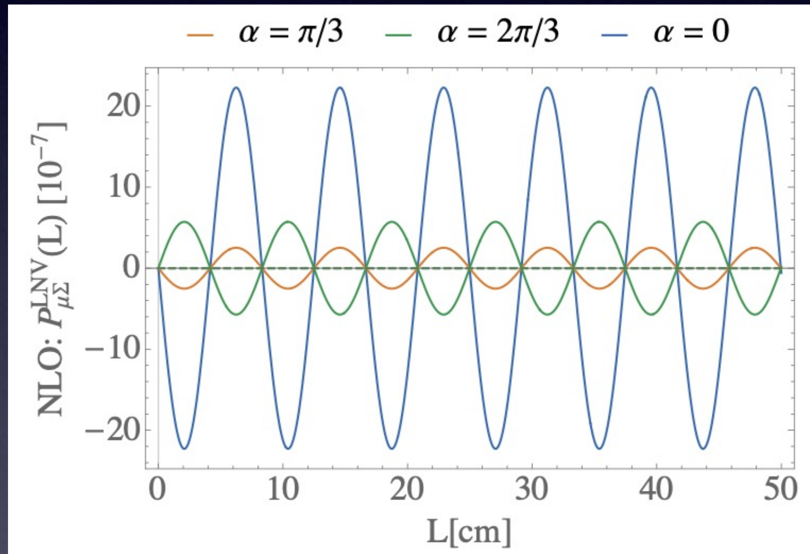
$$P_{\alpha\beta}^{LNV}(L) = \frac{1}{2\sum_\beta |\theta_\alpha|^2|\theta_\beta|^2}\Big(|\theta_\alpha|^2|\theta_\beta|^2(1-\cos(\phi_{45}L)) - 2(I_\beta|\theta_\alpha|^2 + I_\alpha|\theta_\beta|^2)\sin(\phi_{45}L)\Big)\,,$$

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

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 ouitgoing flavours

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

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

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

Furthermore:

- 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 (as additional parameter) 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 region

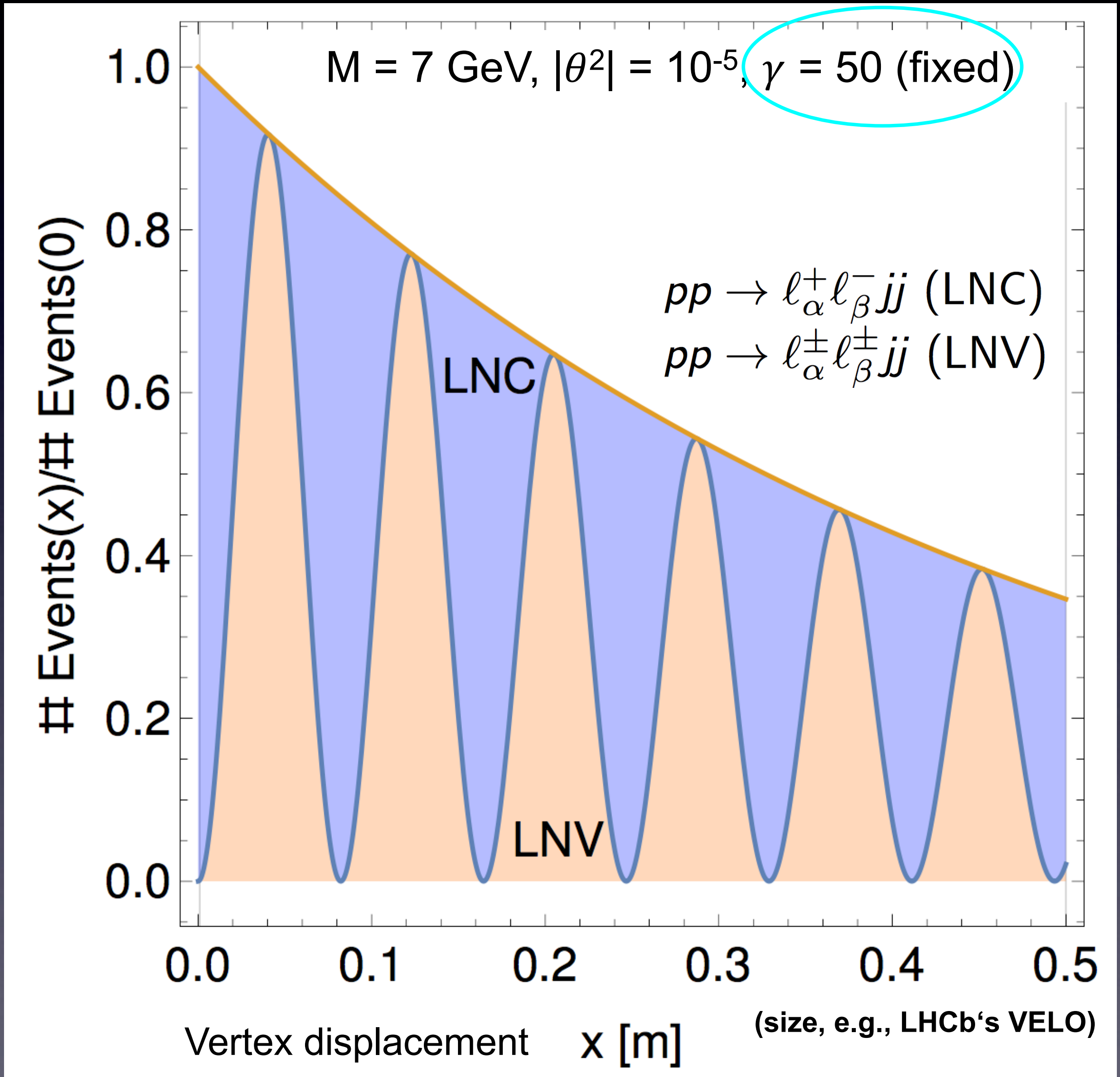
- We discussed the NLO effects (i.e. the flavour oscillations) and showed that for the considered benchmark point they are tiny.

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

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

Example: Linear seesaw (inverse mass ordering)

(using the prediction for ΔM in the minimal linear seesaw model for inverse neutrino mass ordering)



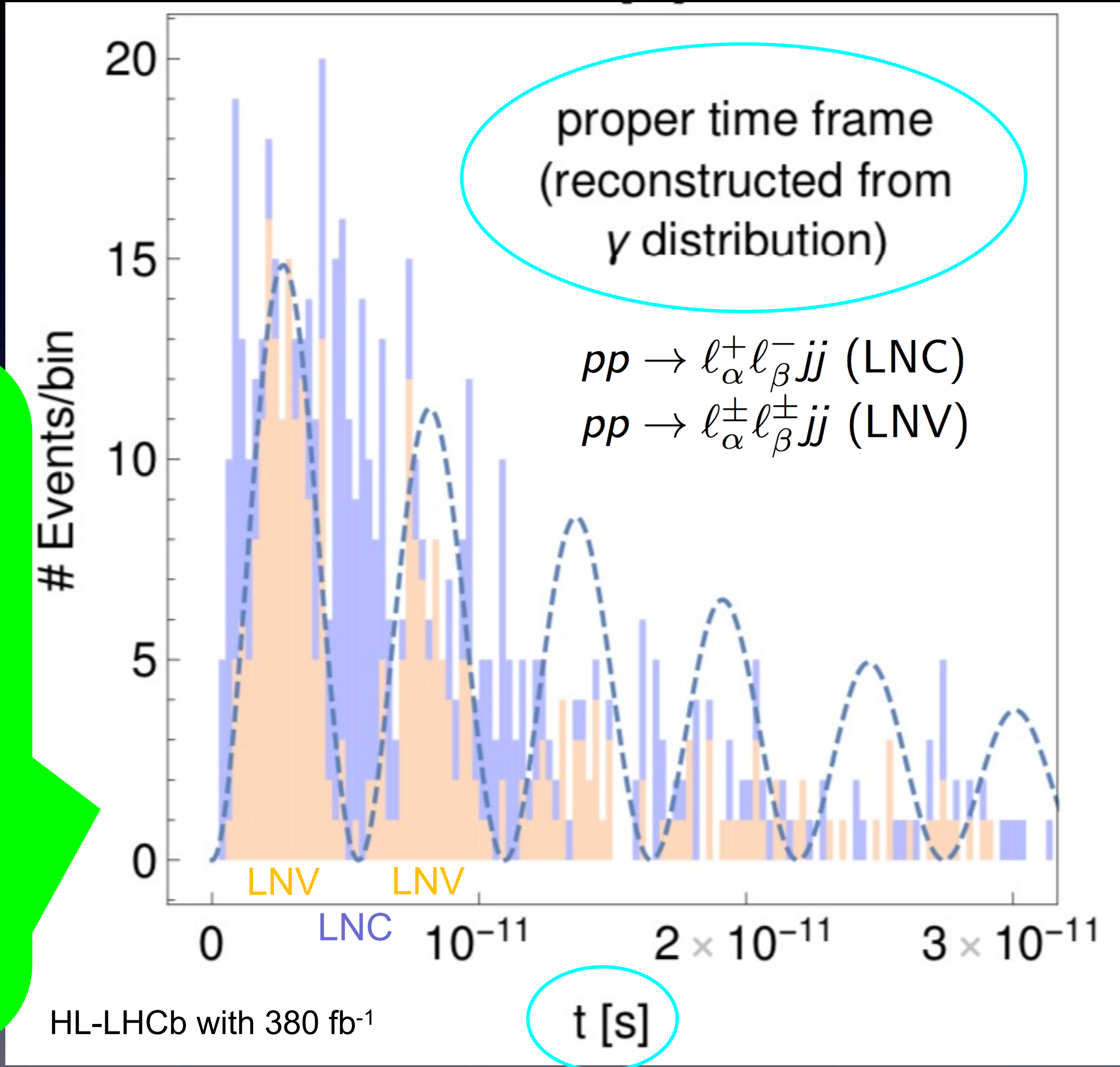
For this plot: fixed γ factor (instead of distribution), no uncertainties yet.

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

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

Example:
Linear seesaw (inverse mass ordering)

Full analysis at the reconstructed level in preparation ... plus Madgraph "patch" for simulating the oscillations, 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)

... a little remark on the 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 free 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 $m_{\nu i}$, 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

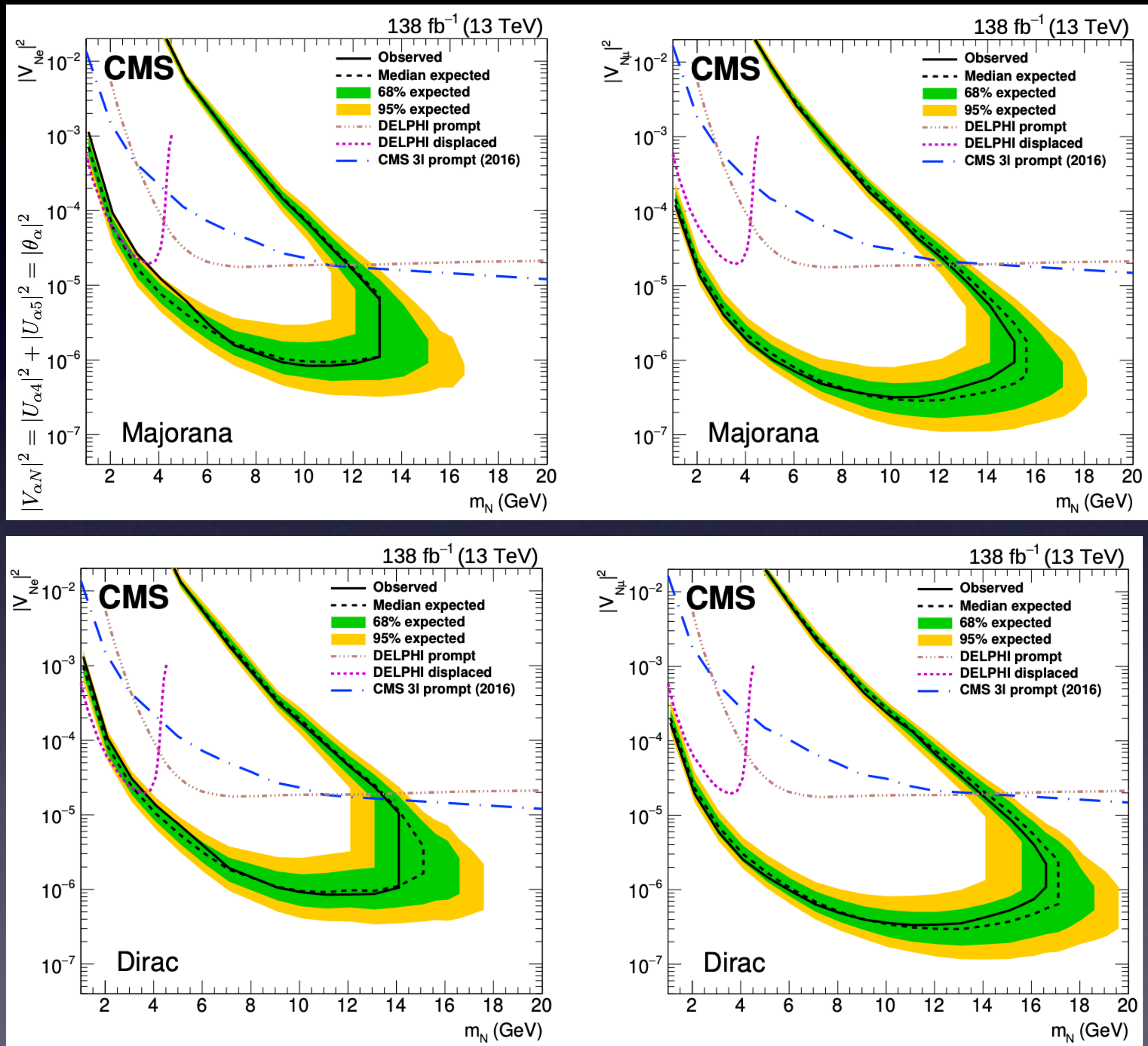
Summary

- With protective "lepton number"-like symmetry, the small observed m_ν can be explained with "large y_ν" and ~ EW/TeV scale M_R. 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 understood as emerging from 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!

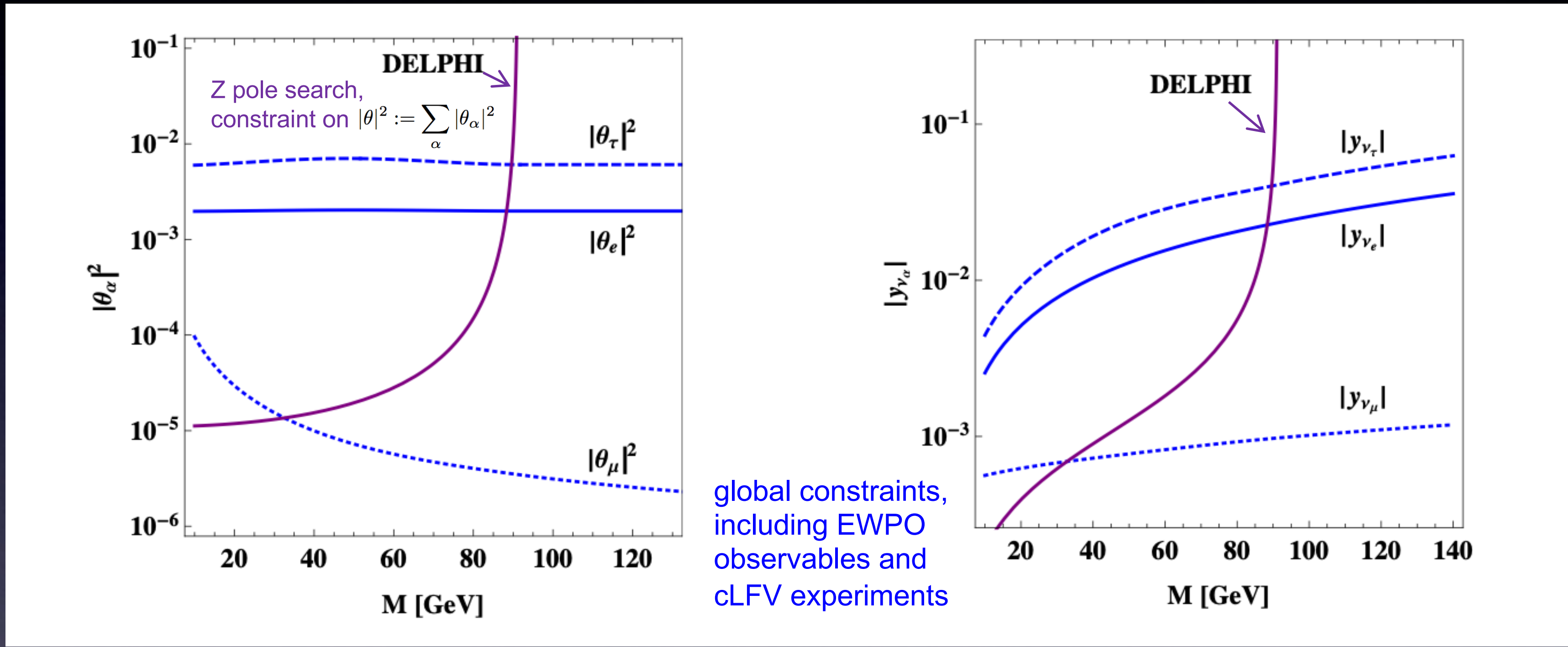
Extra Slides 1: Present constraints

Strongest bounds for $M < M_W$ currently by CMS



CMS Collaboration
arXiv: 2201.05578

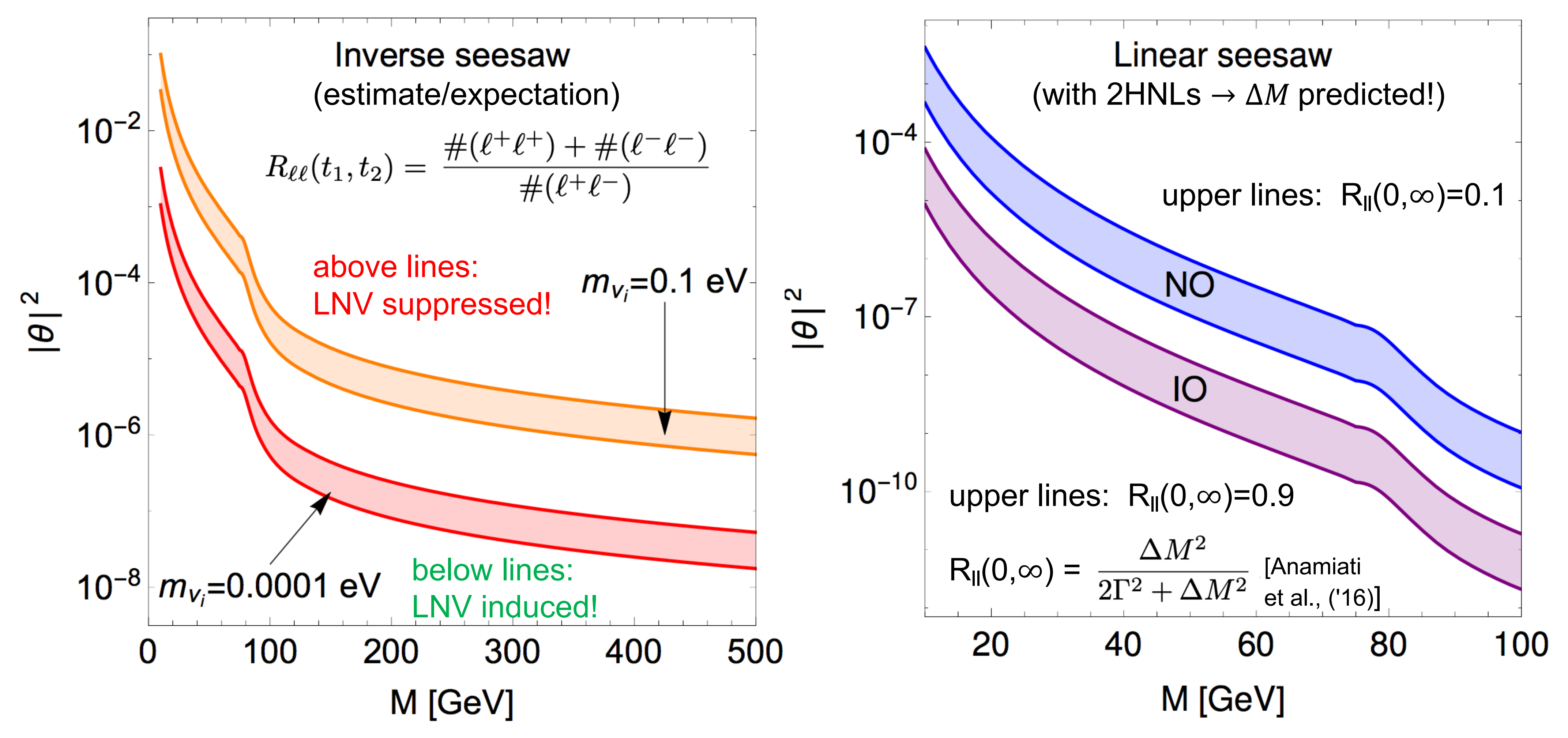
In addition: Constraints from precision experiments (EWPO, cLFV, ...) – also apply to higher M



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)

Extra Slides 2: SPSS parameters for which LNV is induced

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



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

Integrated effect, see also: G. Anamiati, M. Hirsch and E. Nardi (hep-ph/1607.05641), M. Drewes, J. Klaric, P. Klose (hep-ph/1907.13034)