

Heavy Neutral Lepton Searches at Future Colliders

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Heavy neutral leptons can be an answer to one of the big open questions in BSM physics:

What is the origin of the observed neutrinos masses?

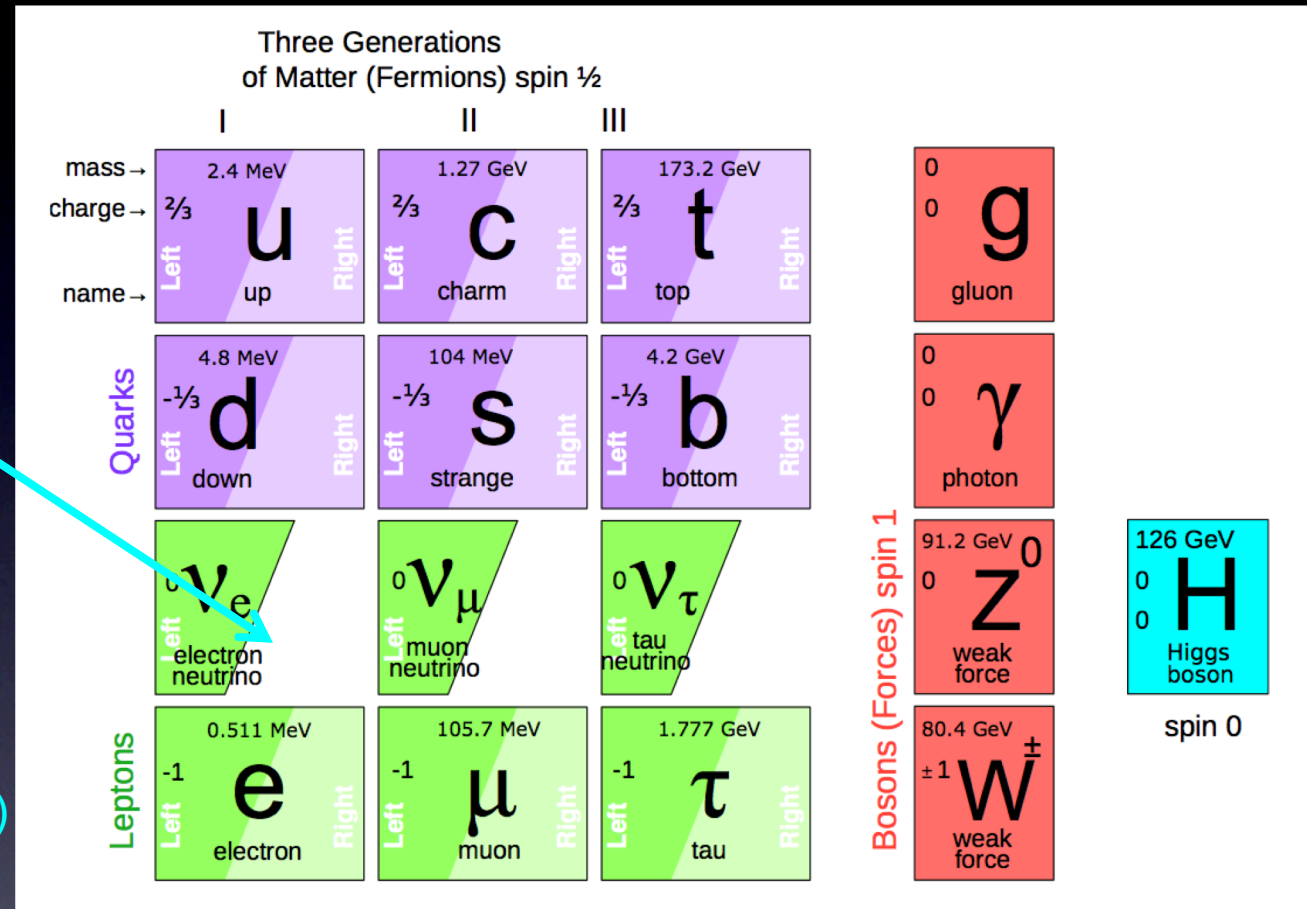
Main topic of my talk:

**EW/TeV scale heavy neutral leptons
(= "right-handed neutrinos" = "sterile ν s")**

Sterile neutrinos – the missing piece of the Standard Model?

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

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



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

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{2} \overline{\nu_R^I} M_{IJ}^N \nu_R^{cJ} - (Y_N)_{I\alpha} \overline{\nu_R^I} \tilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

M: sterile ν mass matrix

Y_N : neutrino Yukawa matrix (Dirac mass terms)

Light neutrino masses via the “seesaw mechanism”

Mass matrix of the (three) light neutrinos

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

$$(m_\nu)_{\alpha\beta} = -\frac{v_{EW}^2}{2} \left(Y_\nu^T \cdot M^{-1} \cdot Y_\nu \right)_{\alpha\beta}$$

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

„Seesaw Formula“

From neutrino oscillation experiments and mass searches:

$$\begin{aligned} |m_3^2 - m_1^2| &\approx 2.4 \cdot 10^{-3} \text{ eV}^2 \\ m_2^2 - m_1^2 &\approx 7.5 \cdot 10^{-5} \text{ eV}^2 \\ \text{all three } m_i &\text{ below } \sim 0.2 \text{ eV} \end{aligned}$$

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

Neutrino Yukawa matrix

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)

What do the measured light neutrino parameters tell us about the heavy neutrino parameters M and Y_ν ?

What do we know about the neutrino parameters?

Getting started: $1 \nu_R, 1 \nu_L$

$$\Rightarrow m_\nu = \frac{1}{2} \frac{v_{EW}^2 |y_\nu|^2}{M_R}$$

→ Knowledge of m_ν implies relation between y_ν and M_R

“Naive” seesaw relation: $y_\nu^2 < O(10^{-13}) (M / 100 \text{ GeV})$

What do we know about the sterile neutrino parameters?

Example 1: $2 \nu_R, 2 \nu_L$

Example of a small perturbation

$$Y_\nu = \begin{pmatrix} \sigma(y_\nu) & 0 \\ 0 & \sigma(y_\nu) \end{pmatrix}, \quad M = \begin{pmatrix} M_R & 0 \\ 0 & M_R + \epsilon \end{pmatrix}$$
$$\Rightarrow m_{\nu_i} = \frac{v_{EW}^2 \sigma(y_\nu^2)}{M_R} (1 + \epsilon \delta_{i2})$$

→ Also in this example: Knowledge of m_{ν_i} implies relation between y_{ν_i} and M_R

What do we know about the sterile neutrino parameters?

Example 2: $2 \nu_R, 2 \nu_L$

Similar: “inverse” seesaw, “linear” seesaw

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), ...

$$Y_\nu = \begin{pmatrix} \sigma(y_\nu) & 0 \\ \sigma(y_\nu) & 0 \end{pmatrix}, \quad M = \begin{pmatrix} 0 & M_R \\ M_R & \epsilon \end{pmatrix}$$
$$\Rightarrow m_\nu = 0 + \epsilon \frac{v_{EW}^2 \sigma(y_\nu^2)}{M_R^2}$$

Example of a small perturbation

→ In general: No “fixed relation” between y_ν and M_R , larger y_ν possible!

What do we know about the sterile neutrino parameters?

Example 2: $2 \nu_R, 2 \nu_L$

Similar: “inverse” seesaw, “linear” seesaw

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Example for “protective” symmetry:

	L_α	ν_{R1}	ν_{R2}
“Lepton-#”	+1	+1	-1

Note: Can be realized by symmetries, e.g. by an (approximate) “lepton number”-like symmetry

What do we know about the sterile neutrino parameters?

Important consequence of such a protective "lepton number"-like symmetry:

Lepton number violating (LNV) effects are suppressed. This applies to

- LNV search channels at colliders (at least for prompt searches, more later)
- Neutrinoless double beta decay (not enhanced by heavy ν_R exchange).

“inverse” seesaw, “linear” seesaw

$$\begin{pmatrix} 0 & M_R \\ M_R & \epsilon \end{pmatrix}$$

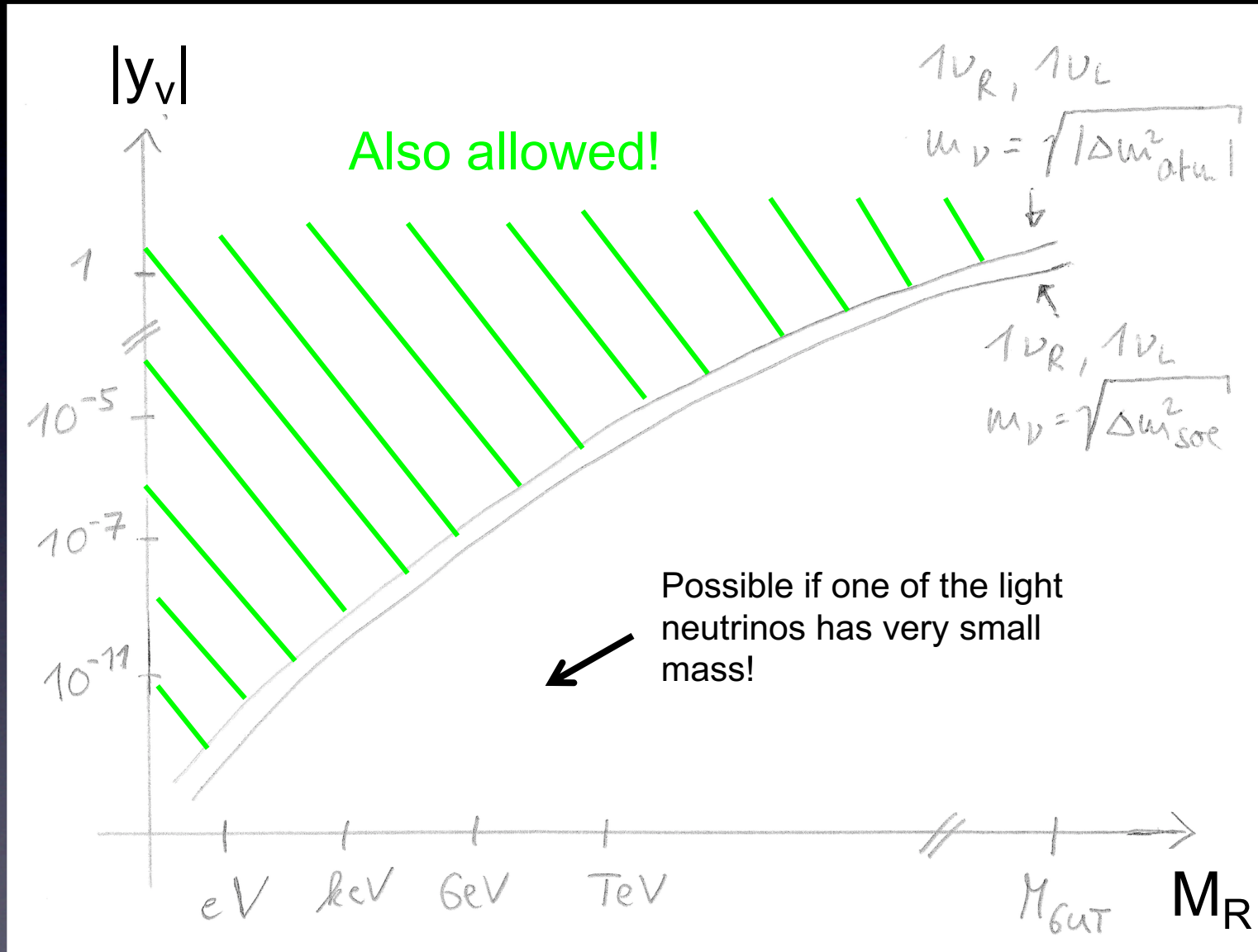
$$\Rightarrow m_\nu = \epsilon \frac{v_{EW}^2 \mathcal{O}(y_\nu^2)}{M_R^2}$$

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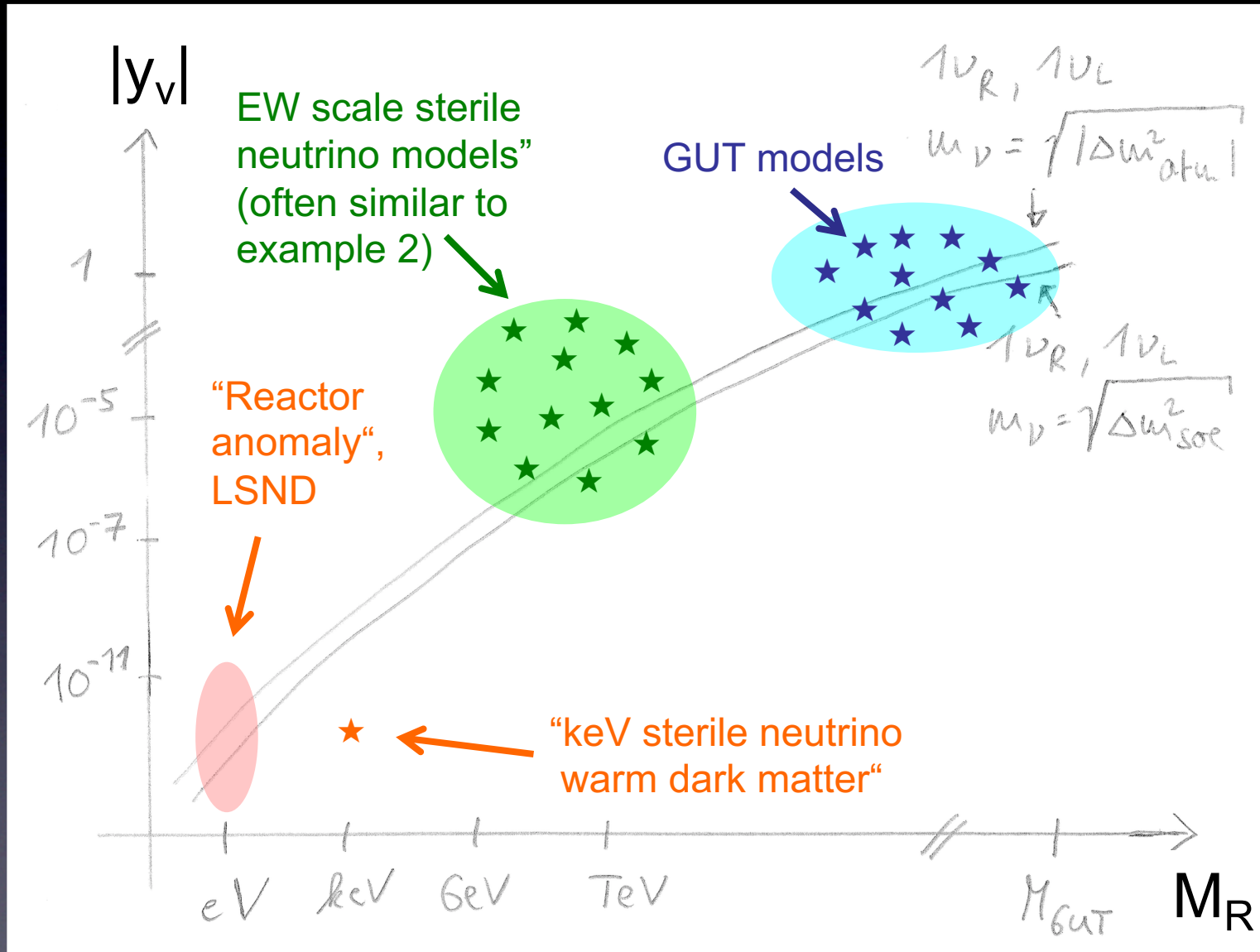
Possible values of M_R and y_ν



Not considering experimental constraints

“Landscape” of sterile neutrino models

Examples, schematic



Not considering experimental constraints

A benchmark model (simplified model) for low scale seesaw scenarios ...

A benchmark model for EW scale sterile ν : SPSS (Symmetry Protected Seesaw Scenario)

Consider $2+n$ sterile neutrinos (plus the three active) \rightarrow with M and Y_ν for two of the steriles as in example 2 due to some generic “lepton number”-like symmetry)

$$Y_\nu = \begin{pmatrix} y_{\nu e} & 0 \\ y_{\nu \mu} & 0 \dots \\ y_{\nu e} & 0 \end{pmatrix}, \quad M = \begin{pmatrix} 0 & M_R & & & \\ M_R & 0 & & & \\ \dots & & \dots & & \\ & & & * & * \dots \\ & & & * & * \dots \end{pmatrix}$$

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

Similar: “inverse” seesaw, “linear” seesaw

For details on the SPSS, see:

S.A., O. Fischer (arXiv:1502.05915)

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

A benchmark model SPSS (Symmetry Protection)

Consider $2+n$ sterile neutrinos (plus the active ones) and treat the steriles as in example 2 due to some

Comment: Since in the SPSS we allow for additional sterile neutrinos, M and y_α ($\alpha=e,\mu,\tau$) are indeed free parameters (not constrained by m_ν). In specific models there are correlations among the y_α . Strategy of the SPSS: study how to measure the y_α independently, in order to test (not a priori assume) such correlations!

$$Y_\nu = \begin{pmatrix} y_{\nu e} & 0 \\ y_{\nu \mu} & 0 \dots \\ y_{\nu \tau} & 0 \end{pmatrix}, \quad M = \begin{pmatrix} 0 & M_R & & & \\ M_R & 0 & & & \\ \dots & & \dots & & \\ & & & * & * \dots \\ & & & * & * \dots \end{pmatrix}$$

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$$Y_\nu = \begin{pmatrix} y_{\nu e} & 0 \\ y_{\nu \mu} & 0 \\ y_{\nu \tau} & 0 \end{pmatrix} \quad M = \begin{pmatrix} 0 & M_R & \\ M_R & 0 & \\ & & 0 \end{pmatrix}$$

+ $O(\epsilon)$
perturbations
to generate the
neutrino

For example: Low scale seesaw with 2 sterile neutrinos: y_α/y_β given in terms of the PMNS parameters. E.g. for NO:

$$Y_N^T \simeq y \begin{pmatrix} e^{i\delta} s_{13} + e^{-i\alpha} s_{12} r^{1/4} \\ s_{23} \left(1 - \frac{\sqrt{r}}{2} \right) + e^{-i\alpha} r^{1/4} c_{12} c_{23} \\ c_{23} \left(1 - \frac{\sqrt{r}}{2} \right) - e^{-i\alpha} r^{1/4} c_{12} s_{23} \end{pmatrix}$$

we can
neglect for
studies)

For details on the SPSS, see:

S.A., O. Fischer (arXiv:1502.05915)

Cf.: Gavela, Hambye, D. Hernandez, P. Hernandez ('09)

What are the observable effects of EW scale heavy neutral leptons?

(This part we neglect the $O(\varepsilon)$ effects; will be discussed later ...)

As example: SPSS (Symmetry Protected Seesaw Scenario)

In the
symmetry
limit:

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

As example: SPSS (Symmetry Protected Seesaw Scenario)

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

4 Parameters:
 $M, y_\alpha, (\alpha=e,\mu,\tau)$

As example: SPSS (Symmetry Protected Seesaw Scenario)

In the
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$$\mathcal{L}_N = - \overline{N_R}^1 M N_R^c - y_\alpha \overline{N_R}^1 \tilde{\phi}^\dagger L^\alpha + \text{H.c.} \\ + \dots \text{ (terms from additional sterile vs)}$$

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:

$$n = (\nu_{eL}, \nu_{\mu L}, \nu_{\tau L}, (N_R^1)^c, (N_R^2)^c)^T$$

“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:

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

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

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

Parameters:

M, y_α ($\alpha=e,\mu,\tau$)
or

equivalently

M, θ_α ($\alpha=e,\mu,\tau$)

- ▶ Active-sterile neutrino mixing parameters:

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

Observable effects of the sterile neutrinos: $M \gg \Lambda_{EW}$

(Effective) mixing matrix of light neutrinos is a submatrix of a larger unitary mixing matrix (mixing with additional heavy particles)

Main effect for $M \gg \Lambda_{EW}$:
“Leptonic non-unitarity”

Langacker, London ('88); S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06), ...
Gives rise to NSIs at source, detector & with matter: see e.g. S.A., Baumann, Fernandez-Martinez (arXiv:0807.1003)
Global constraints on $\epsilon_{\alpha\beta}$: S.A., Fischer (arXiv:1407.6607)

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

Non-unitarity parameters:

$$(NN^\dagger)_{\alpha\beta} = (1_{\alpha\beta} + \epsilon_{\alpha\beta})$$

$\Rightarrow U_{PMNS} \equiv N \Rightarrow$ various obs. effects!
is non-unitary

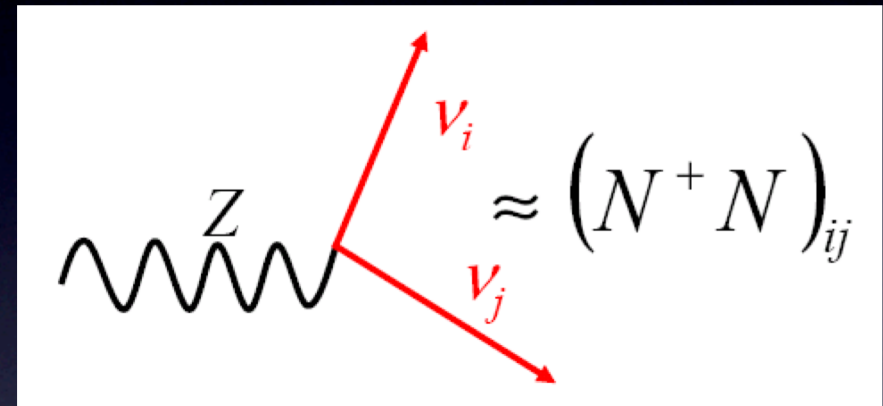
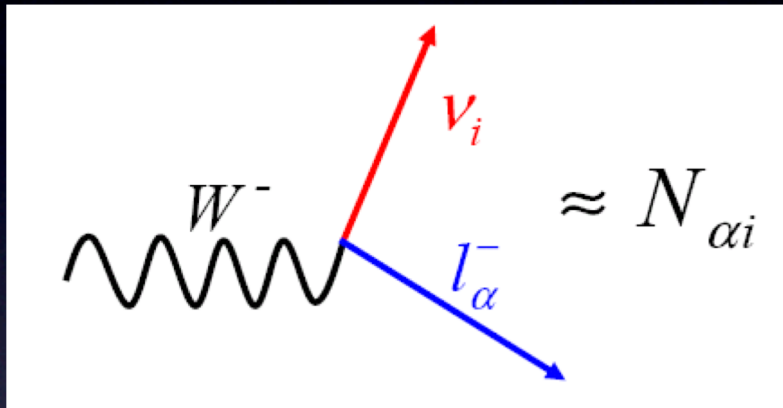
Relation to the parameters of the SPSS benchmark model

	$y_{\nu\alpha}$	θ_α	$\epsilon_{\alpha\beta}$
$y_{\nu\alpha} =$	–	$\frac{\sqrt{2M}}{v_{EW}} \theta_\alpha^*$	$-\frac{\sqrt{2M}}{v_{EW}} \epsilon_{\beta\alpha} / \sqrt{-\epsilon_{\beta\beta}}$
$\theta_\alpha =$	$\frac{v_{EW}}{\sqrt{2M}} y_{\nu\alpha}^*$	–	$-\epsilon_{\beta\alpha} / \sqrt{-\epsilon_{\beta\beta}}$
$\epsilon_{\alpha\beta} =$	$-\frac{v_{EW}^2 y_{\nu\alpha}^* y_{\nu\beta}}{2M^2}$	$-\theta_\alpha^* \theta_\beta$	–

Non-unitarity
parameters

Active-sterile
neutrino mixing

EW interactions of the light neutrinos are modified



- Theory predictions for various observables which involve weak interactions get modified!

Since it changes, for example, the **determination of G_F from muon decay**, it has indirect effects on a large number of observables (e.g. on all the **Electroweak Precision Observables (EWPOs)**).

Indirect effects of sterile neutrinos: electroweak precision observables modified

Prediction in MUV	Prediction in the SM	Experiment
$[R_\ell]_{\text{SM}} (1 - 0.15(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\text{SM}} (1 + 0.03(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.21577(4)	0.21629(66)
$[R_c]_{\text{SM}} (1 - 0.06(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.17226(6)	0.1721(30)
$[\sigma_{had}^0]_{\text{SM}} (1 - 0.25(\varepsilon_{ee} + \varepsilon_{\mu\mu}) - 0.27\varepsilon_{\tau\tau})$	41.470(15) nb	41.541(37) nb
$[R_{inv}]_{\text{SM}} (1 + 0.75(\varepsilon_{ee} + \varepsilon_{\mu\mu}) + 0.67\varepsilon_{\tau\tau})$	5.9721(10)	5.942(16)
$[M_W]_{\text{SM}} (1 - 0.11(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	80.359(11) GeV	80.385(15) GeV
$[\Gamma_{\text{lept}}]_{\text{SM}} (1 - 0.59(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	83.966(12) MeV	83.984(86) MeV
$[(s_{W,\text{eff}}^{\ell,\text{lep}})^2]_{\text{SM}} (1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[(s_{W,\text{eff}}^{\ell,\text{had}})^2]_{\text{SM}} (1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.23150(1)	0.23222(27)

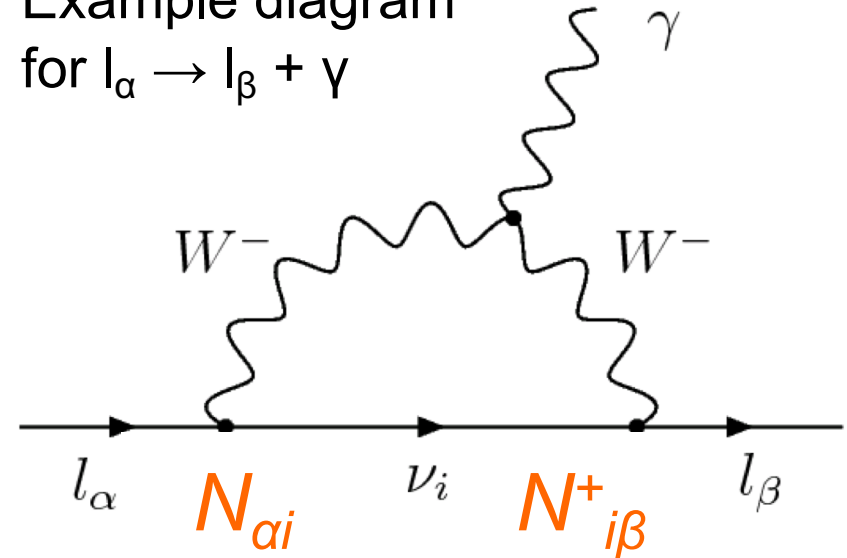
taken from: S.A., O. Fischer (arXiv:1407.6607)

Sensitivity via G_F !

Constraints from cLFV

- Bounds on LFV μ and τ decays $l_i \rightarrow l_j \gamma$ (and on $\mu \rightarrow 3e$ and $\mu \rightarrow e$ conversion in nuclei) lead to constraints on the $|\epsilon_{\alpha\beta}|$:

Example diagram for $l_\alpha \rightarrow l_\beta + \gamma$



$$\frac{\Gamma(l_\alpha \rightarrow l_\beta \gamma)}{\Gamma(l_\alpha \rightarrow \nu_\alpha l_\beta \bar{\nu}_\beta)} = \frac{3\alpha}{32\pi} \frac{|\sum_k N_{\alpha k} N_{k\beta}^\dagger F(x_k)|^2}{(NN^\dagger)_{\alpha\alpha} (NN^\dagger)_{\beta\beta}}$$

irrelevant for unitary mixing matrix, but can lead to sizable Br's for non-unitary N!

$$F(x) \equiv \frac{10 - 43x + 78x^2 - 49x^3 + 4x^4 + 18x^3 \ln x}{3(x-1)^4}$$

where:

$$x_k \equiv m_k^2 / M_W^2$$

m_k : light neutrinos' masses

Observable effects of the sterile neutrinos: $M \cong \Lambda_{EW}$

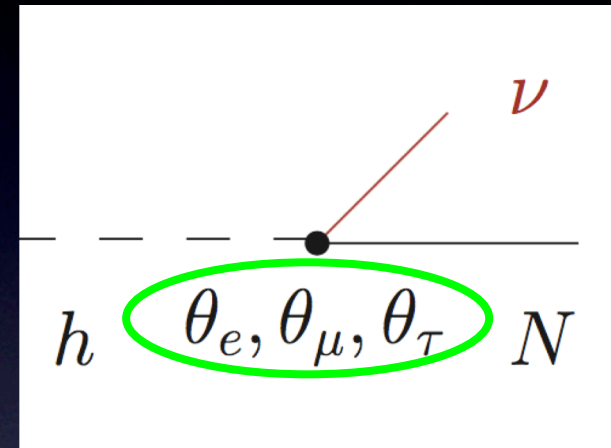
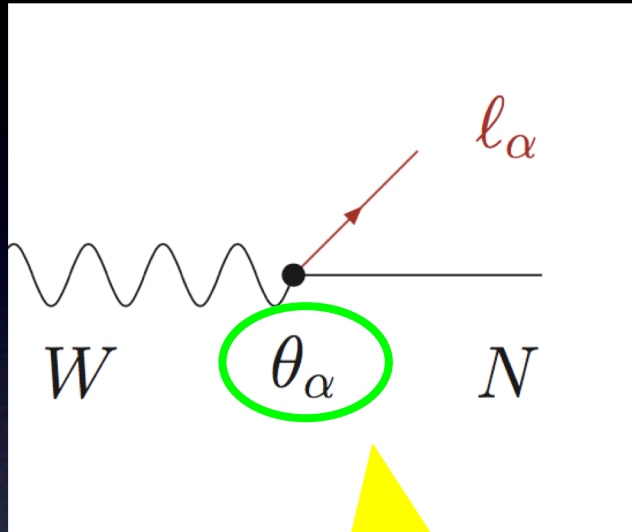
In addition for $M \cong \Lambda_{EW}$: Effects
from on-shell heavy neutrinos

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

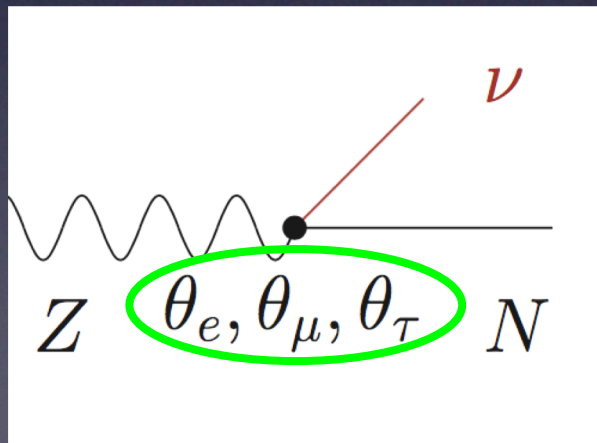
$$U = \begin{pmatrix} \mathcal{N}_{1e} & \mathcal{N}_{1\mu} & \mathcal{N}_{1\tau} & -\frac{i}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{2e} & \mathcal{N}_{2\mu} & \mathcal{N}_{2\tau} & -\frac{i}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{3e} & \mathcal{N}_{3\mu}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

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

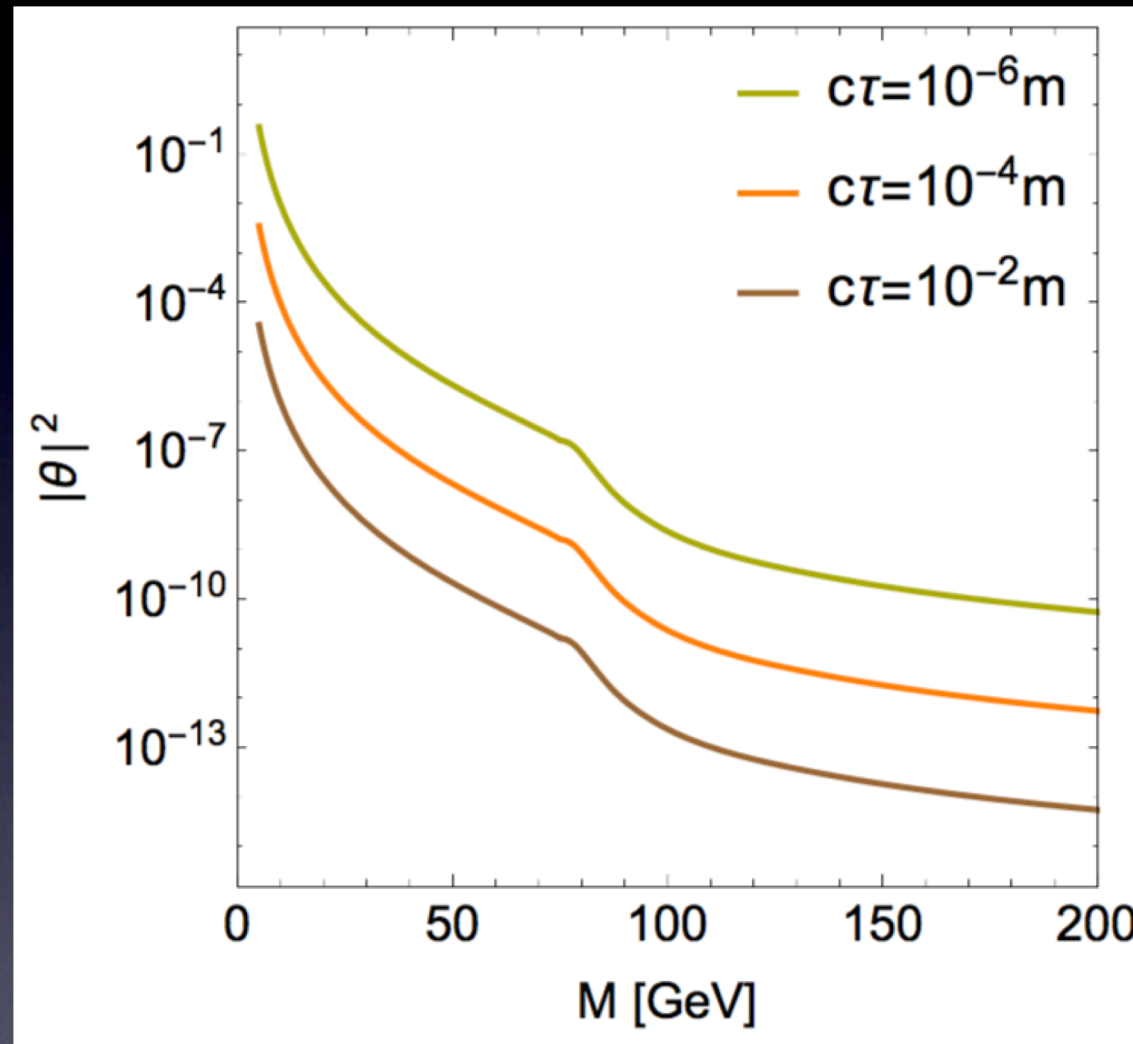
Heavy neutrino interactions



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



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

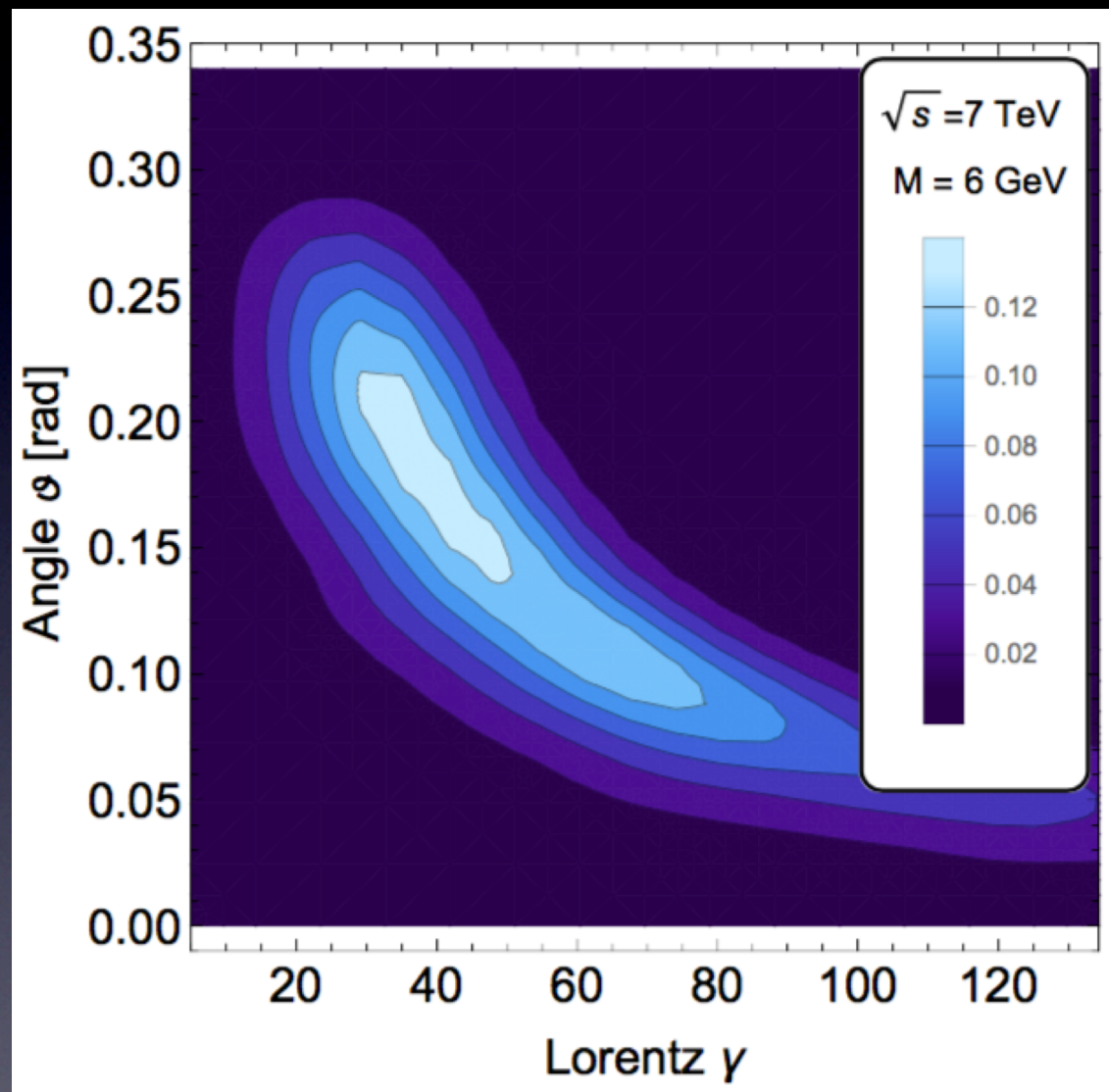


Note: Decay length in the laboratory frame is:

$$c\tau \sqrt{\gamma^2 - 1}$$

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

A typical distribution for the γ -factor for heavy neutrinos N at the LHC



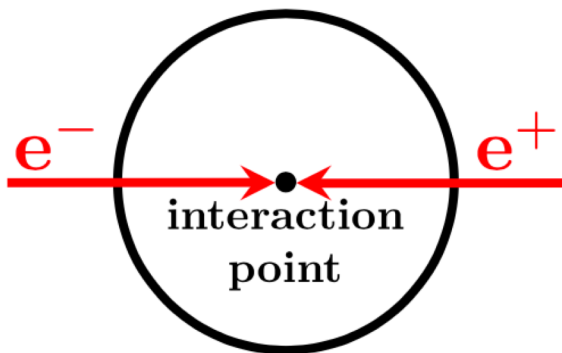
S. A., E. Cazzato, O. Fischer; arXiv:1706.05990

Very sensitive searches possible for $M < m_W$ via “displaced vertices”

E.g. at an e^+e^- collider:

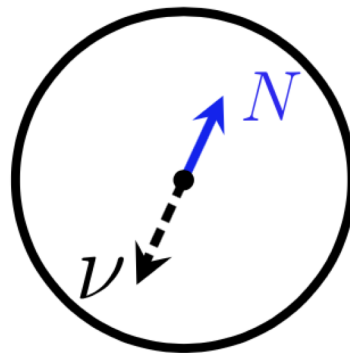
$t = 0$

electron-positron
collision



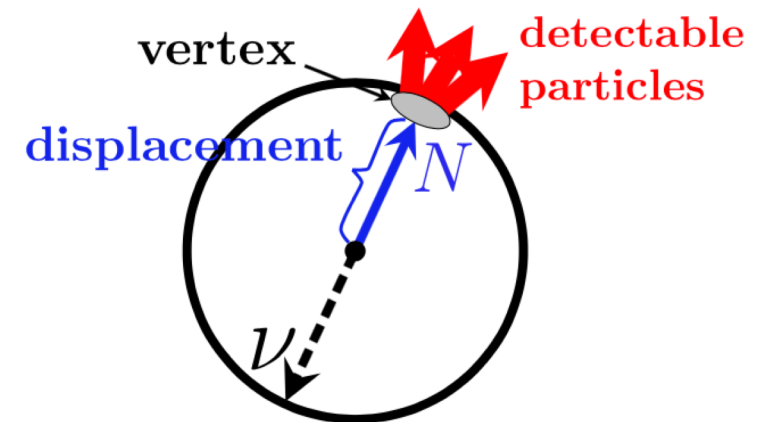
$0 < t < \text{lifetime of } N$

production of N
and propagation



$\text{lifetime of } N < t$

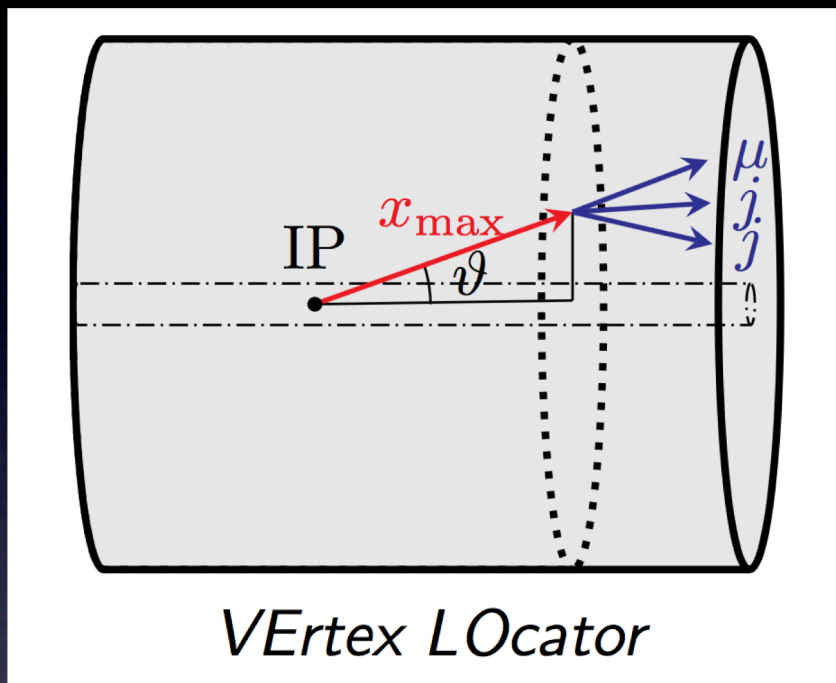
decay of N into
detectable particles



Present constraints on EW scale heavy (sterile) neutrinos

Note: I will consider the SPSS as a benchmark and restrict myself to $M > 5 \text{ GeV}$

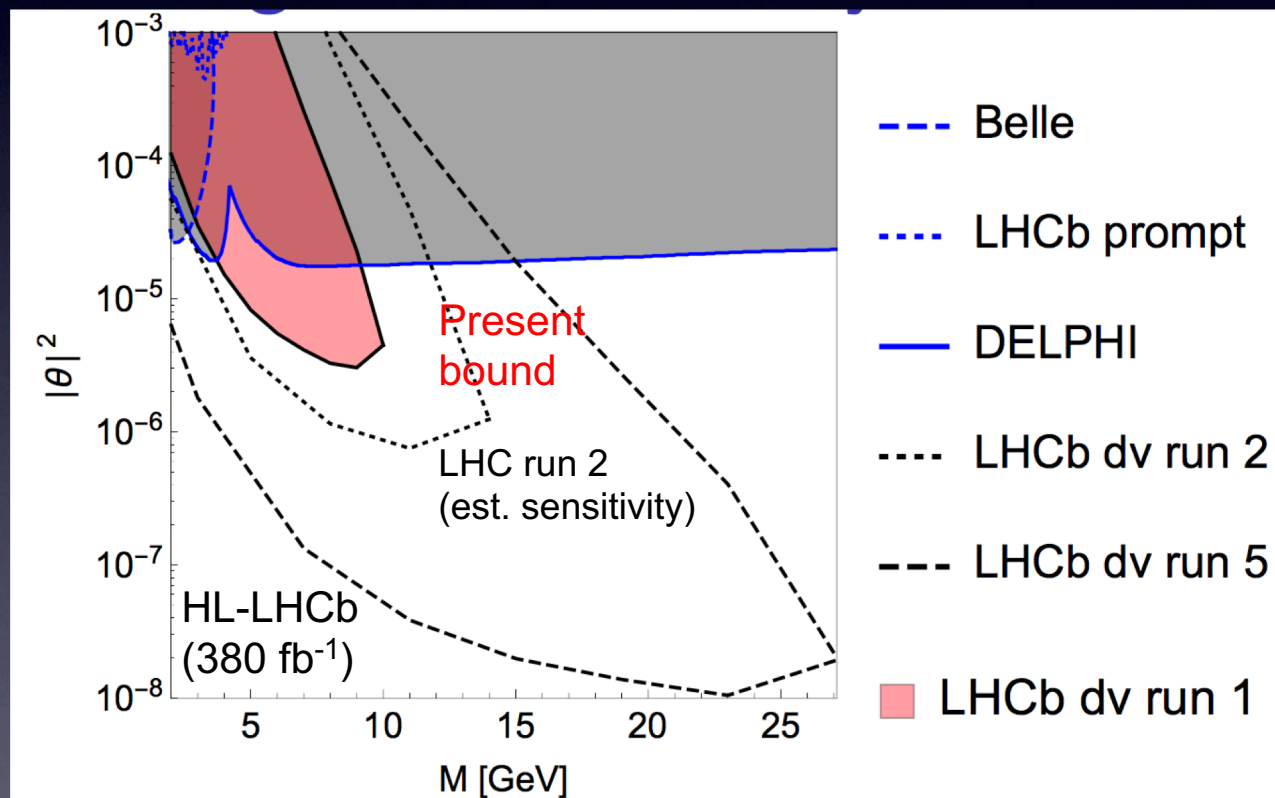
Present bounds (& estim. future sensitivities) from displaced vertex searches at LHCb



LHCb analysis exists for LHC run 1 data:

LHCb Collaboration, Eur. Phys. J. C 77 (2017) no.4, 224 arXiv:1612.00945

The results can be translated into bounds on $|\theta|^2$
(here for $\theta_e = \theta_\tau = 0$):



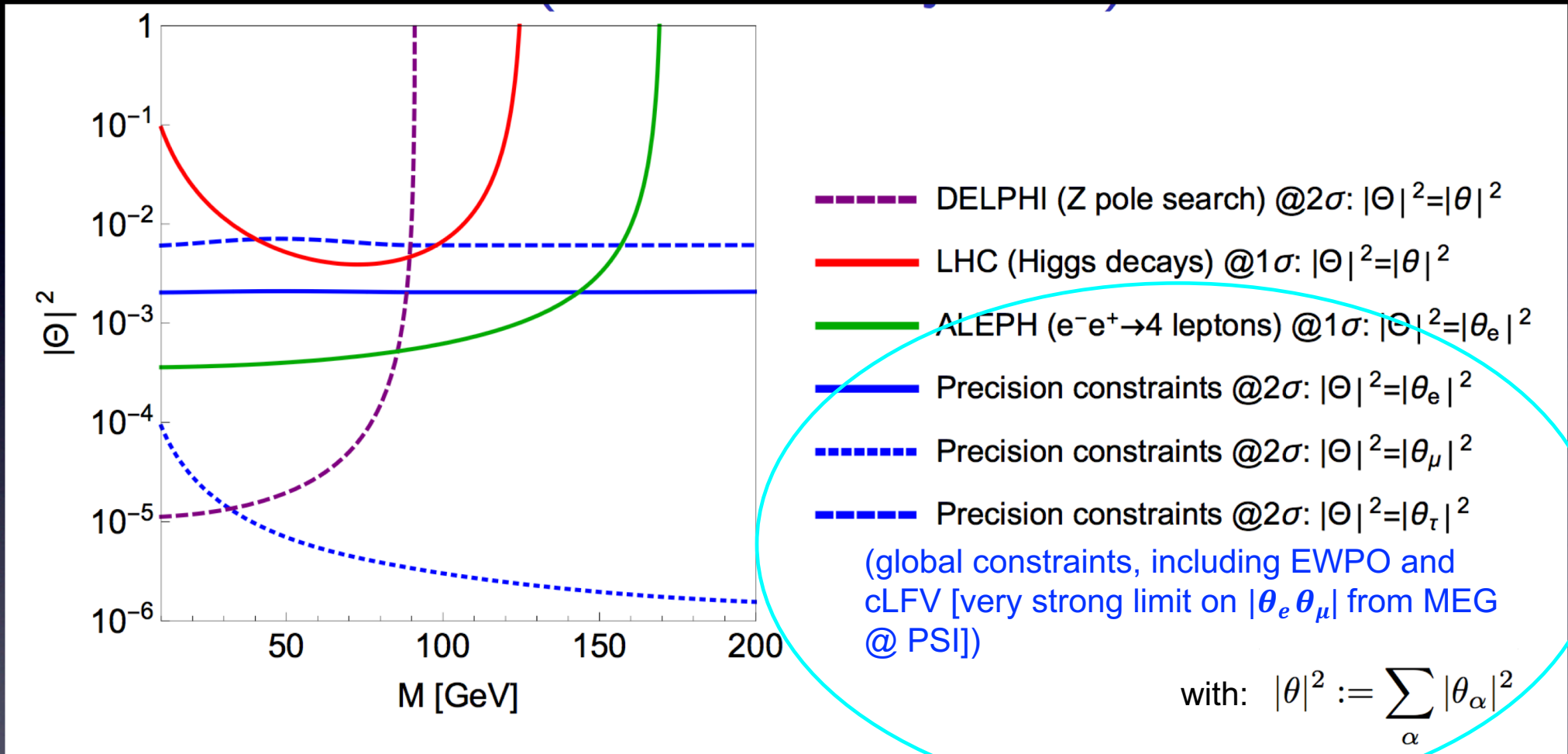
See also recent bounds from ATLAS
and CMS:

ATLAS Collaboration, arXiv:1905.09787

CMS Collaboration, arXiv:1802.02965

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

Present constraints on sterile neutrino parameters (conv. searches, $M > 10$ GeV)



Constraints from present data ($M > 10$ 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 prospects for discovering such heavy neutrinos at future experiments?

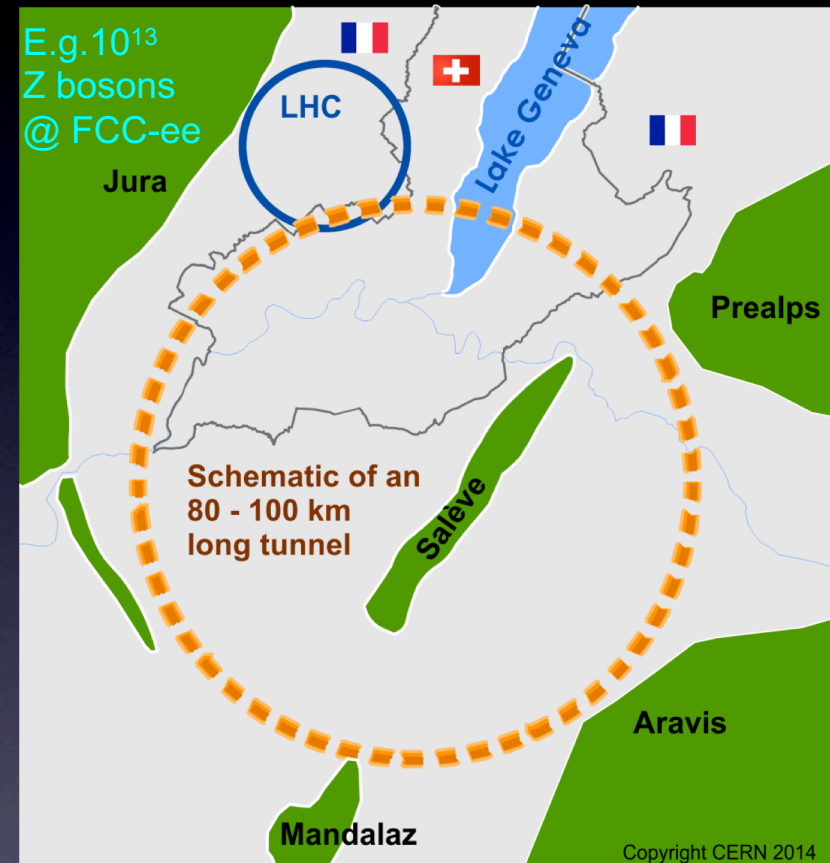
Note: I will consider the SPSS as a benchmark and restrict myself to $M > 10 \text{ GeV}$

Ambitious plans for future colliders ...

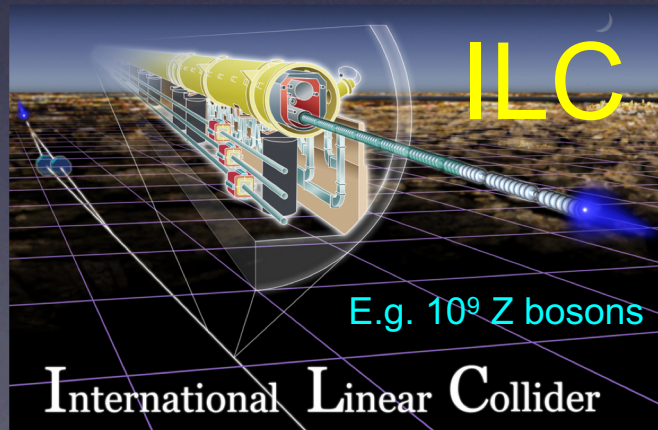
FCC (-ee, -hh, -eh)



plans for circular collider in China



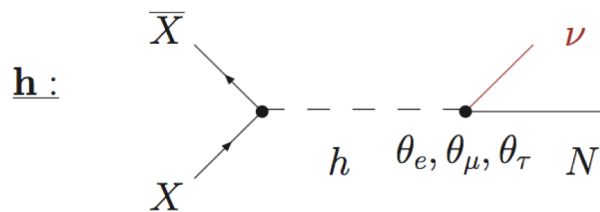
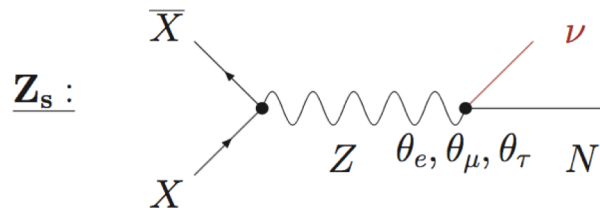
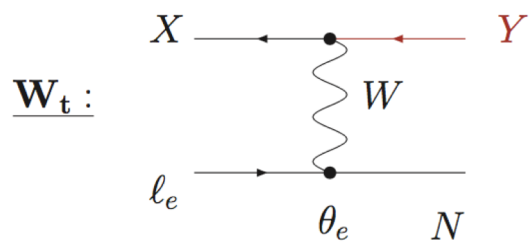
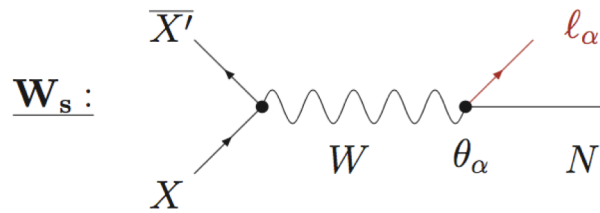
FCC and CEPC may be operated with e^+e^- (in first stage) \rightarrow Z,W,h factory



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 ...

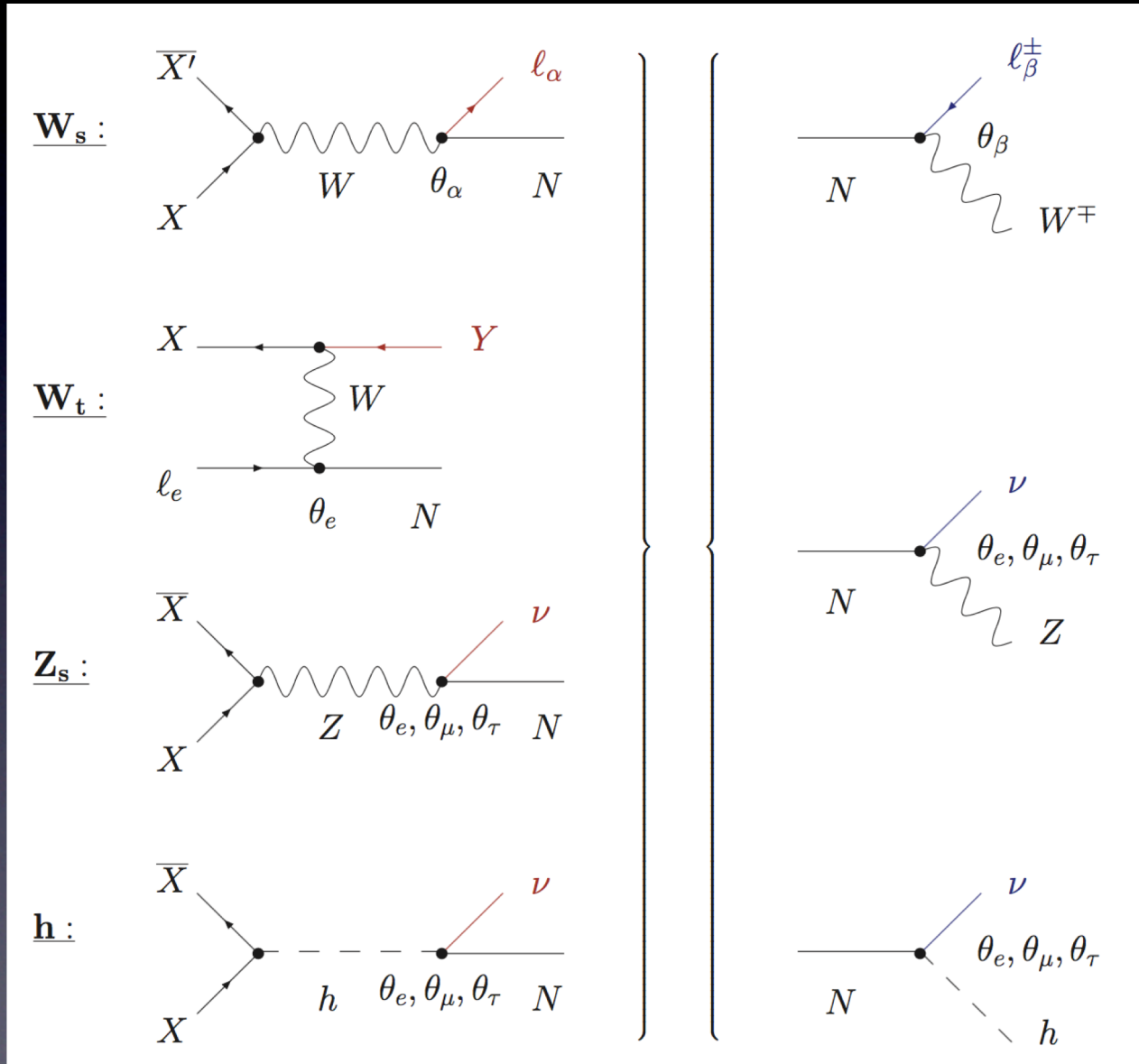
Different collider types feature different production channels ...



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

Systematic assessment of signatures of sterile neutrinos at colliders

(at LO)

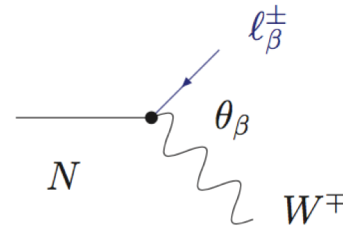
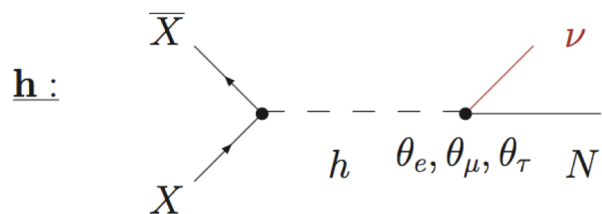
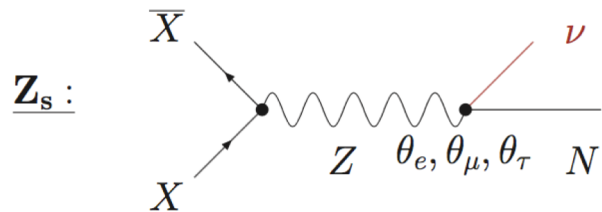
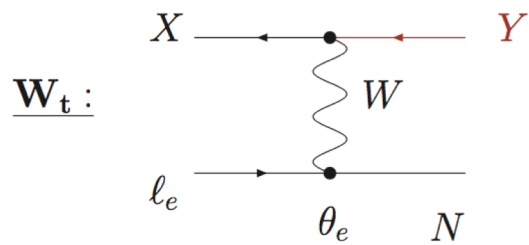
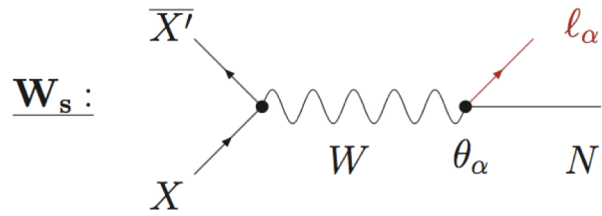


... and, including the different decay channels, sensitivity to different combinations of active-sterile mixing parameters:

		Decay channel	
		W	$Z(h)$
Production channel	\underline{W}_s	$\frac{ \theta_\alpha \theta_\beta ^2}{ \theta ^2}$	$ \theta_\alpha ^2$
	\underline{W}_t	$\frac{ \theta_e \theta_\beta ^2}{ \theta ^2}$	$ \theta_e ^2$
	$\underline{Z}_s(h)$	$ \theta_\beta ^2$	$ \theta ^2$

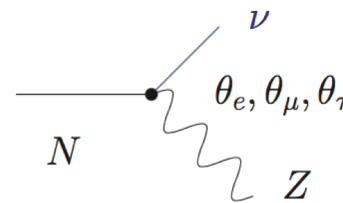
Systematic assessment of signatures of sterile neutrinos at colliders

(at LO)

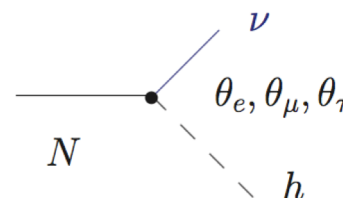


- pp : $l_{\alpha\beta}^{\pm}jj, l_{\alpha\beta}^{\pm}l_{\gamma}^{\mp}\nu$
- e^-e^+, e^-p : $Yl_{\beta}^{\pm}jj, Yl_{\beta}^{\pm}l_{\gamma}^{\mp}\nu$
- e^-e^+, pp : $\nu l_{\beta}^{\pm}jj, \nu l_{\beta}^{\pm}l_{\gamma}^{\mp}\nu$

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

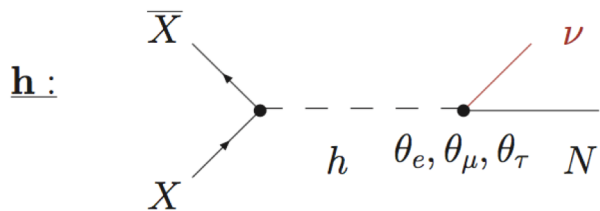
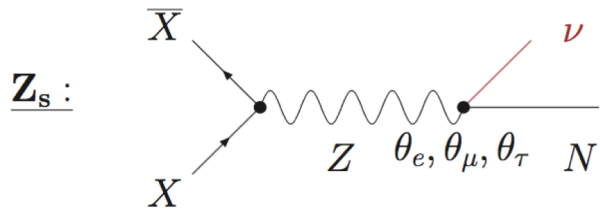
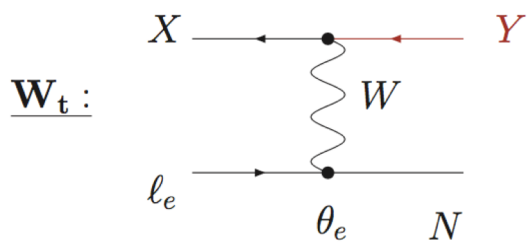
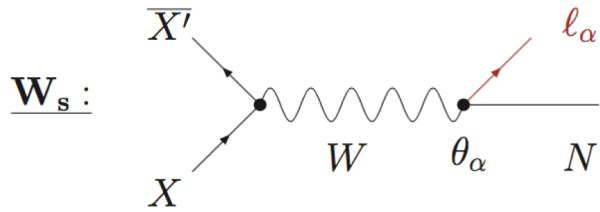


- pp : $l_{\alpha}\nu jj, l_{\alpha}\nu l_{\beta}^{\pm}l_{\beta}^{\mp}, l_{\alpha}\nu\nu\nu$
- e^-e^+, e^-p : $Y\nu jj, Y\nu l_{\beta}^{\pm}l_{\beta}^{\mp}, Y\nu\nu\nu$
- e^-e^+, pp : $\nu\nu jj, \nu\nu l_{\beta}^{\pm}l_{\beta}^{\mp}, \nu\nu\nu\nu$



- pp : $l_{\alpha}\nu jj, l_{\alpha}\nu l_{\beta}^{\pm}l_{\beta}^{\mp}, l_{\alpha}\nu VV$
- e^-e^+, e^-p : $Y\nu jj, Y\nu l_{\beta}^{\pm}l_{\beta}^{\mp}, Y\nu VV$
- e^-e^+, pp : $\nu\nu jj, \nu\nu l_{\beta}^{\pm}l_{\beta}^{\mp}, \nu\nu VV$

Signatures for lepton number violation from sterile neutrinos



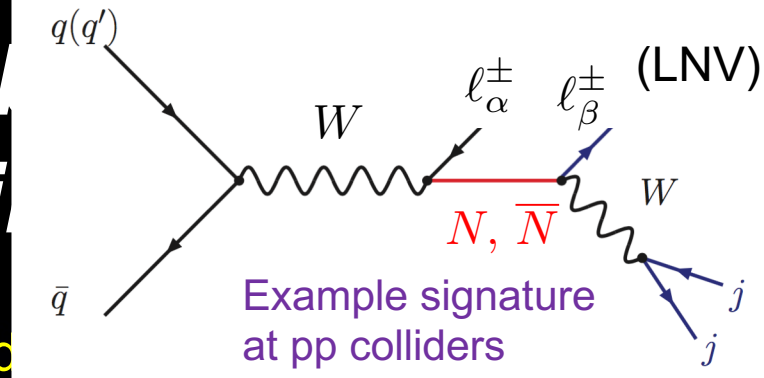
Different collider types feature different production channels:

	e^-e^+	$p\bar{p}$	e^-p
\underline{W}_s	×	✓ +LNV /LFV	×
\underline{W}_t	✓	×	✓ +LNV /LFV
\underline{Z}_s	✓	✓	×
\underline{h}	(✓)	(✓)	(✓)

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

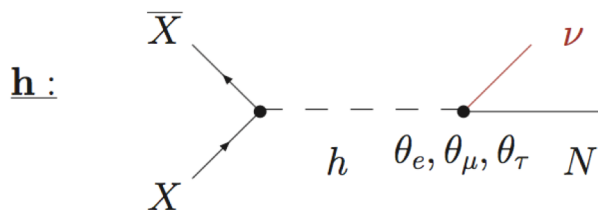
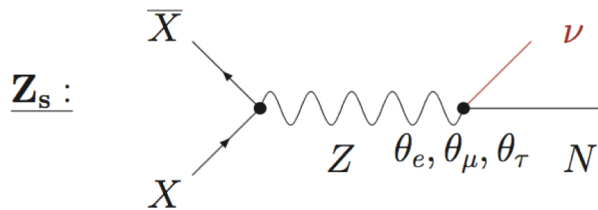
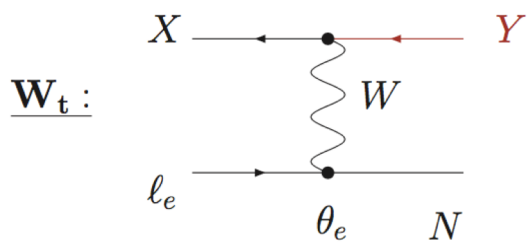
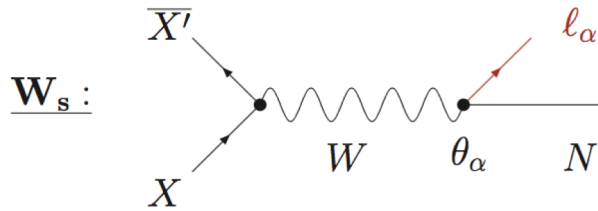
However: LNV can get induced by heavy neutrino-antineutrino oscillations!

Signatures for lepton number violation from sterile neutrinos



Different collision
different production channels:

	e^-e^+	$p\bar{p}$	e^-p
\mathbf{W}_s	×	✓ +LNV /LFV	×
\mathbf{W}_t	✓	×	✓ +LNV /LFV
\mathbf{Z}_s	✓	✓	×
\mathbf{h}	(✓)	(✓)	(✓)



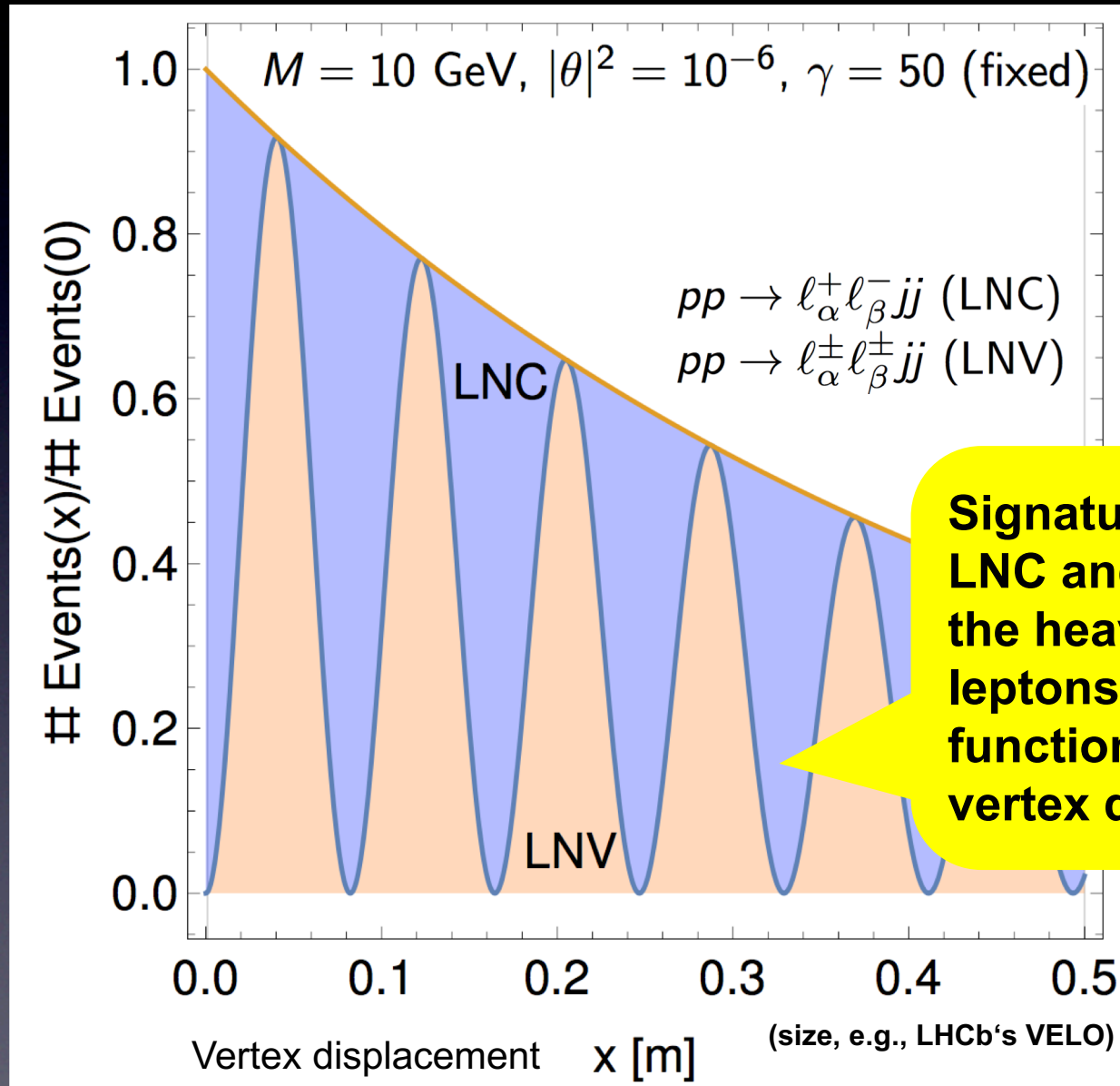
Lepton-number violating (LNV) signatures possible (with no SM background at parton level) but expected to be suppressed by the protective “lepton number”-like symmetry!

However: LNV can get induced by heavy neutrino-antineutrino oscillations!

Recent result: Heavy neutrino-antineutrino oscillations could be resolvable

Example:
Linear seesaw
(inverse mass ordering)

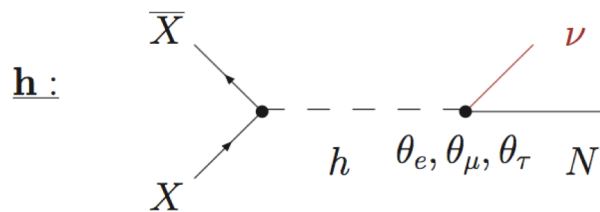
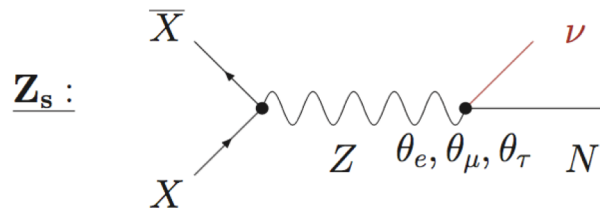
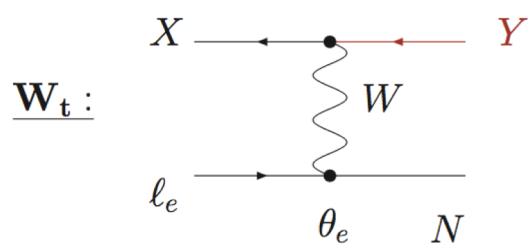
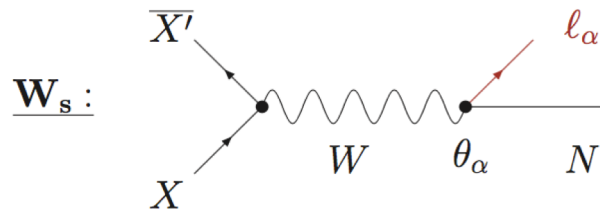
(using the prediction for ΔM in the minimal linear seesaw model for inverse neutrino mass ordering)



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

Signatures with lepton flavour violation

(at LO)



Different collider types feature different production channels:

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

Lepton flavour violating LFV (and lepton number conserving LNC) signatures possible (with no SM background at parton level*). Very promising for future searches!

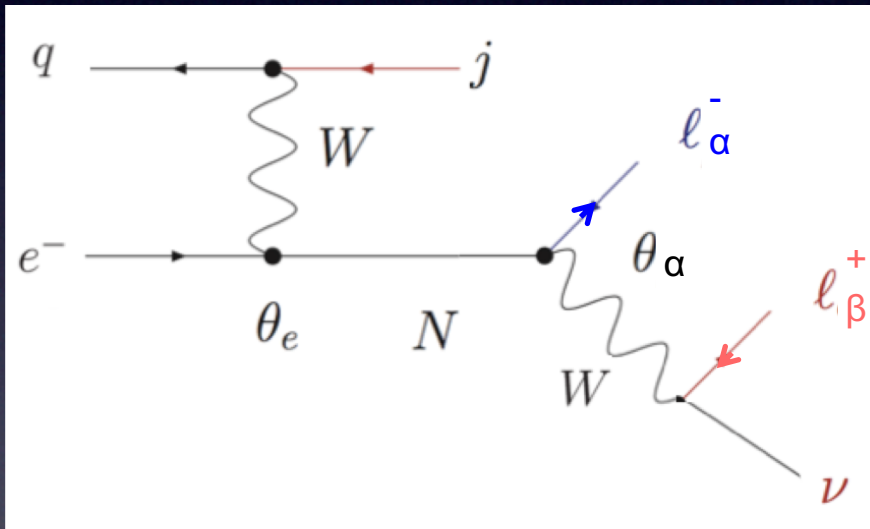
*) Note: Relevant SM background from final states with additional light neutrinos!

Signatures with lepton flavour violation

(at LO)

Different collider types feature different production channels:

Example: Final state at ep colliders (LHeC, FCC-eh): “jet-dilepton”
 $j l_\alpha^- l_\beta^+ \nu$ with e.g. $\alpha = \tau^-$ and $\beta = \mu^+$



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

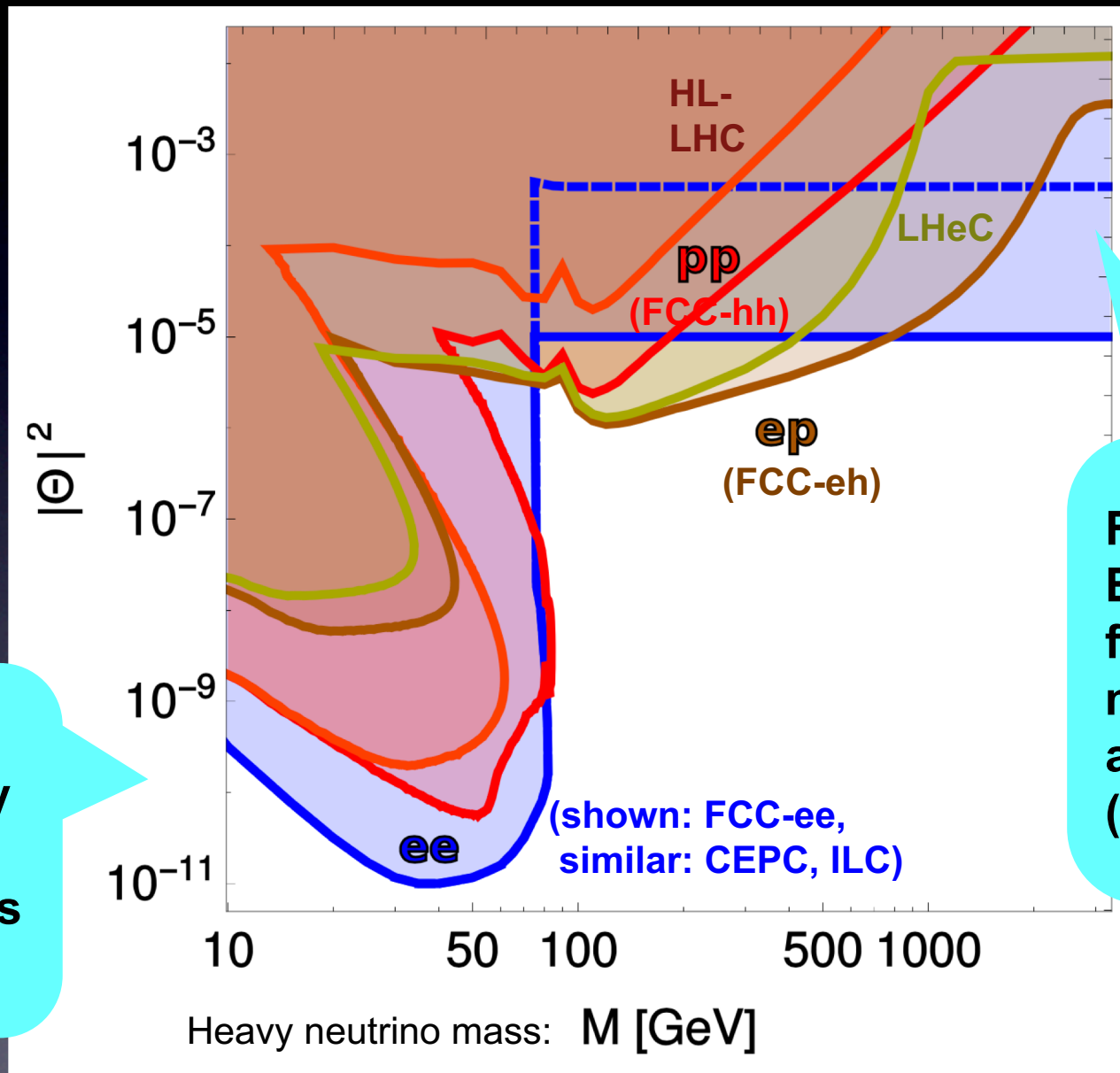
Or e.g.: “dilepton-dijet” at pp colliders (LHC, FCC-hh) $l_\alpha^- l_\beta^+ jj$ with e.g. $\alpha \neq \beta$

	e^-e^+	pp	e^-p
W_s	×	✓ + LNV/LFV	×
W_t	✓	×	✓ + LNV/LFV
Z_s	✓	✓	×
h	(✓)	(✓)	(✓)

Lepton flavour violating LFV (and lepton number conserving LNC) signatures possible (with no SM background at parton level*). Very promising for future searches!

*) Note: Relevant SM background from final states with additional light neutrinos!

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

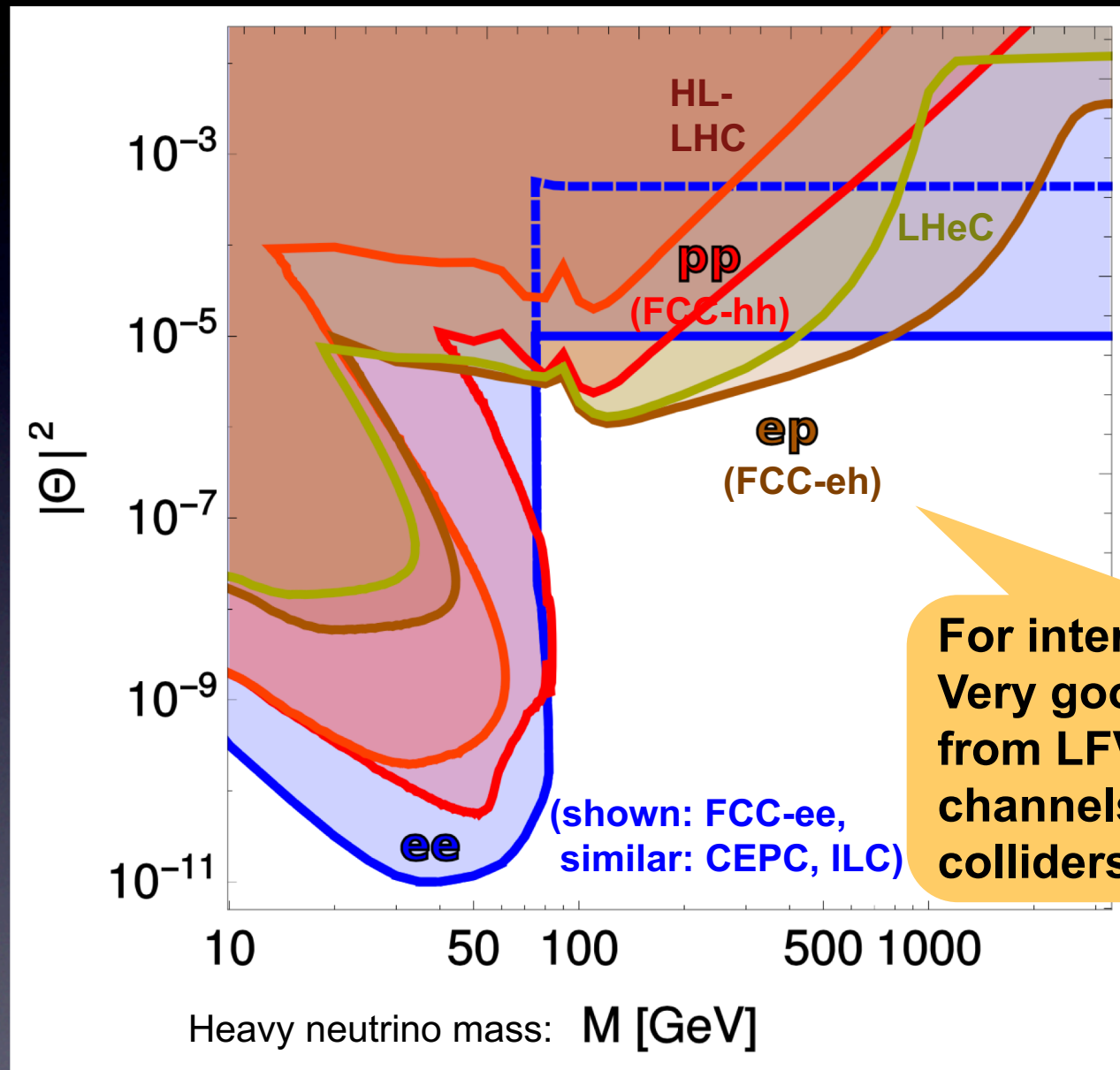


For $M < m_W$:
Best sensitivity
from displaced
vertex searches
at FCC-ee

For $M \gg O(\text{TeV})$:
Best sensitivity
from EWPO
measurements
at FCC-ee
(also: cLFV)

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

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



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

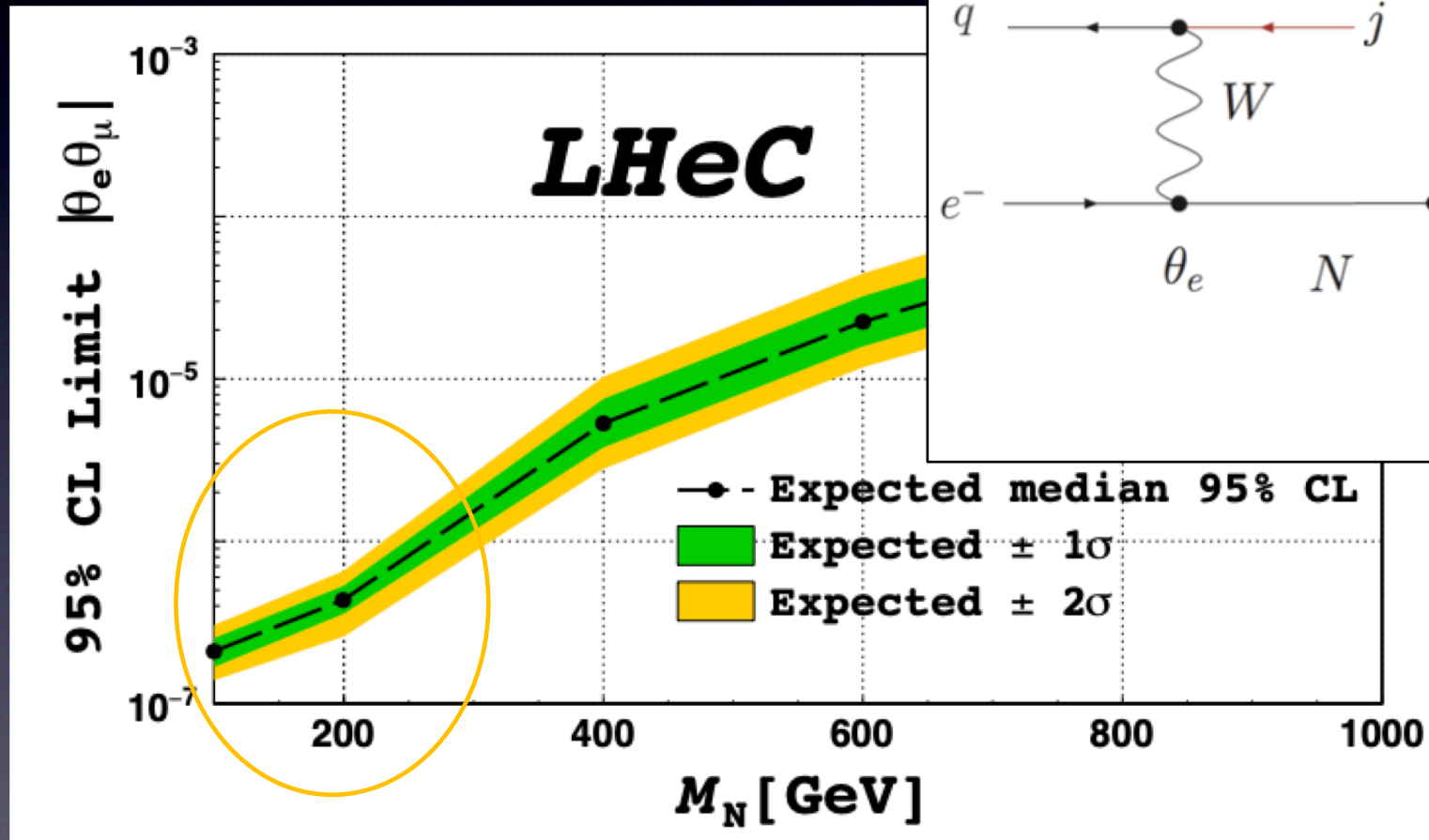
For intermediate M :
 Very good sensitivities from LFV (but LNC) channels at pp and ep colliders (FCC-hh & -eh)

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

Recent result: Sensitivities at ep colliders even better than previously estimated

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

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



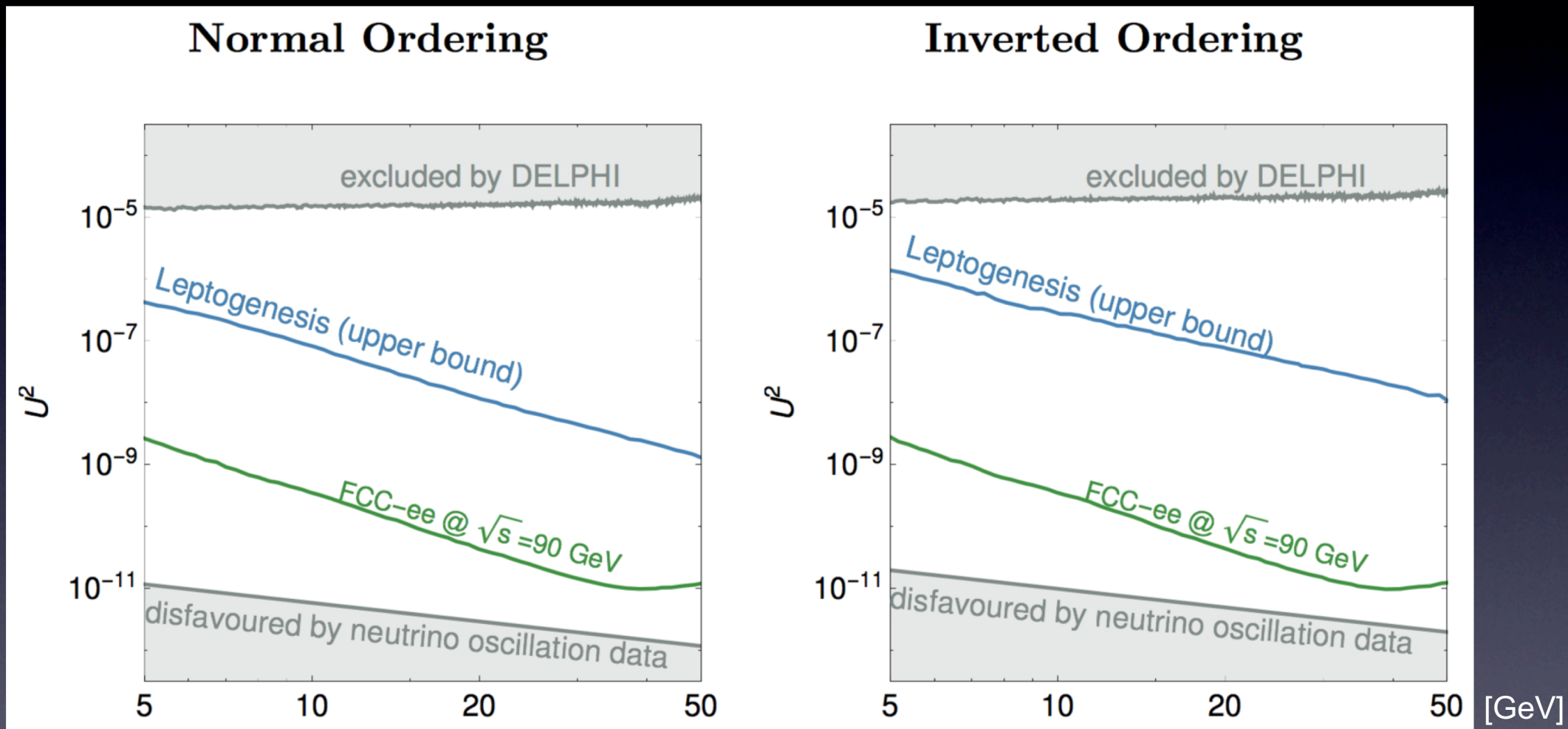
Extremely sensitive!

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

Towards probing leptogenesis at Future Colliders

Remark: Excellent prospects for probing the parameter region for leptogenesis ...

Here: only 2 RH neutrinos assumed!



With: $U^2 = |\theta|^2$

S.A., E. Cazzato, M. Drewes, O. Fischer, B. Garbrecht, D. Gueter, J. Klaric (arXiv:1710.03744)

Probing leptogenesis – and precision for the flavoured active-sterile mixing angles

Probing Leptogenesis

NO, FCC-ee at $\sqrt{s} = 90$ GeV

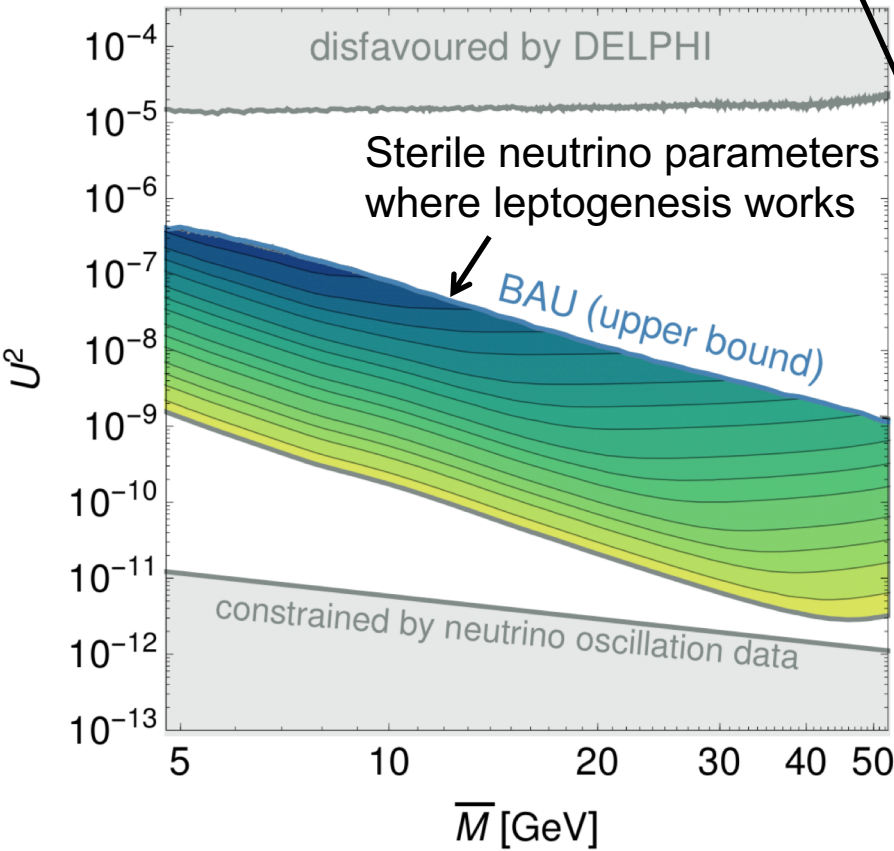
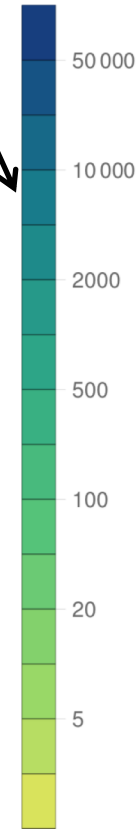
Colour code: number of events

disfavoured by DELPHI

Sterile neutrino parameters where leptogenesis works

BAU (upper bound)

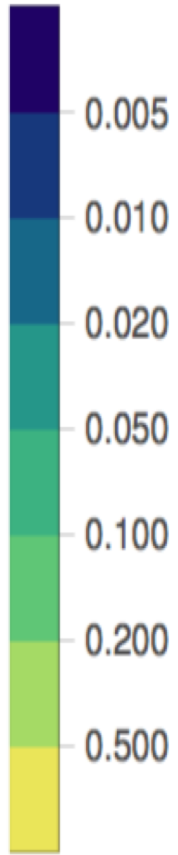
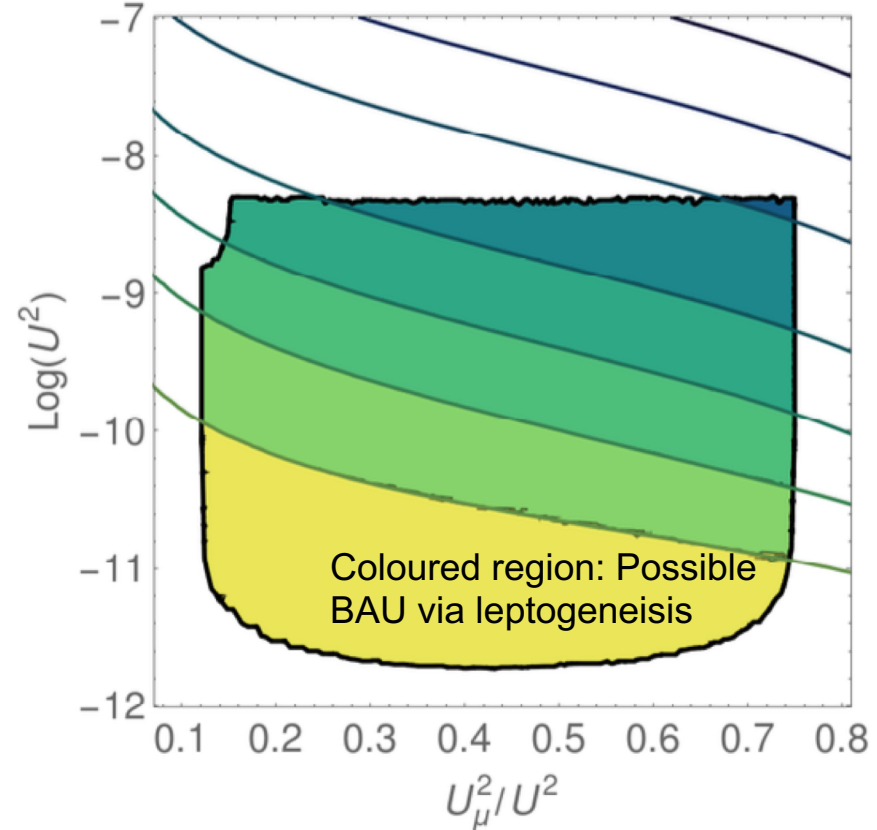
constrained by neutrino oscillation data



With: $U^2 = |\theta|^2$ and, for example, $U_\mu^2 = |\theta_\mu|^2$
(NO = normal light neutrino mass ordering)

Precision for U_μ^2 / U^2 (Example: $M = 30$ GeV)

NO, FCC-ee at $\sqrt{s} = 90$ GeV



Estimates from semi-leptonic heavy neutrino decays $N \rightarrow \mu jj$, measurements also possible for the other flavours e and τ !

S.A., E. Cazzato, M. Drewes, O. Fischer, B. Garbrecht, D. Gueter, J. Klaric (arXiv:1407.6607)

Is the flavour-dependent active-sterile mixing consistent with leptogenesis?

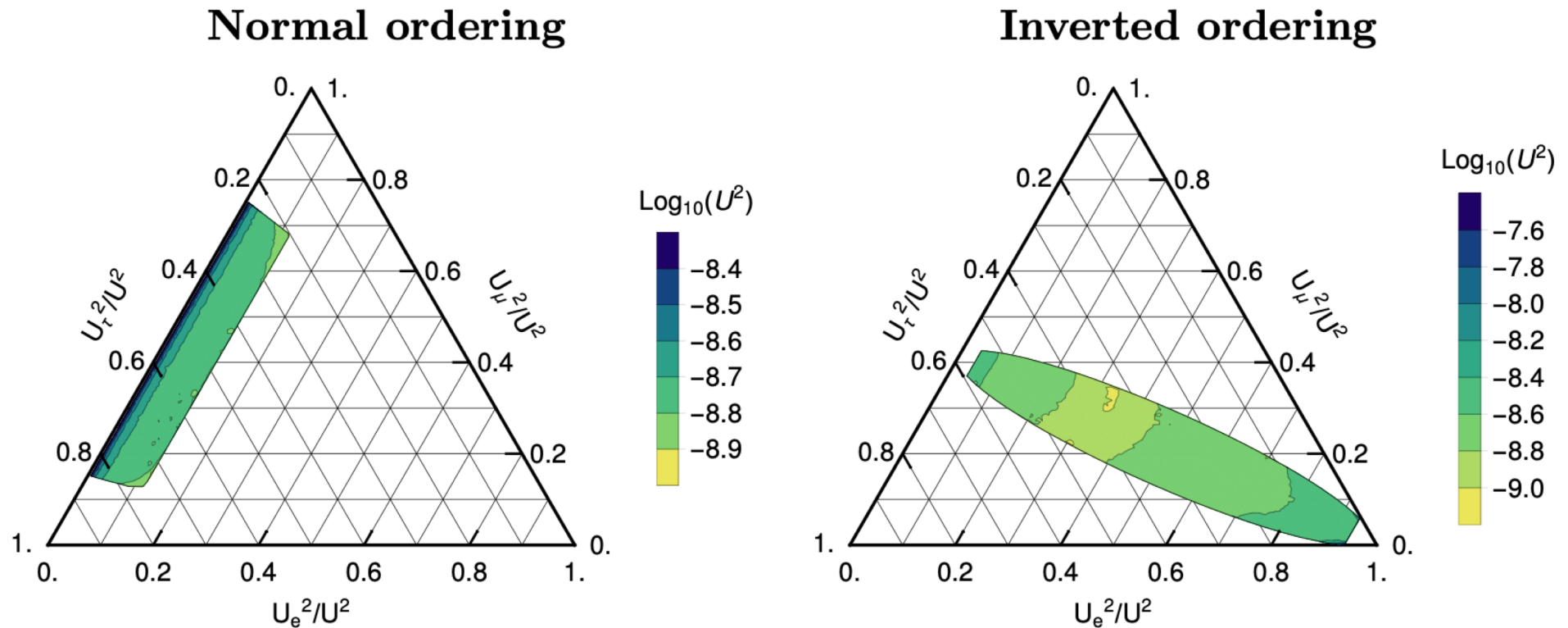


Figure 9: The region within the black lines is allowed by light neutrino oscillation data. The colour indicates the largest mixing angle U^2 consistent with the observed BAU and seesaw constraints for the cases of normal ordering (left) and inverted ordering (right) for right-handed neutrino with an average mass $\bar{M} = 30$ GeV. Note that the largest viable mixing angles are found in the case of a highly flavour asymmetric flavour pattern, where $U_a^2 \ll U^2$ for any of the flavours.

Is the flavour-dependent active-sterile mixing consistent with leptogenesis?

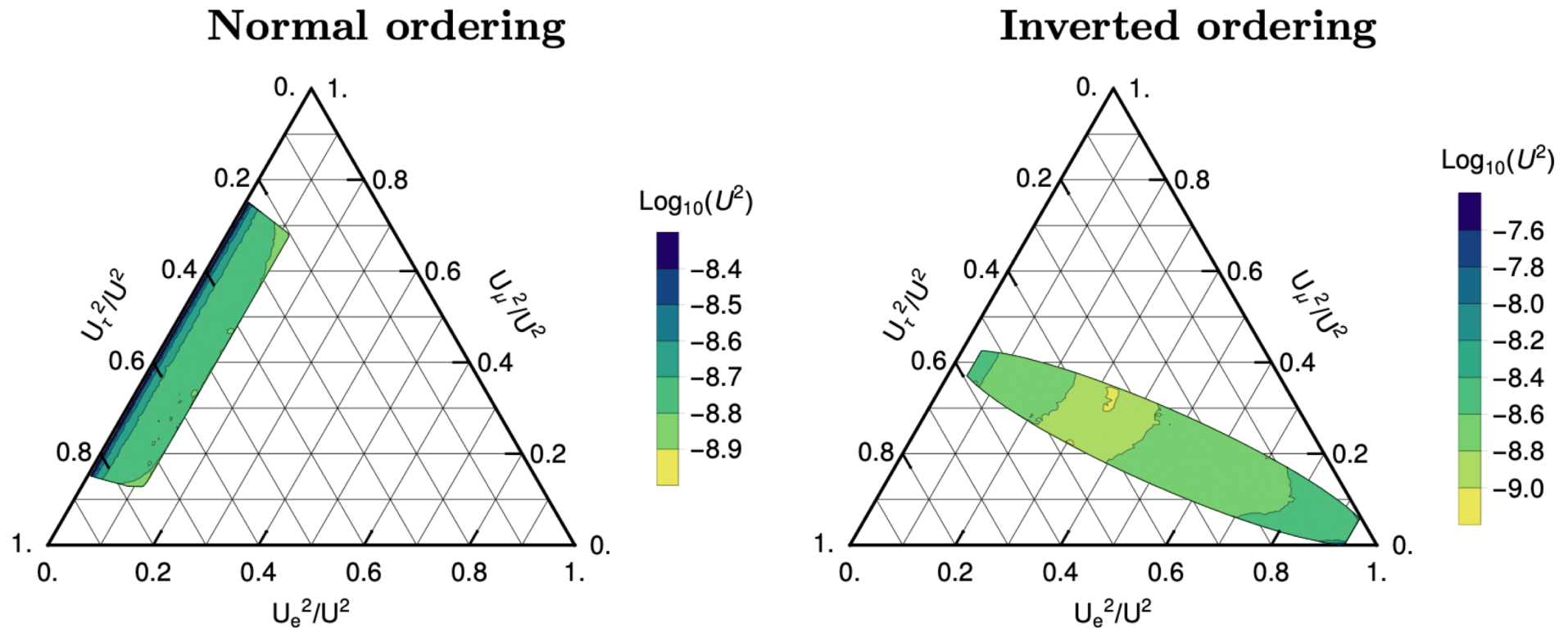


Figure 9: The region within the black colour indicates the largest mixing and constraints for the cases of normal or inverted ordering. Large mass splittings are found in the case of a highly hierarchical mass spectrum for any of the flavours.

And finally: Also the heavy neutrino mass splitting ΔM (plus lepton-number violation) could be tested via resolvable heavy neutrino-antineutrino oscillations!

Summary

- Heavy neutral leptons (\leftrightarrow sterile “right-handed” neutrinos) are well motivated SM extensions to explain the masses of the light neutrinos.
- With protective “lepton number”-like symmetry, “large y_ν ” and EW scale M are possible (& technically natural)!
 - Low scale seesaw models: Attractive and testable scenarios!
- Benchmark models need at least 2 heavy neutral leptons to correctly capture LNV effects in low scale seesaw models.
 - SPSS (Symmetry Protected Seesaw Scenario).
- Future experiments have interesting discovery prospects. New signatures and measurements of the flavour-dependent mixing could
 - ... allow a fascinating deep insight into the neutrino mass mechanism (e.g. via heavy neutrino-antineutrino oscillations)
 - ... allow to probe the mechanism underlying baryogenesis

**Thanks for
your attention!**