Sterile Neutrino Searches at Colliders

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Sterile neutrinos can be an answer to one of the big open questions in BSM physics:

What is the origin of the observed neutrinos masses?

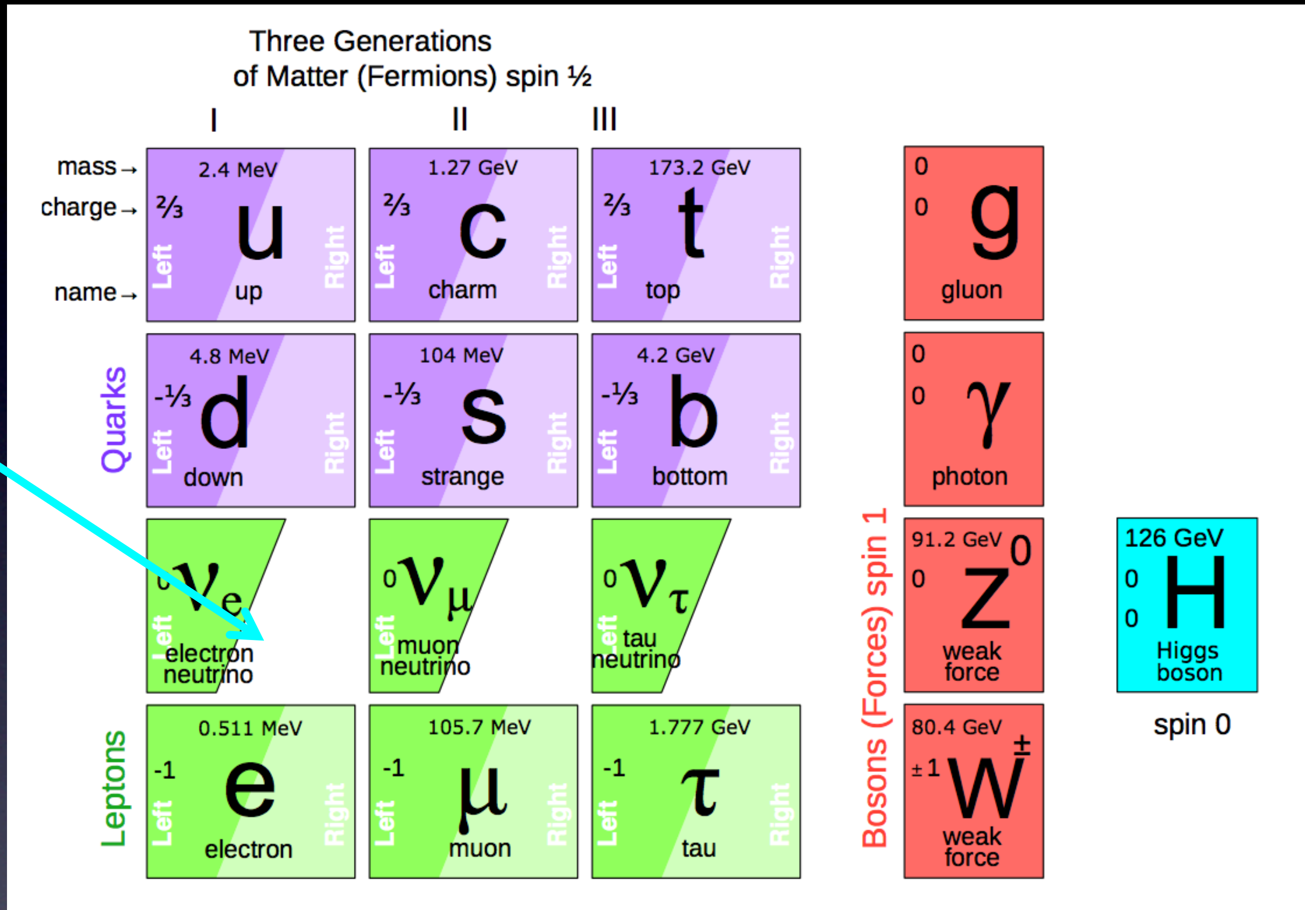
Topic of my talk:

EW/TeV scale sterile neutrinos and their phenomenology

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:

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

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"

Neutrino Yukawa matrix

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

From neutrino oscillation experiments and mass searches:

$|m_3^2 - m_1^2| \approx 2.4 \cdot 10^{-3}\,\mathrm{eV}^2$

$m_2^2 - m_1^2 \approx 7.5 \cdot 10^{-5}\,\mathrm{eV}^2$

all three m_i below ~ 0.2 eV

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

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 neutrino parameters M and Y_ν?

What do we know about the neutrino parameters?

Getting started: **1 ν_R, 1 ν_L**

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

➔ **Knowledge of m_ν implies relation between y_ν and M_R**

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

What do we know about the sterile neutrino parameters?

Example 1: 2 ν_R, 2 ν_L

Example of a small perturbation

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ 0 & \mathcal{O}(y_\nu) \end{pmatrix}, \quad M = \begin{pmatrix} M_R & 0 \\ 0 & M_R + \varepsilon \end{pmatrix}$$

$$\Rightarrow \quad m_{\nu_i} = \frac{v_{EW}^2\, \mathcal{O}(y_\nu^2)}{M_R} \left(1 + \varepsilon\, \delta_{i2}\right)$$

➔ Also in this example: Knowledge of $m_{\nu i}$ implies relation between $y_{\nu i}$ and M_R

What do we know about the sterile neutrino parameters?

Example 2: 2 ν_R, 2 ν_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), ⋯

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ \mathcal{O}(y_\nu) & 0 \end{pmatrix}, \quad M = \begin{pmatrix} 0 & M_R \\ M_R & \varepsilon \end{pmatrix}$$

Example: small perturbation in the “inverse seesaw”

$$\Rightarrow \quad m_\nu = 0 + \varepsilon \frac{v_{EW}^2 \, \mathcal{O}(y_\nu^2)}{M_R^2}$$

➔ 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 ν_R, 2 ν_L

Similar: "inverse" seesaw, "linear" seesaw

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ \mathcal{O}(y_\nu) & 0 \end{pmatrix}, \quad M = \begin{pmatrix} 0 & M_R \\ M_R & \cancel{\varepsilon} \end{pmatrix}$$

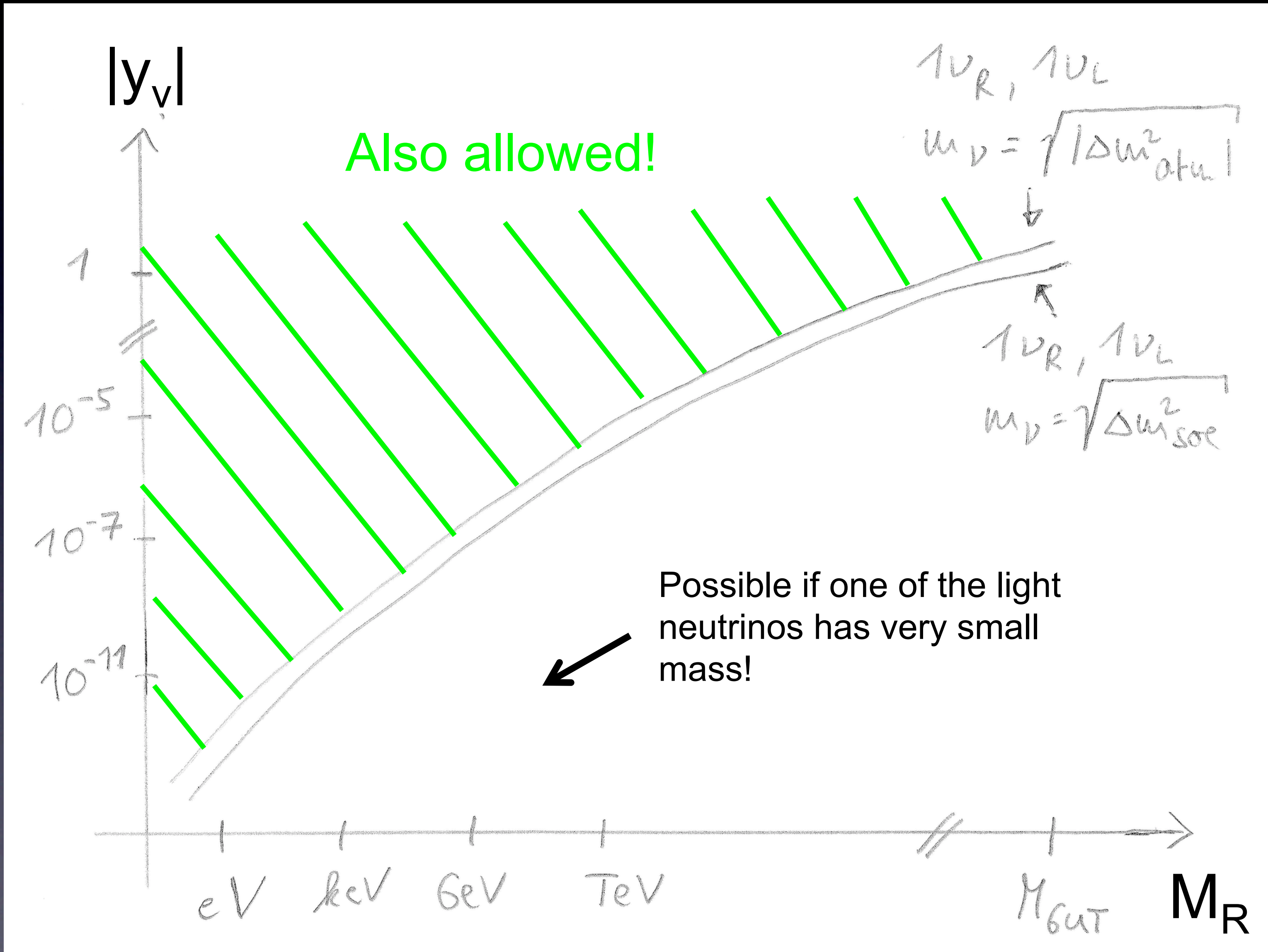
$$\Rightarrow \quad m_\nu = 0 + \cancel{\varepsilon} \frac{v_{EW}^2 \, \mathcal{O}(y_\nu^2)}{M_R^2}$$

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

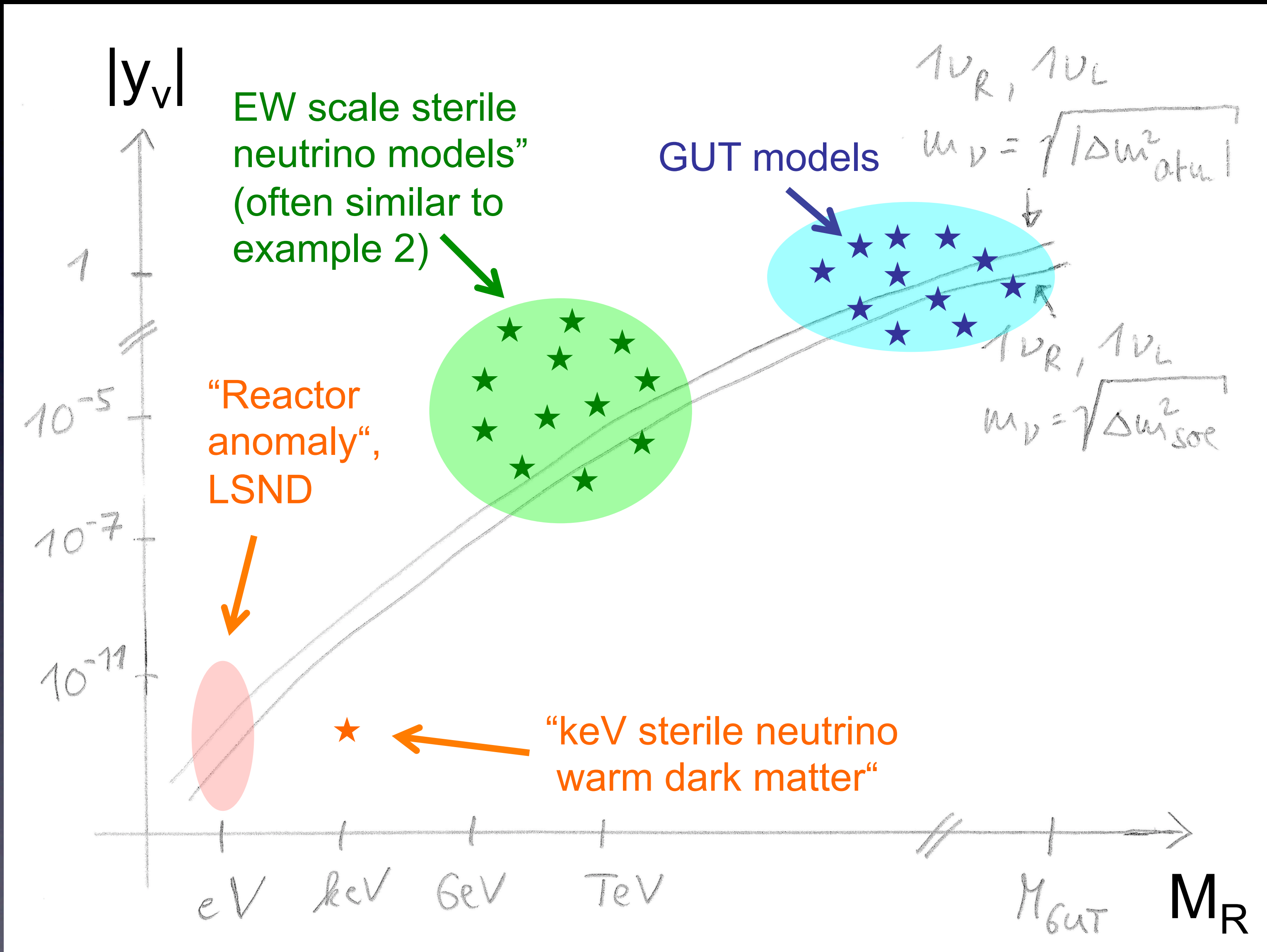
Possible values of M_R and y_ν



Not considering experimental constraints

"Landscape" of sterile neutrino models

Examples, schematic



Not considering experimental constraints

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

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

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

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

Similar: “inverse” seesaw, “linear” seesaw

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

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

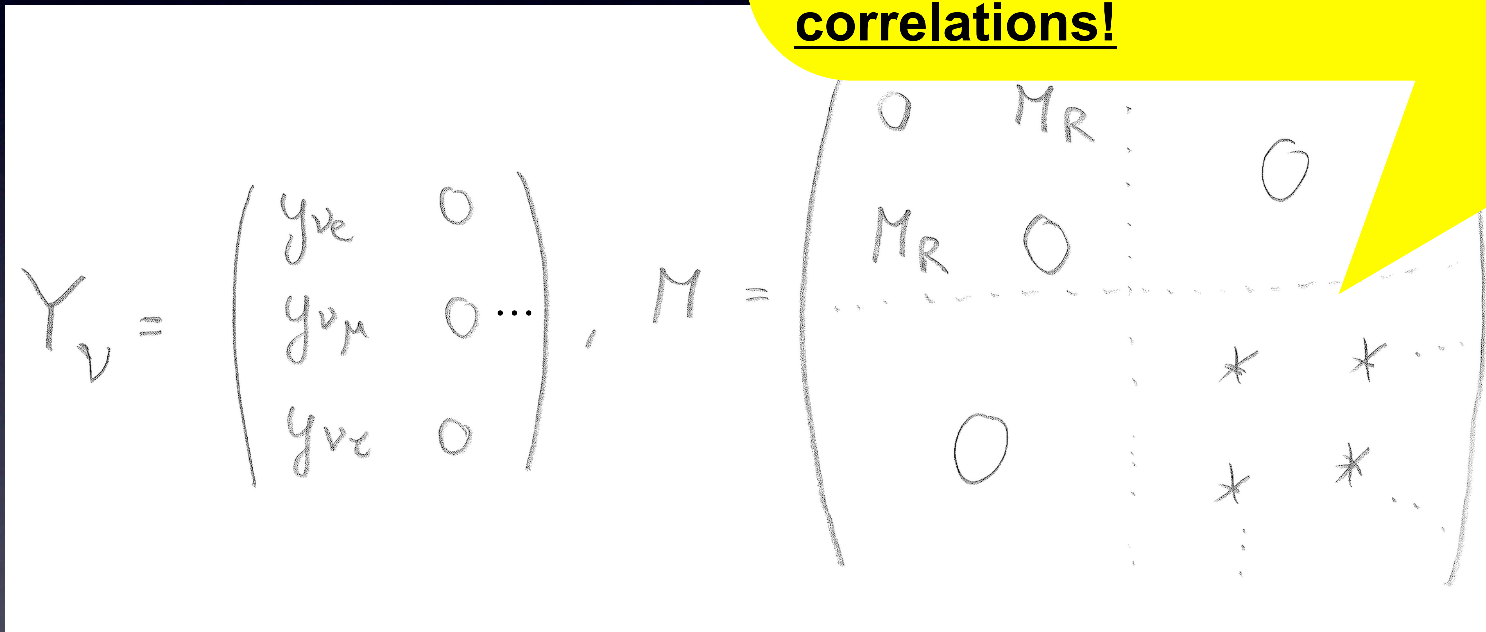
A benchmark model

SPSS (Symmetry Prot

Comment: Since in the SPSS we allow for additional sterile neutrinos, M and y_α (α=e,μ,τ) 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!

Consider 2+n sterile neutrinos (plus the

the steriles as in example 2 due to som



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

Similar: "inverse" seesaw, "linear" seesaw

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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:

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

$+$ … (terms from additional sterile vs)

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4 Parameters: M, y_α, (α=e,μ,τ)

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$$+ \ldots \text{ (terms from additional sterile vs)}$$

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:

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

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

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

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

- Active-sterile neutrino mixing parameters:

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

Observable effects of the sterile neutrinos: M >> Λ_{EW}

Main effect for M >> Λ_{EW}:
"Leptonic non-unitary"

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

Langacker, London ('88); S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06), $\cdots$

Gives rise to NSIs at source, detector & with matter: see e.g. S.A., Baumann, Fernandez-Martinez (arXiv:0807.1003)

Global constraints on $\varepsilon_{\alpha\beta}$: S.A., Fischer (arXiv:1407.6607)

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

Non-unitarity parameters:

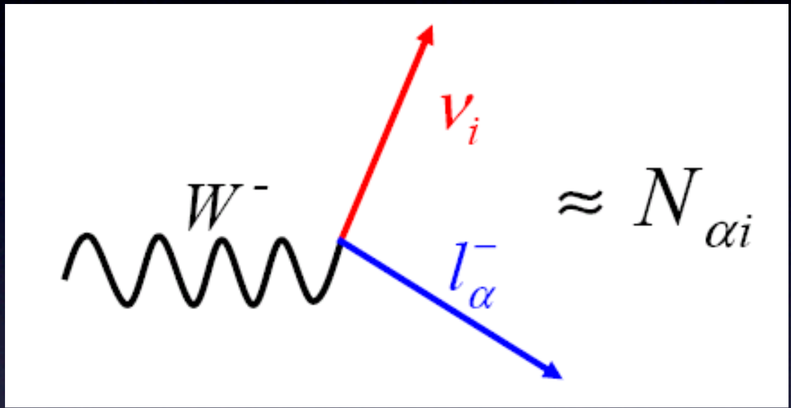
$$(NN^\dagger)_{\alpha\beta} = (1_{\alpha\beta} + \boxed{\varepsilon_{\alpha\beta}})$$

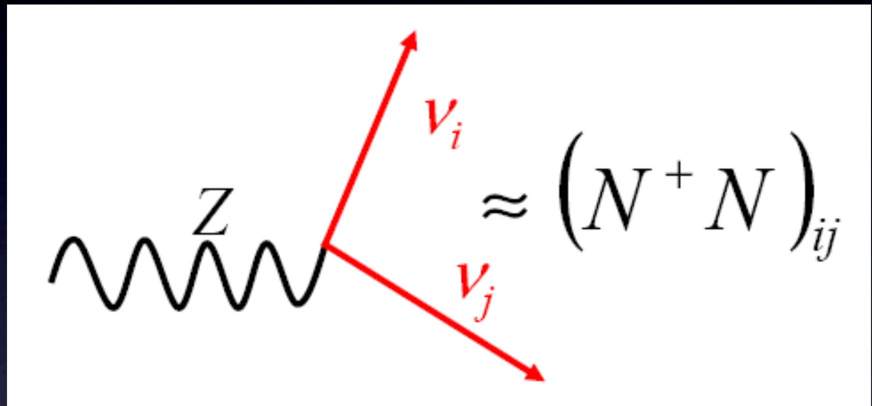
$\Rightarrow$ $U_{PMNS} \equiv N$ is non-unitary

$\Rightarrow$ various obs. effects!

EW interactions of the light neutrinos are modified

In the effective theory below M_R:





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

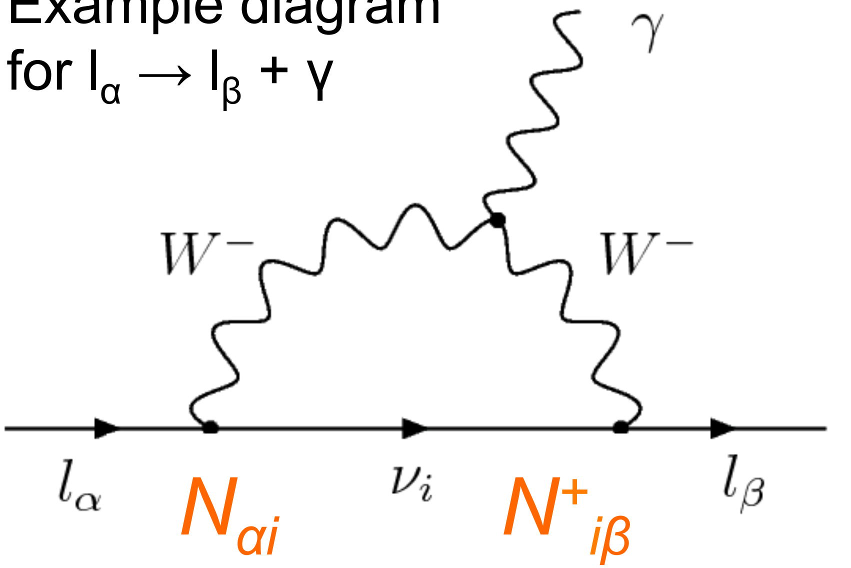
taken from: S.A., O. Fischer (arXiv:1407.6607)

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 $|\varepsilon_{\alpha\beta}|$:

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



$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \nu_\alpha \ell_\beta \overline{\nu}_\beta)} = \frac{3\alpha}{32\pi} \frac{|\sum_k N_{\alpha k} N^\dagger_{k\beta} F(x_k)|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}}$$

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

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

where:

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

m_k: light neutrinos' masses

Relation to the parameters of the SPSS benchmark model

	y_{ν_α}	θ_α	$\varepsilon_{\alpha\beta}$
$y_{\nu_\alpha} =$	–	$\frac{\sqrt{2}M}{v_{\mathrm{EW}}}\theta_\alpha^*$	$-\frac{\sqrt{2}M}{v_{\mathrm{EW}}}\varepsilon_{\beta\alpha}/\sqrt{-\varepsilon_{\beta\beta}}$
$\theta_\alpha =$	$\frac{v_{\mathrm{EW}}}{\sqrt{2}M}y_{\nu_\alpha}^*$	–	$-\varepsilon_{\beta\alpha}/\sqrt{-\varepsilon_{\beta\beta}}$
$\varepsilon_{\alpha\beta} =$	$-\frac{v_{\mathrm{EW}}^2 y_{\nu_\alpha}^* y_{\nu_\beta}}{2M^2}$	$-\theta_\alpha^*\theta_\beta$	–

Non-unitarity parameters

Active-sterile neutrino mixing

Observable effects of the sterile neutrinos: M ≅ Λ_{EW}

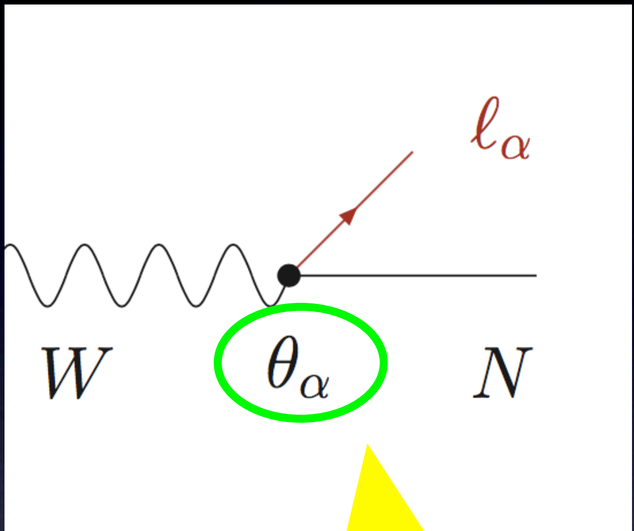
Sterile neutrinos mix with the active ones ➔ the heavy neutrinos (= mass eigenstates) participate in weak interactions!

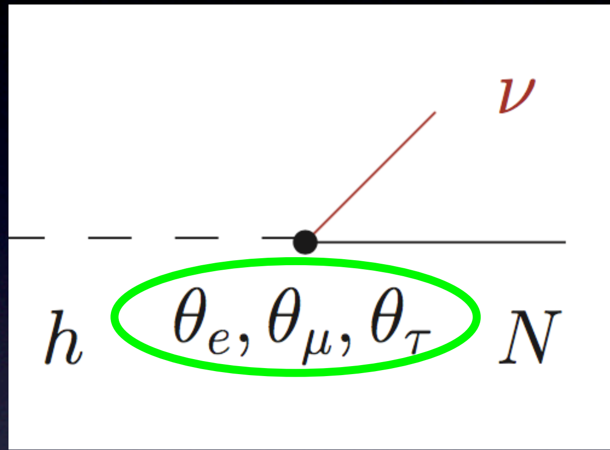
In addition for M ≅ Λ_{EW}: Effects from on-shell heavy neutrinos

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

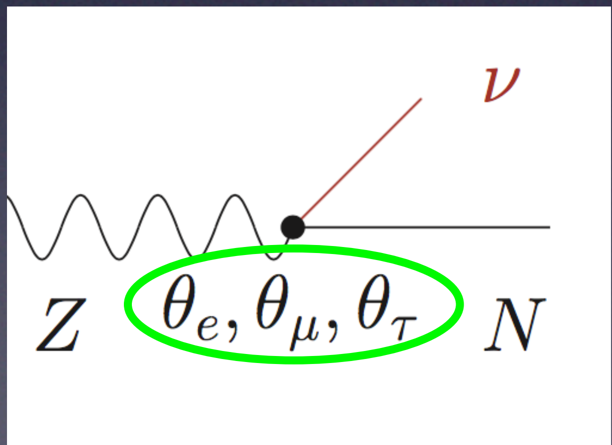
⇒ heavy neutrinos can get produced also in weak interaction processes!

Heavy neutrino interactions



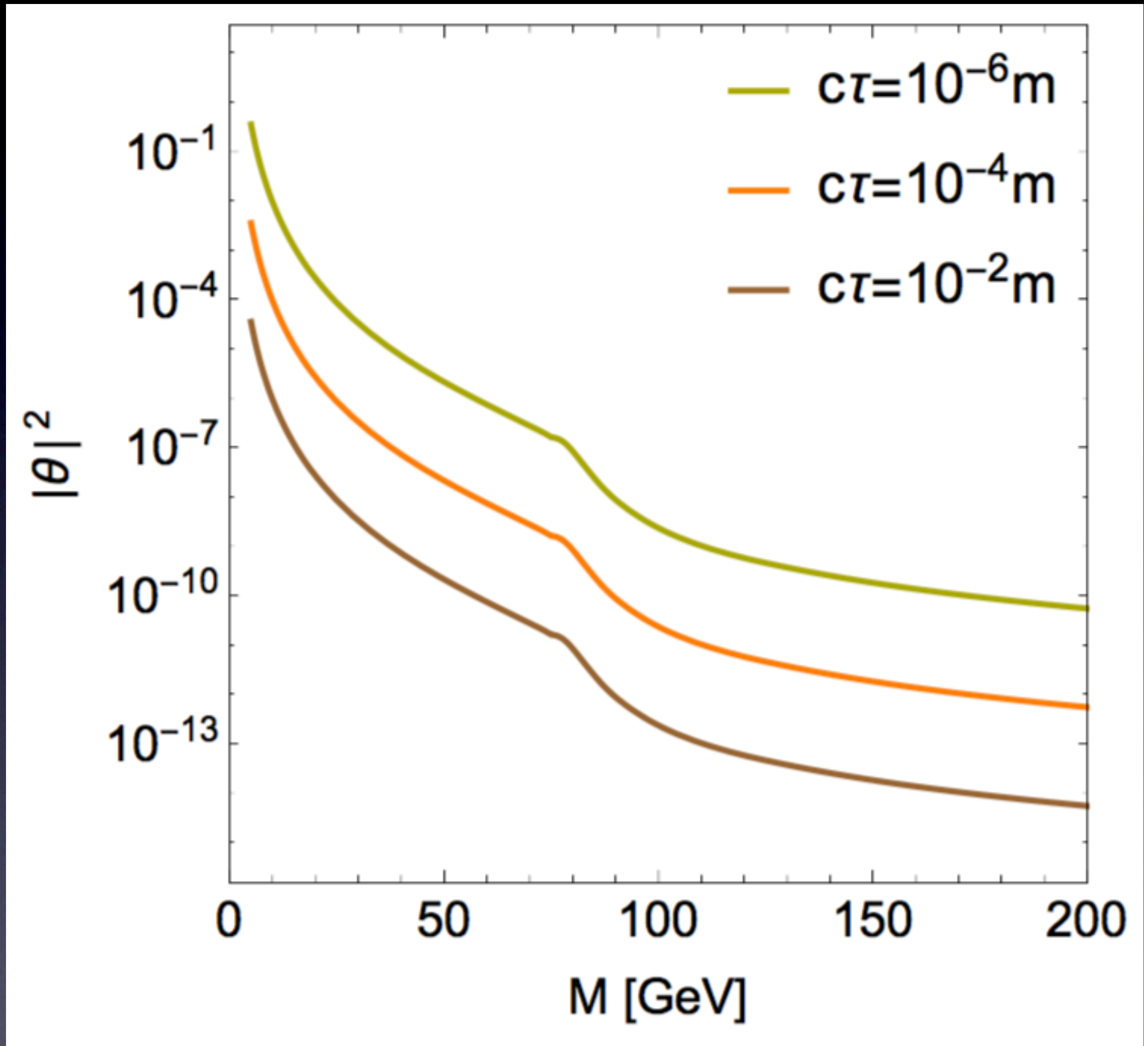


When W bosons are involved, there is a possible sensitivity to the flavour-dependent θ_α



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

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

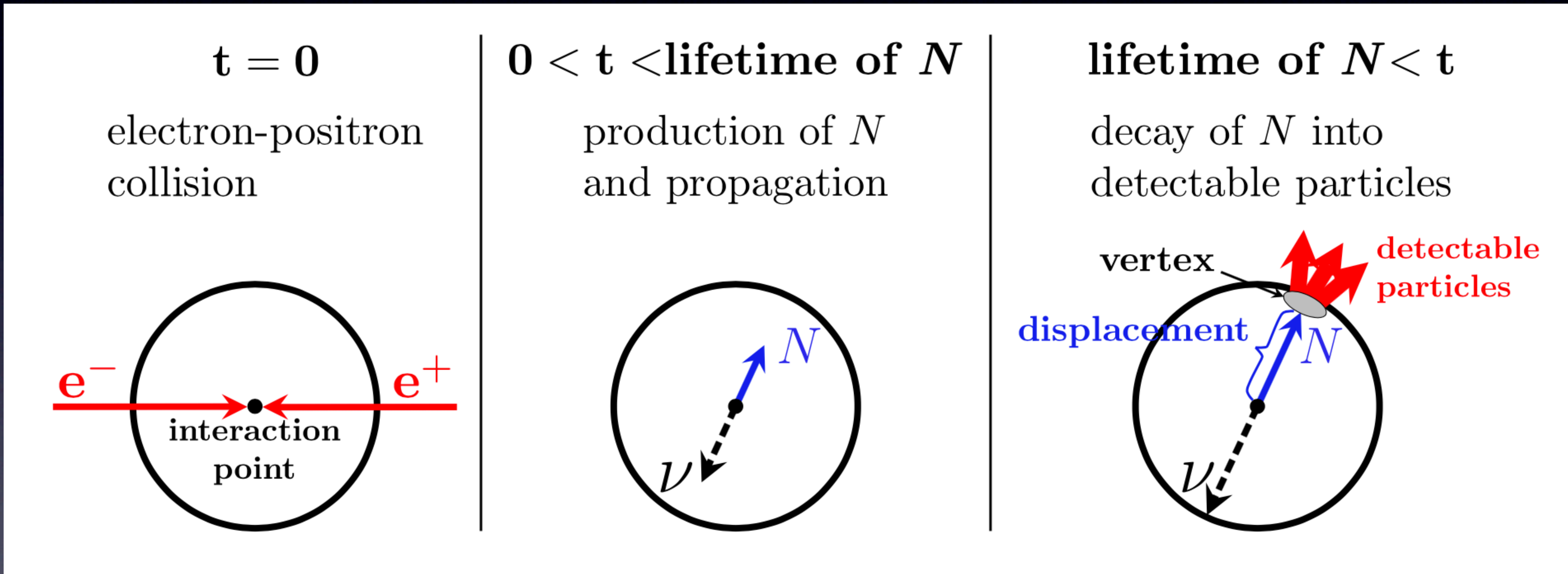


cf. S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

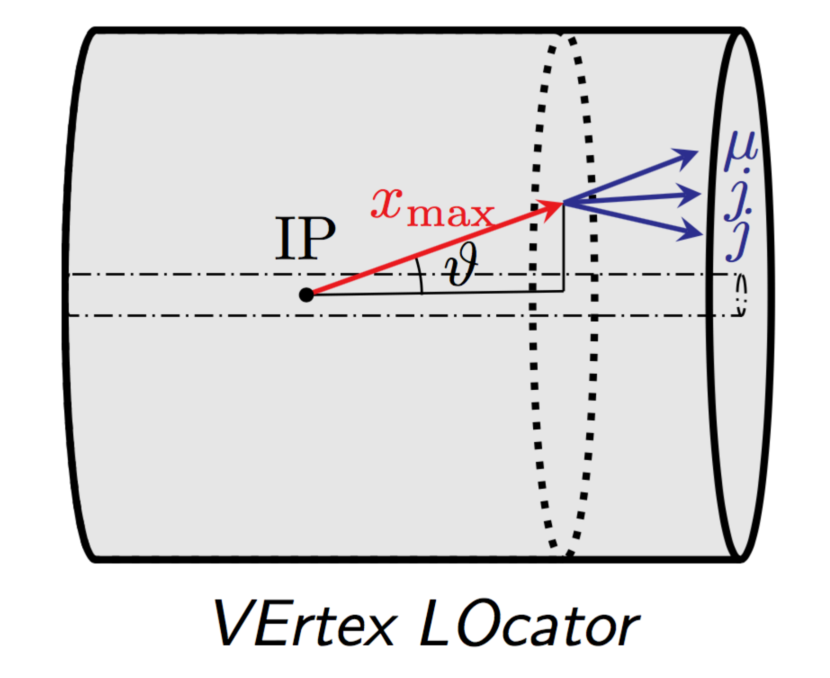
Note: Decay length in the laboratory frame is: $c\tau\sqrt{\gamma^2 - 1}$

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

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



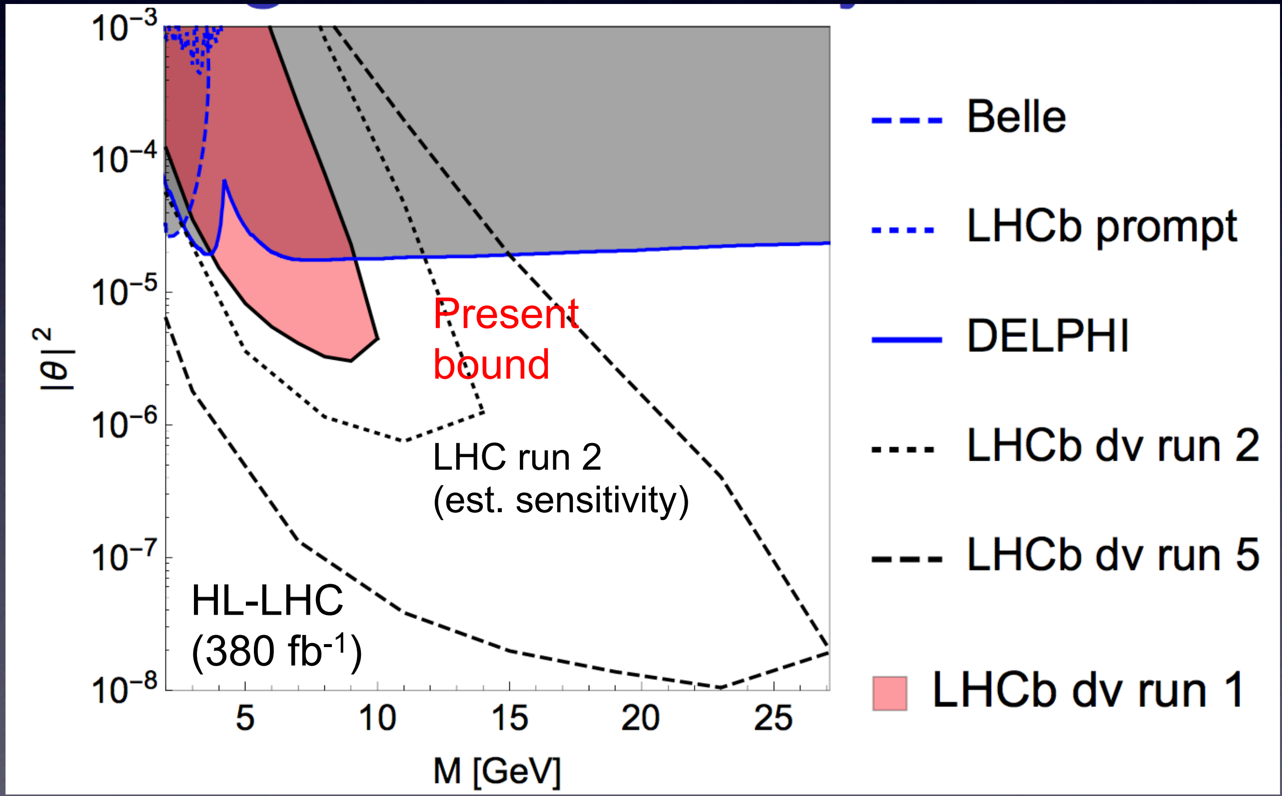
Present bounds (& estim. future sensitivities) from displaced vertex searches at LHCb



LHCb analysis exists for LHC run 1 data:

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

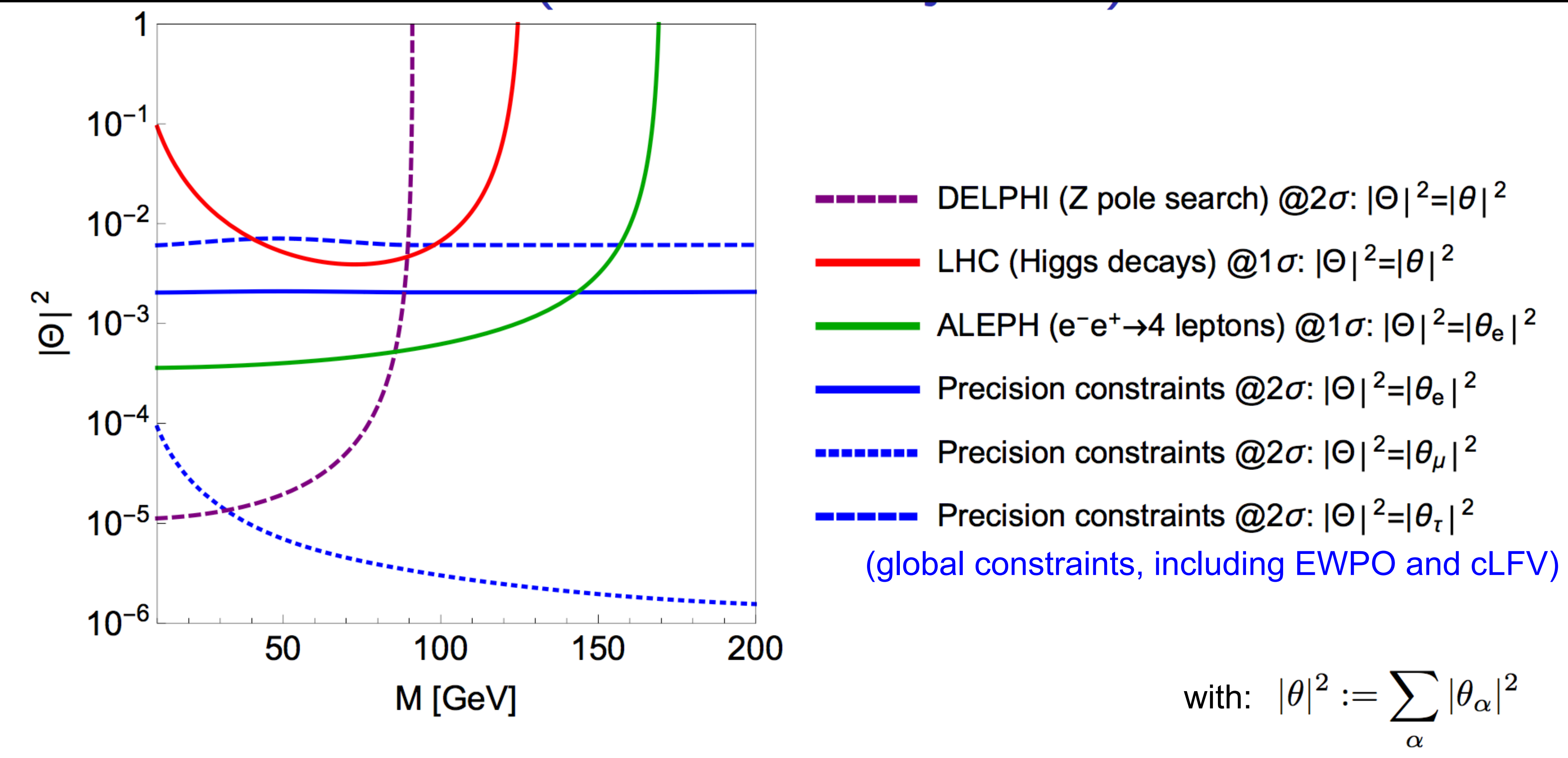
The results can be translated into bounds on $|\theta|^2$ (here for $\theta_e = \theta_\tau = 0$):



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

Remark: Forecasts for the sensitivities at Atlas and CMS for the HL-LHC phase are comparable, cf.:
E. Izaguirre, B. Shuve (2015)

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



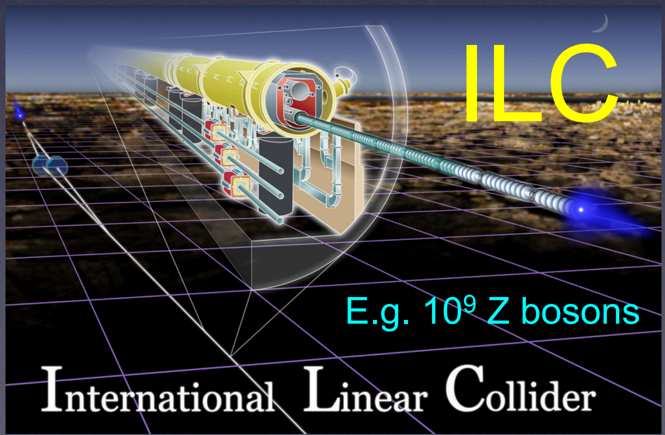
Constraints from present data (M > 10 GeV): S.A., O. Fischer (arXiv:1502.05915)
For a similar study, see also: E. Fernandez-Martinez, J .Hernandez-Garcia, J. Lopez-Pavon (arXiv:1605.08774)
Constraints for smaller M, see e.g.: M. Drewes, B. Garbrecht (arXiv:1502.00477)

What are the prospects for discovering such heavy neutrinos at future experiments?

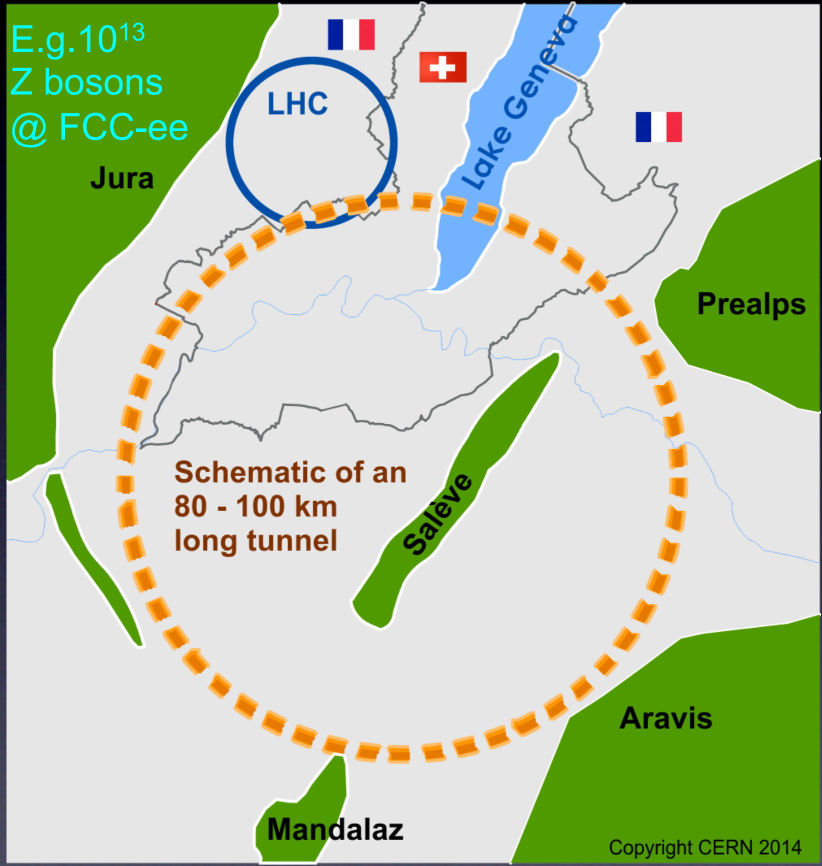
Note: I will consider the SPSS as a benchmark and restrict myself to M > 10 GeV

Ambitious plans for future colliders …

plans for circular collider in China

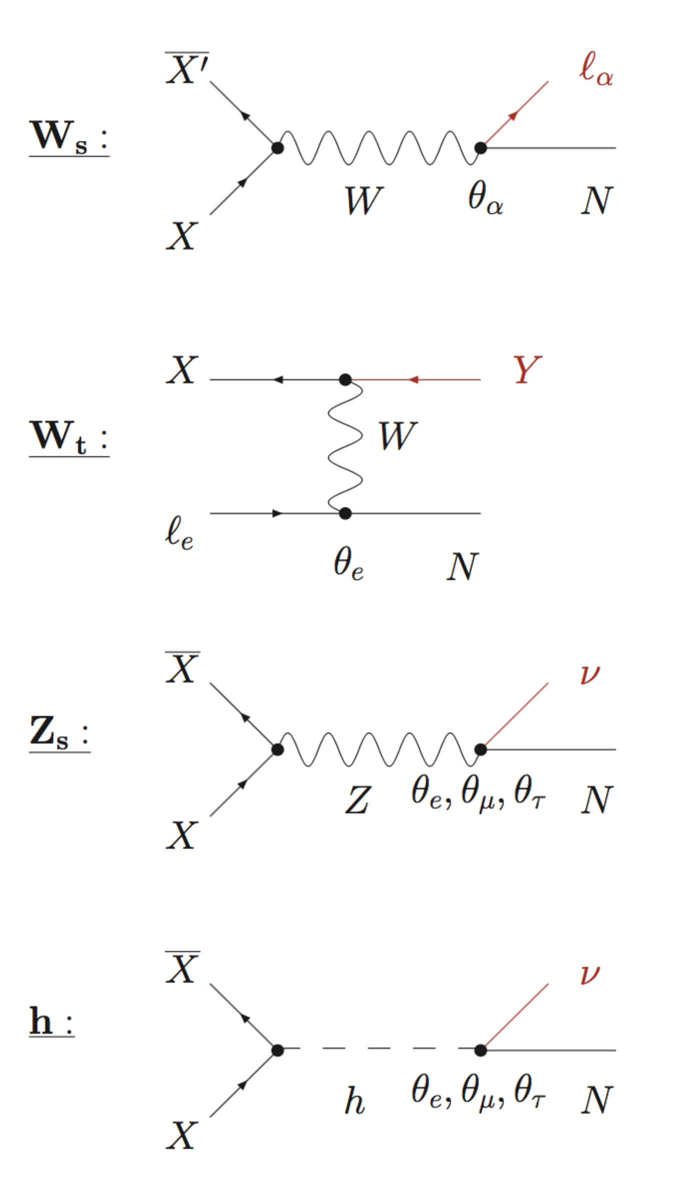


FCC (-ee, -hh, -eh)



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

Systematic assessment of signatures of sterile neutrinos at colliders



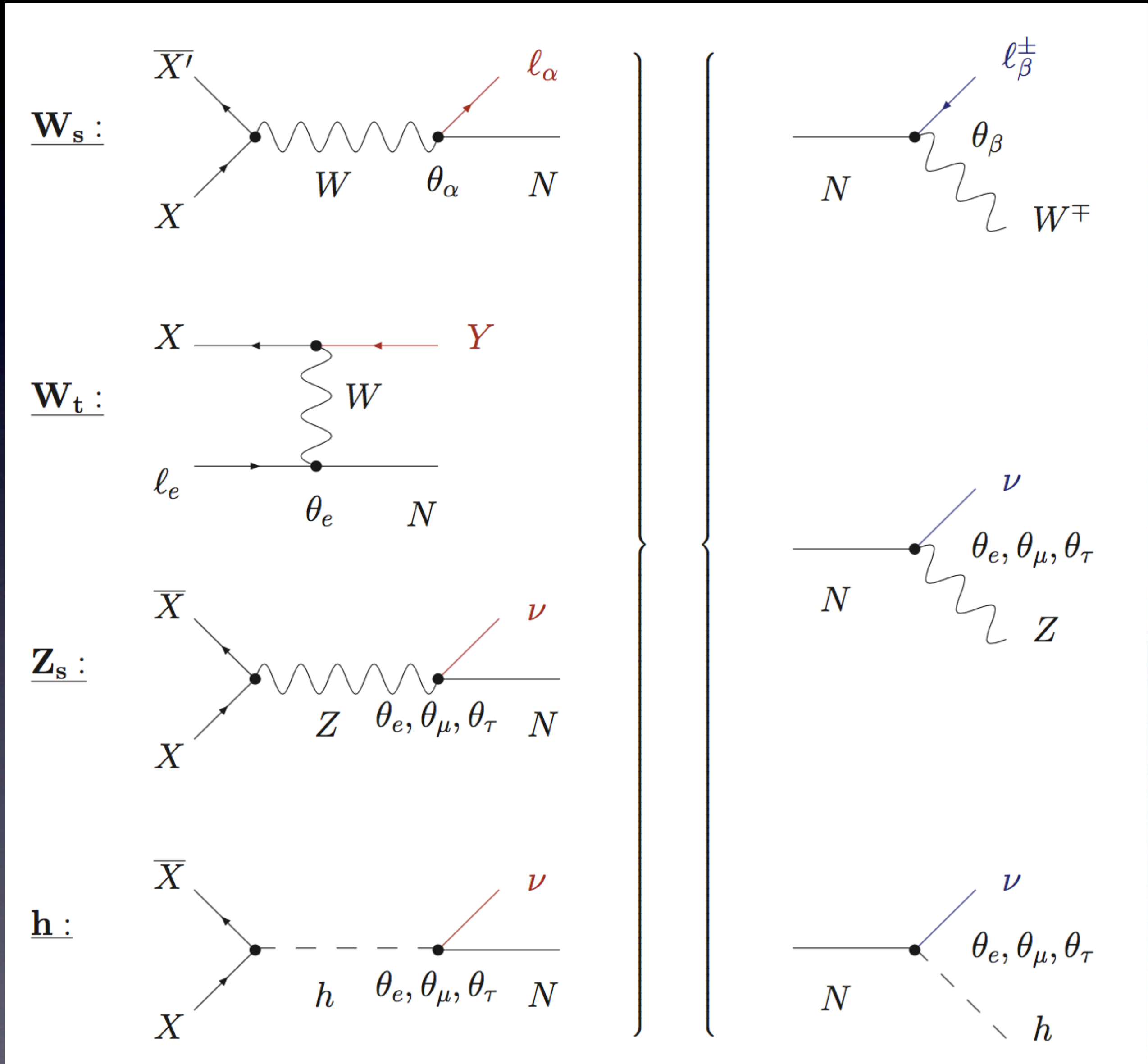
S.A., E. Cazzato, O. Fischer (arXiv:1612.02728),
See also many other works by many authors ...

Different collider types feature different production channels ···

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

Systematic assessment of signatures of sterile neutrinos at colliders

(at LO)

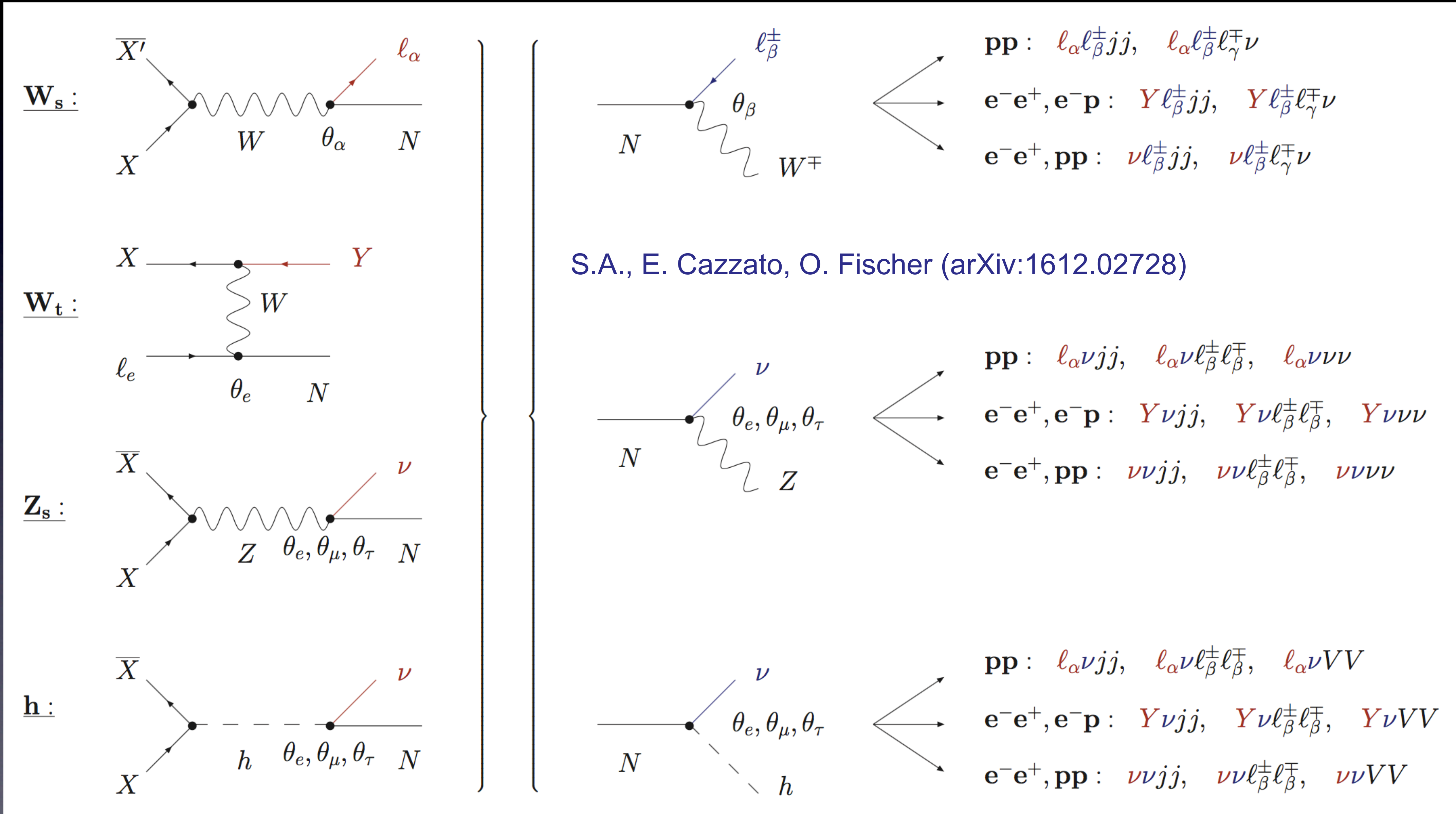


··· and, including the different decay channels, sensitivity to different combinations of active-sterile mixing parameters:

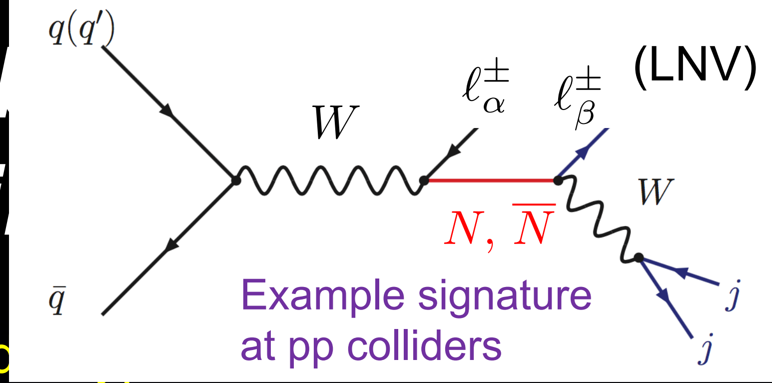
		Decay channel	
		W	$Z(h)$
Production channel	$\mathbf{W_s}$	$\frac{\lvert\theta_\alpha\theta_\beta\rvert^2}{\lvert\theta\rvert^2}$	$\lvert\theta_\alpha\rvert^2$
	$\mathbf{W_t}$	$\frac{\lvert\theta_e\theta_\beta\rvert^2}{\lvert\theta\rvert^2}$	$\lvert\theta_e\rvert^2$
	$\mathbf{Z_s(h)}$	$\lvert\theta_\beta\rvert^2$	$\lvert\theta\rvert^2$

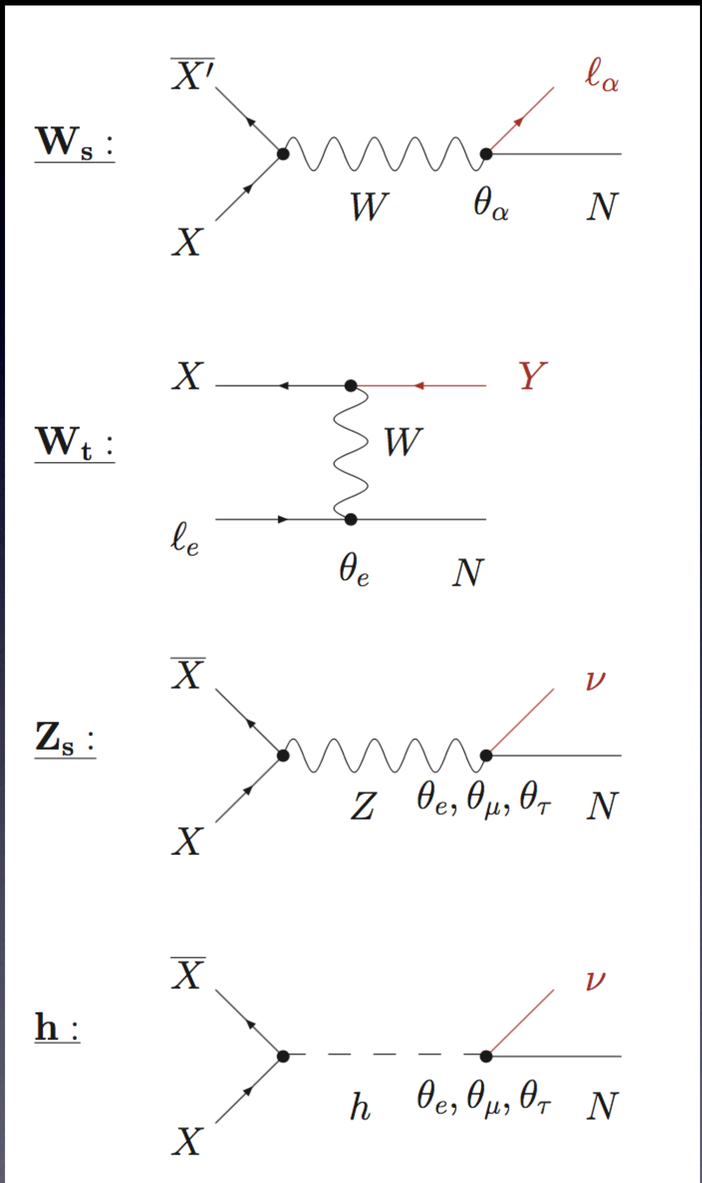
Systematic assessment of signatures of sterile neutrinos at colliders

(at LO)



Signatures for lepton numb… from sterile neutri…





Different collid… different production channels:

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

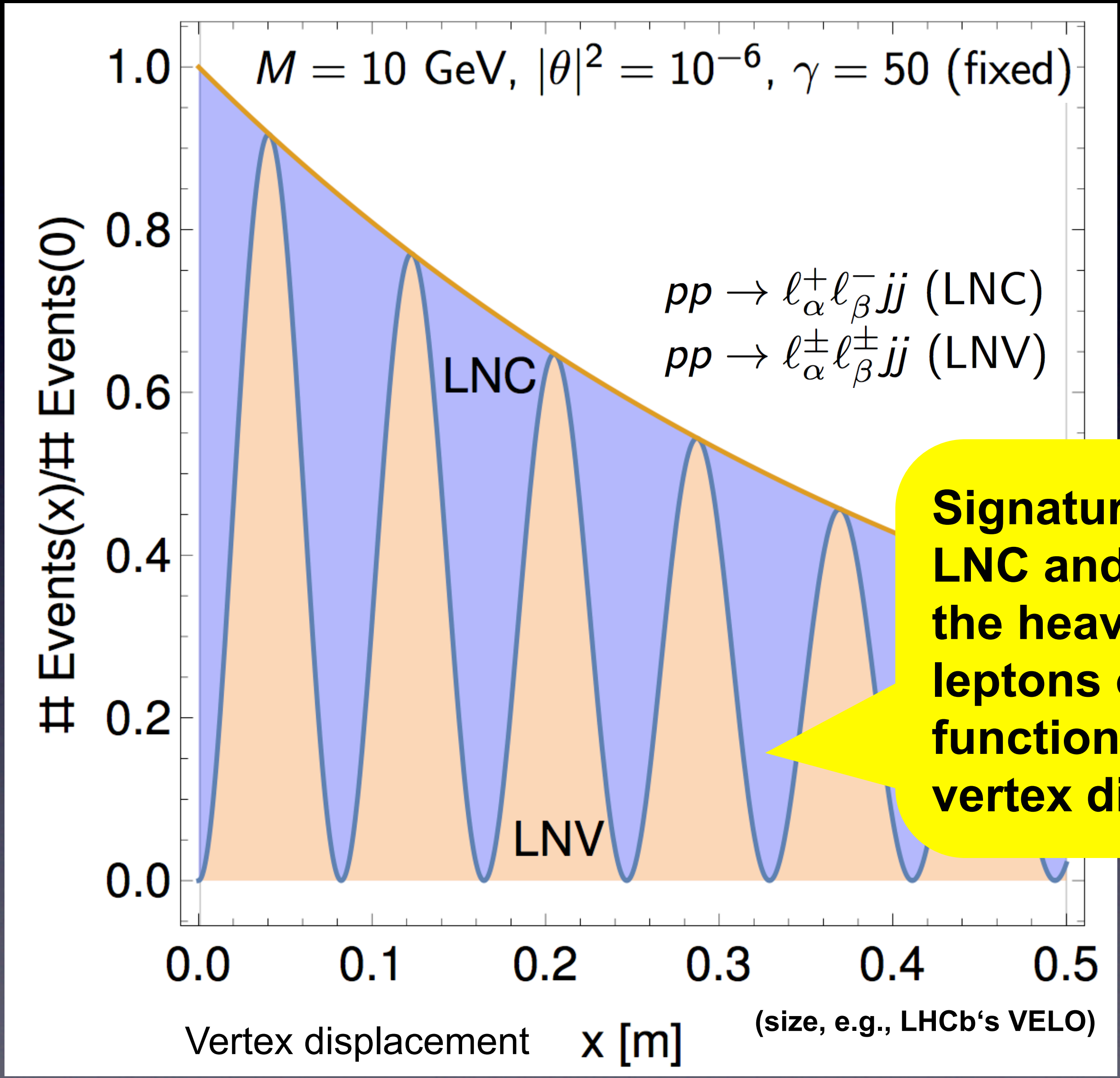
Lepton-number violating (LNV) signatures possible (with no SM background at parton level) but expected to be suppressed by the (approximate) protective "lepton number"-like symmetry!

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)

(Now andding the symmetry breaking terms and using the prediction for ΔM in the minimal linear seesaw model (= only 2 RH Nus) for inverse neutrino mass ordering)



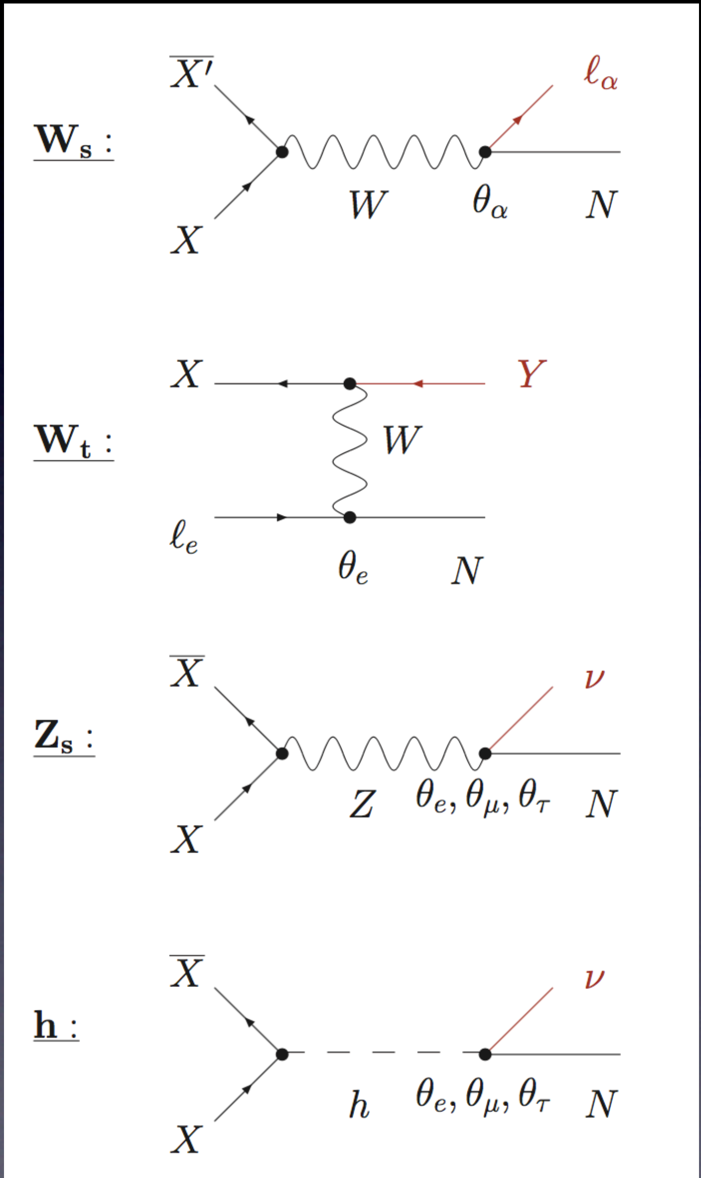
S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

Signature: The ratio of LNC and LNV decays of the heavy neutral leptons oscillates as a function of lifetime (or vertex displacement)

Integrated effect discussed in:
J. Gluza and T. Jelinski (2015),
G. Anamiati, M. Hirsch and E. Nardi (2016),
S.A., Cazzato, Fischer (2017),
A. Das, P. S. B. Dev and R. N. Mohapatra (2017)

Signatures with lepton flavour violation

(at LO)



Different collider types feature different production channels:

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

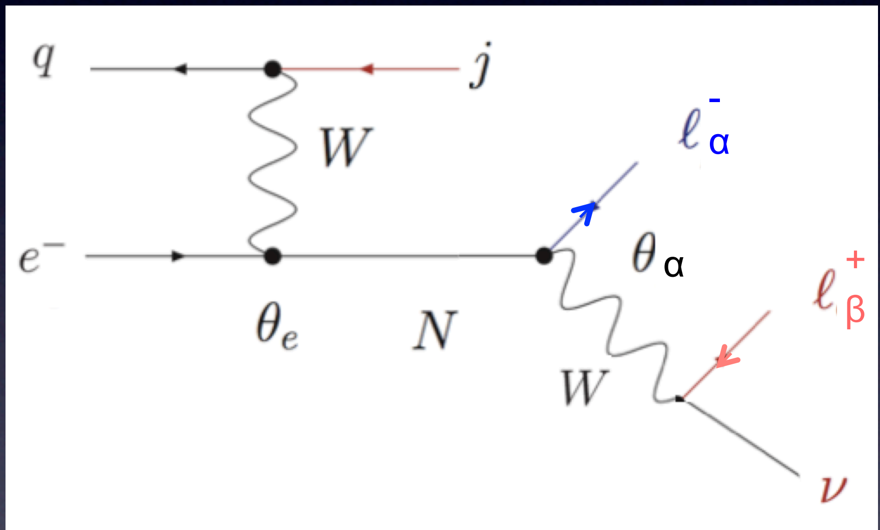
<u>Lepton flavour violating LFV</u> (and lepton number conserving LNC) signatures possible (with no SM background at parton level*). <u>Promising for future searches!</u>

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

Signatures with lepton flavour violation

(at LO)

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. $\alpha \neq \beta$

FCC-hh sensitivity: cf. ArXiv:1805.11400

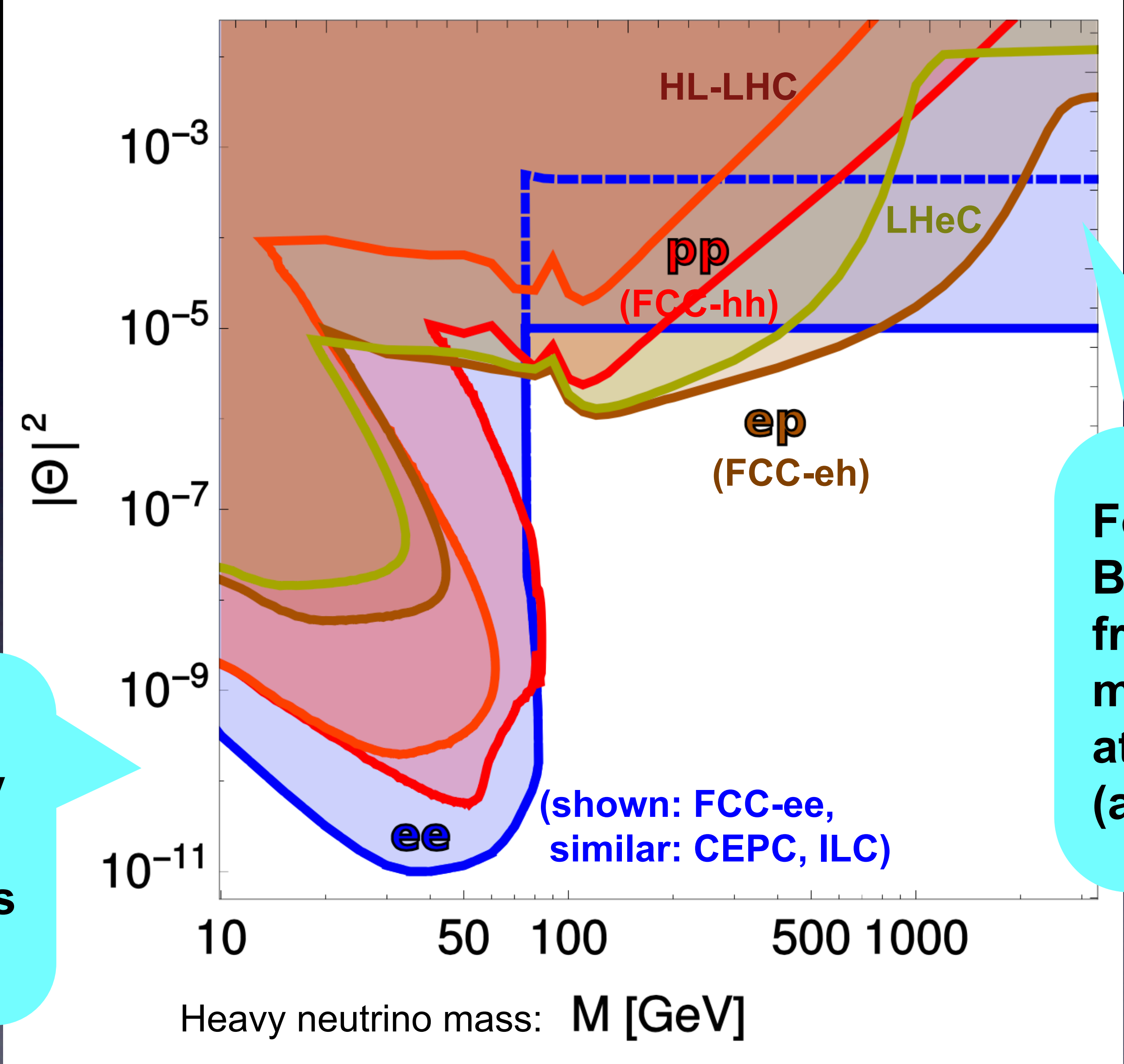
Different collider types feature different production channels:

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

Lepton flavour violating LFV (and lepton number conserving LNC) signatures possible (with no SM background at parton level*). 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

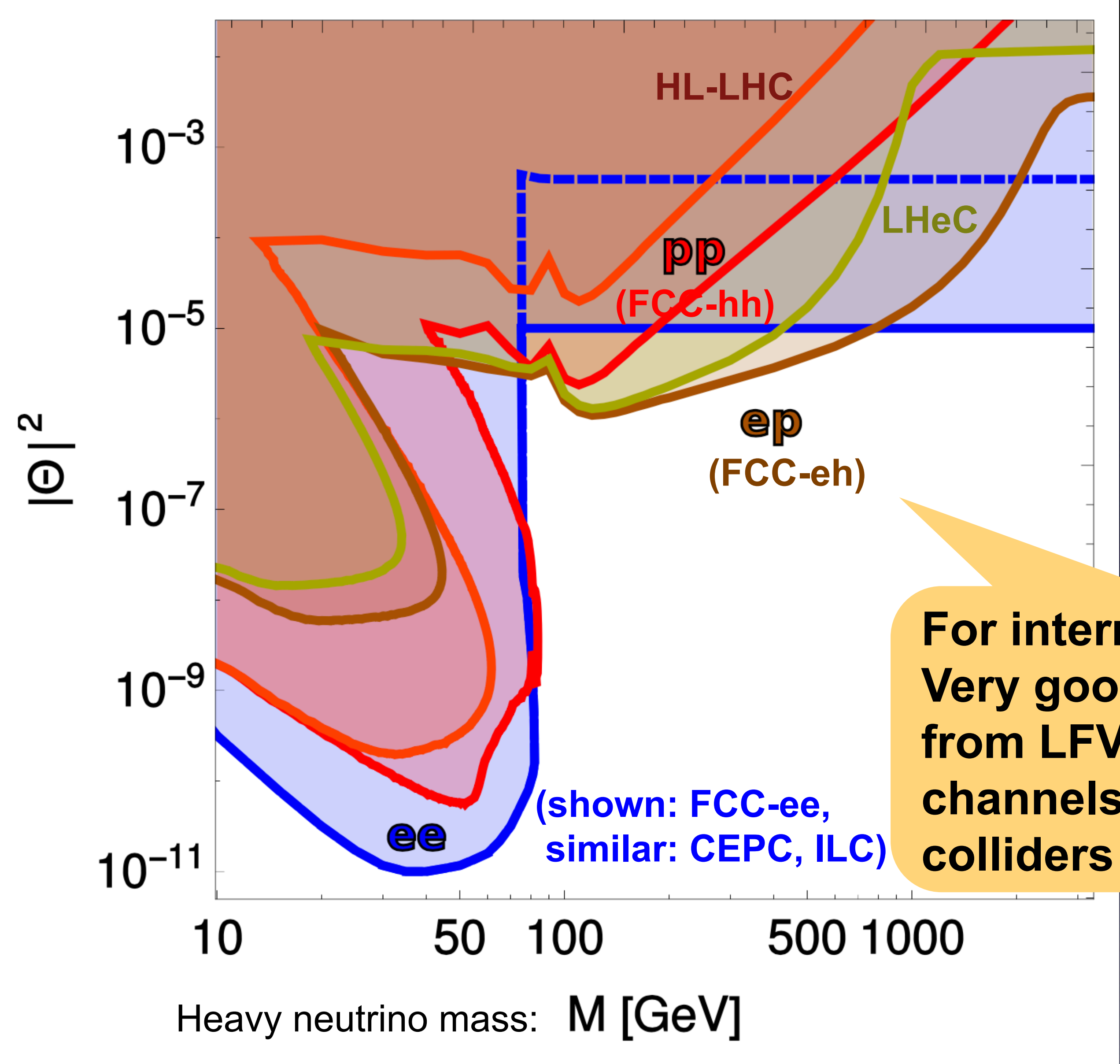


For M < m_W: Best sensitivity from displaced vertex searches at FCC-ee

For M >> O(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



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)

Summary

- Sterile neutrinos (= "heavy neutral leptons") 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_R are possible (& technically natural).
- Using a benchmark scenario (SPSS: Symmetry Protected Seesaw Scenario) we discussed various promising signatures …
  - Displaced vertex searches: very powerful (for $M_R < M_W$).
  - LNV suppressed for prompt decays (for LHC searches with $M_R > M_W$, LNV is unobservable due to "lepton number"-like symmetry suppression).
  - *But: For $M_R < M_W$, heavy neutrino-antineutrino oscillations can lead to resolvable oscillating LNV signatures as function of lifetime/displacement.*
  - LFV (but LNC) signatures (especially with taus) and indirect (non-unitarity) signatures could be very powerful at future colliders.
- Fascinating possibilities for probing sterile neutrinos at future colliders!

Thanks for your attention!

Extra Slides

Possible sensitivities of future cLFV searches

Sensitivites of future cLFV searches

- Estimated sensitivities of planned experiments at 90% C.L.:

Process	MUV Prediction	Exp. reach	Sensitivity
$Br_{\tau e}$	$4.3 \times 10^{-4} \vert\varepsilon_{\tau e}\vert^2$	10^{-9}	$\vert\varepsilon_{\tau e}\vert \geq 1.5 \times 10^{-3}$
$Br_{\tau \mu}$	$4.1 \times 10^{-4} \vert\varepsilon_{\tau \mu}\vert^2$	10^{-9}	$\vert\varepsilon_{\tau \mu}\vert \geq 1.6 \times 10^{-3}$
$Br_{\mu eee}$	$1.8 \times 10^{-5} \vert\varepsilon_{\mu e}\vert^2$	10^{-16}	$\vert\varepsilon_{\mu e}\vert \geq 2.4 \times 10^{-6}$
$R^{Ti}_{\mu e}$	$1.5 \times 10^{-5} \vert\varepsilon_{\mu e}\vert^2$	2×10^{-18}	$\vert\varepsilon_{\mu e}\vert \geq 3.6 \times 10^{-7}$

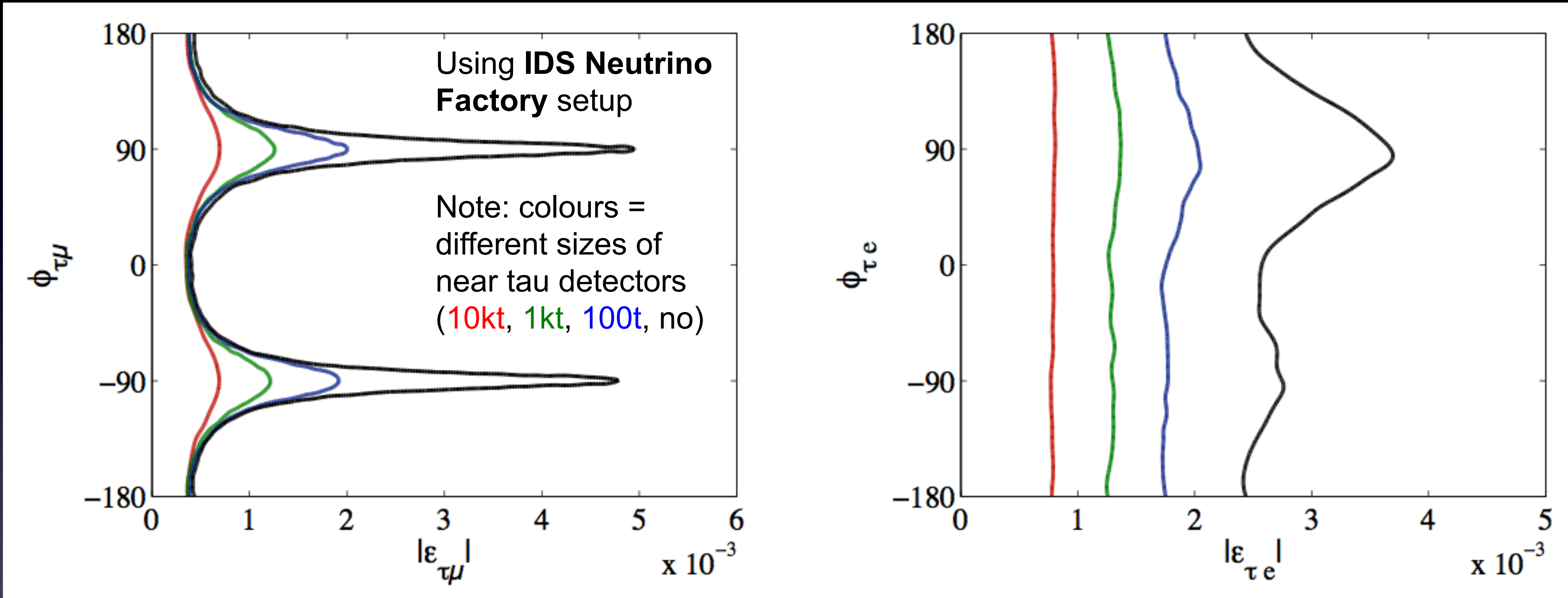
taken from: S.A., O. Fischer (arXiv:1407.6607)

→ Sensitivity to the products $|\theta^*_\mu \theta_e|$, $|\theta^*_\tau \theta_\mu|$, $|\theta^*_\tau \theta_e|$, due to the relation

$$\varepsilon_{\alpha\beta} = -\frac{v_{\mathrm{EW}}^2 y^*_{\nu_\alpha} y_{\nu_\beta}}{2M^2} = -\theta^*_\alpha \theta_\beta$$

Possible sensitivities of future neutrino oscillation experiments

Possible sensitivity of future neutrino oscillation experiments → phases of θ_α



S.A., M. Blennow, E. Fernandez-Martinez, J. Lopez-Pavon (arXiv:0903.3986)

- From the interplay of (tau-sensitive) near and far detectors at, e.g., a neutrino factory, neutrino oscillations could provide information on the phase of the non-unitarity parameters $\varepsilon_{\tau\mu}$ and $\varepsilon_{\tau e}$ (i.e. on the phases of $-\theta_\tau^*\theta_\mu$ and $-\theta_\tau^*\theta_e$)

Predictions of specific classes of low scale seesaw models: Examples

A benchmark model f...

SPSS (Symmetry Prote...

Note: Since in the SPSS we allow for additional sterile neutrinos, <u>M and y_α</u> (α=e,μ,τ) are indeed <u>free parameters</u> (not constrained by m_ν). In specific models there are correlations among the y_α. <u>Strategy of the SPSS: study how to measure the y_α independently, in order to test (not a priori assume) such correlations!</u>

Consider 2+n sterile neutrinos (plus the th... the steriles as in example 2 due to some ...

$$Y_\nu = \begin{pmatrix} y_{\nu_e} & 0 \\ y_{\nu_\mu} & 0 \\ y_{\nu_\tau} & 0 \end{pmatrix} \qquad M = \begin{pmatrix} 0 & M_R & \vdots & \\ M_R & 0 & \vdots & 0 \\ \cdots & \cdots & & \end{pmatrix}$$

+ O(ε) perturbations to generate the ...utrino

...we can ...eglect for ... studies)

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

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

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

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

Further predictions in specific types of low scale seesaw mechanisms: ΔM of heavy ν's

*) Basis: (ν_L^α, N_1, N_2)

Perturbations of the mass matrix:* $M_\nu = \begin{pmatrix} 0 & m_D & \varepsilon_{\text{lin}} \\ (m_D)^T & \tilde{\varepsilon} & M \\ \varepsilon_{\text{lin}}^T & M & \varepsilon_{\text{inv}} \end{pmatrix}$

ε_{lin} linear seesaw

ε_{inv} inverse seesaw

($\tilde{\varepsilon}$ additional parameter, no contribution to light neutrino masses)

Perturbations O(ε) generate the light neutrino masses and. E.g. in the case of the minimal linear seesaw model, we obtain lead to a **prediction for the heavy neutrino mass splitting ΔM** (**in terms of the light neutrino mass splittings**):

$$\Delta M^{\text{lin,NO}} = \frac{2\rho_{\text{NO}}}{1-\rho_{\text{NO}}}\sqrt{\Delta m_{21}^2} = 0.0416\,\text{eV}$$

$$\Delta M^{\text{lin,IO}} = \frac{2\rho_{\text{IO}}}{1+\rho_{\text{IO}}}\sqrt{\Delta m_{23}^2} = 0.000753\,\text{eV}$$

$$\rho_{\text{NO}} = \frac{\sqrt{r+1}-\sqrt{r}}{\sqrt{r}+\sqrt{r+1}} \text{ and } r = \frac{|\Delta m_{21}^2|}{|\Delta m_{32}^2|}$$

$$\rho_{\text{IO}} = \frac{\sqrt{r+1}-1}{\sqrt{r+1}+1} \text{ and } r = \frac{|\Delta m_{21}^2|}{|\Delta m_{13}^2|}$$

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

Resolvable heavy neutrino-antineutrino oscillations at colliders

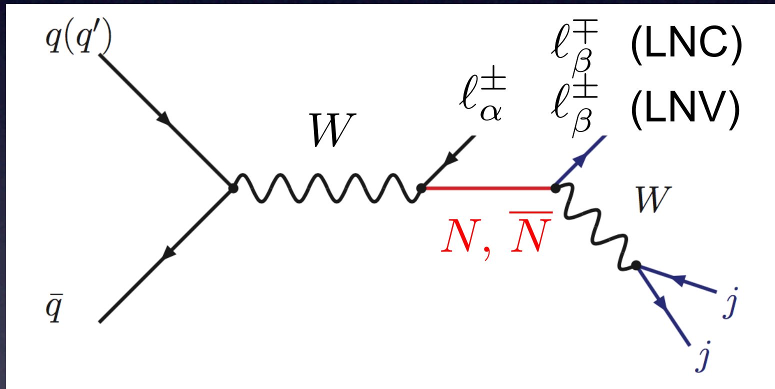
Heavy neutrino-antineutrino oscillations at colliders

Definition: Heavy (anti)neutrino defined via production; superposition of mass eigenstates N_4, N_5

antineutrino, $W^- \to \overline{N}\ell^-$
neutrino, $W^+ \to N\ell^+$

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

Consider, e.g., the "dilepton-dijet" signature at pp colliders, pp ➔ l_α l_β jj:



In the symmetry limit of the SPSS benchmark model, lepton number is exactly conserved ➔ only LNC processes!

$pp \to \ell_\alpha^+ \ell_\beta^- jj$ (LNC) ✓
$pp \to \ell_\alpha^\pm \ell_\beta^\pm jj$ (LNV) ×

Heavy neutrino-antineutrino oscillations at colliders

However with the O(ε) perturbations included to generate the light neutrino masses:
A mass splitting ΔM between heavy neutrinos is generated which induces oscillations!

Probability that a produced N oscillates into $\bar{N}$ (or vice versa) given by $|g\_(t)|^2$, with

$$g_-(t) \simeq -ie^{-iMt}e^{-\frac{\Gamma}{2}t}\sin\left(\frac{\Delta M}{2}t\right)$$

Mass splitting ΔM predicted e.g. in minimal low scale linear seesaw models

Such an oscillation induces LNV!

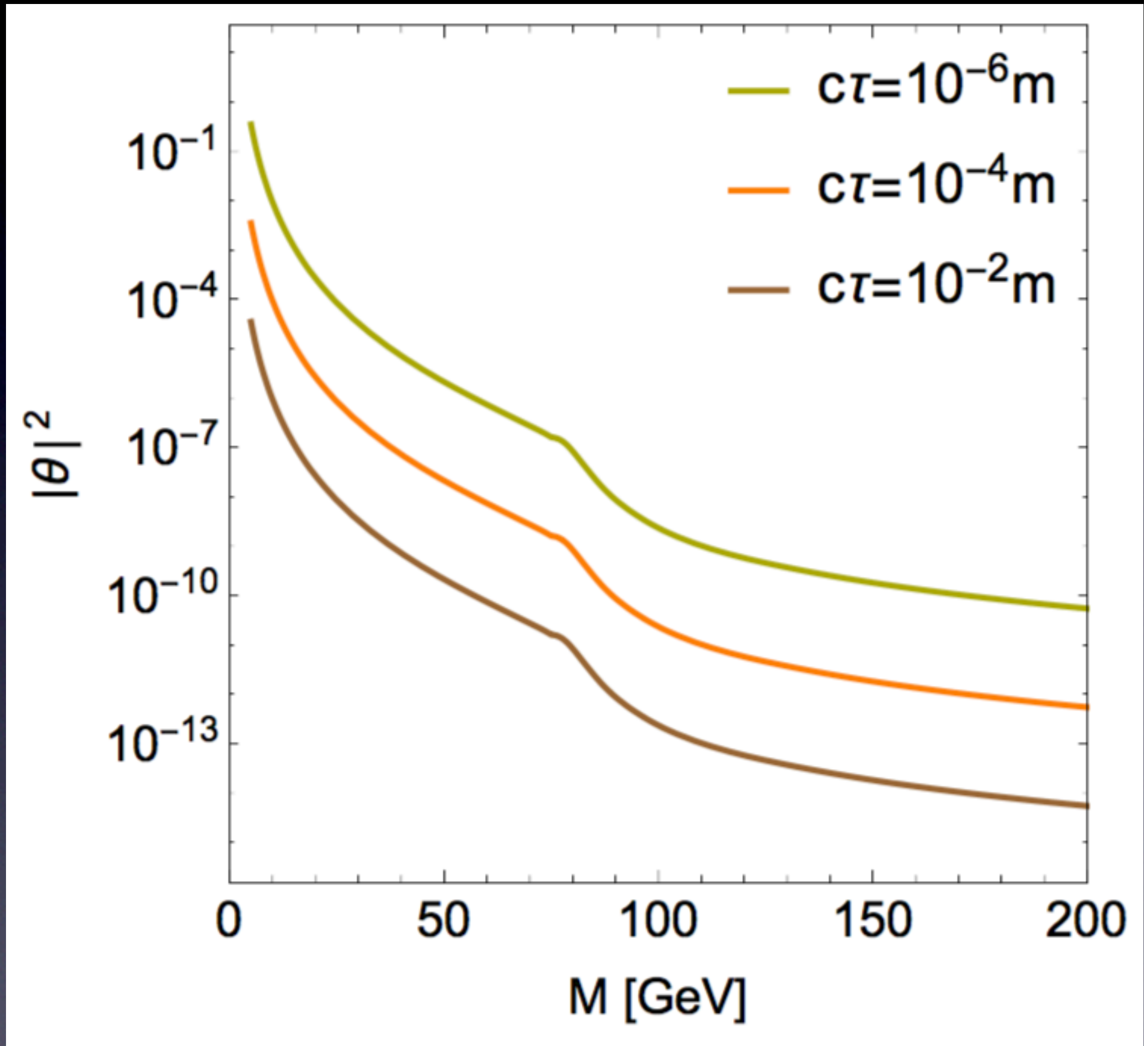
Signature: Ratio of LNV/LNC final states oscillates as function of heavy neutrino lifetime (or of vertex displacement in the laboratory system)

$$R_{\ell\ell}(t_1,t_2) = \frac{\int_{t_1}^{t_2}|g_-(t)|^2 dt}{\int_{t_1}^{t_2}|g_+(t)|^2 dt} = \frac{\#(\ell^+\ell^+)+\#(\ell^-\ell^-)}{\#(\ell^+\ell^-)}$$

J. Gluza and T. Jelinski (2015), G. Anamiati, M. Hirsch and E. Nardi (2016),
S.A., E. Cazzato, O. Fischer (2017), A. Das, P. S. B. Dev and R. N. Mohapatra (2017)

With: $g_+(t) \simeq e^{-iMt}e^{-\frac{\Gamma}{2}t}\cos\left(\frac{\Delta M}{2}t\right)$

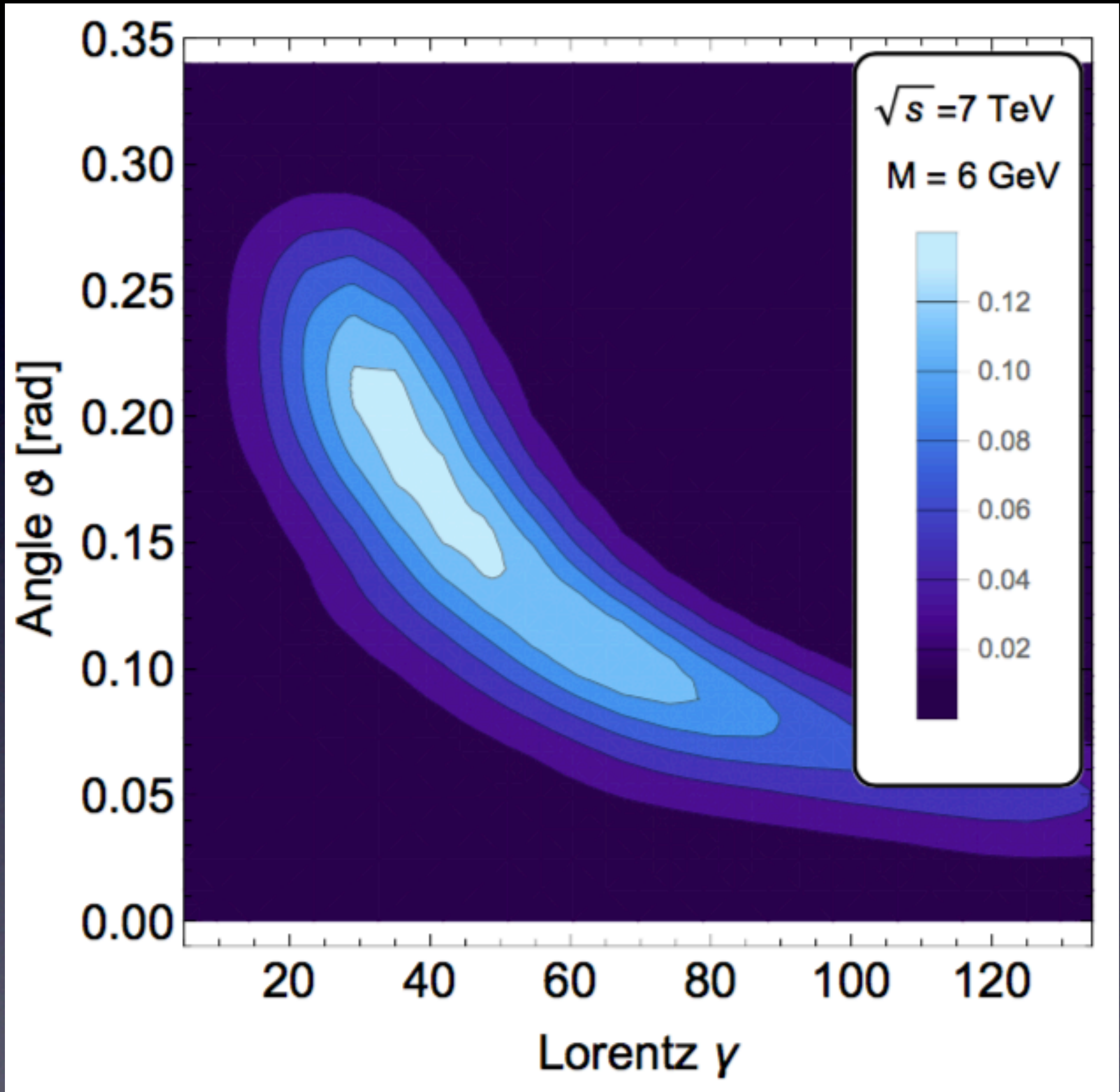
As shown earlier: Lifetime and decay length of heavy neutrinos



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

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

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

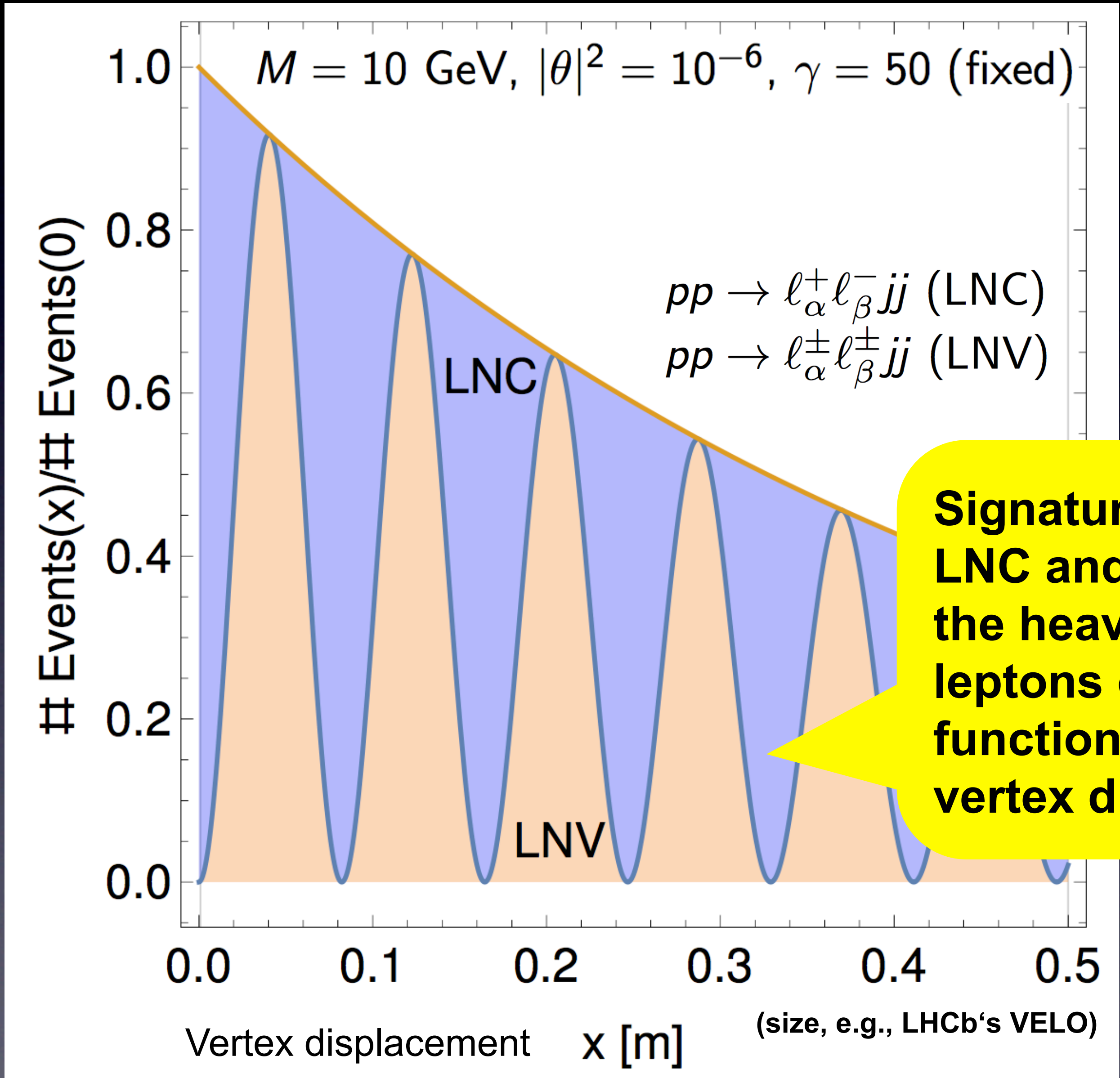


S. A., E. Cazzato, O. Fischer; arXiv:1706.05990

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)

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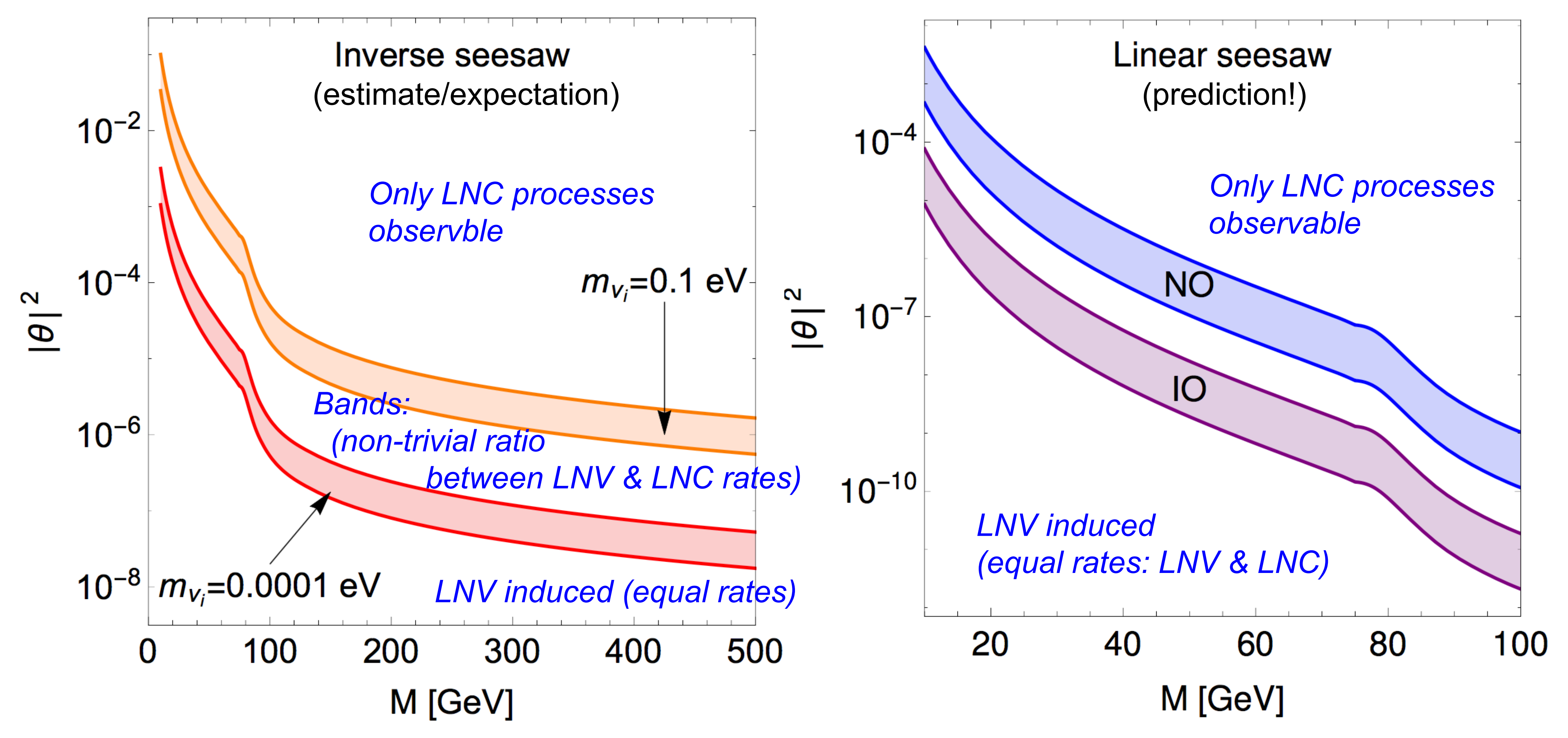
S.A., Cazzato, Fischer (2017),
A. Das, P. S. B. Dev and B. R. N. Mohapatra (2017)

Intrgrated effects of (non-resolvable) heavy neutrino-antineutrino oscillations

Even if these oscillations are not resolvable, induced LNV can be relevant (depends on θ^2)

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



See also: J. Gluza and T. Jelinski (2015), P. S. Bhupal Dev and R. N. Mohapatra (2015),
G. Anamiati, M. Hirsch and E. Nardi, JHEP 1610 (2016),A. Das, P. S. B. Dev and R. N. Mohapatra (2017)

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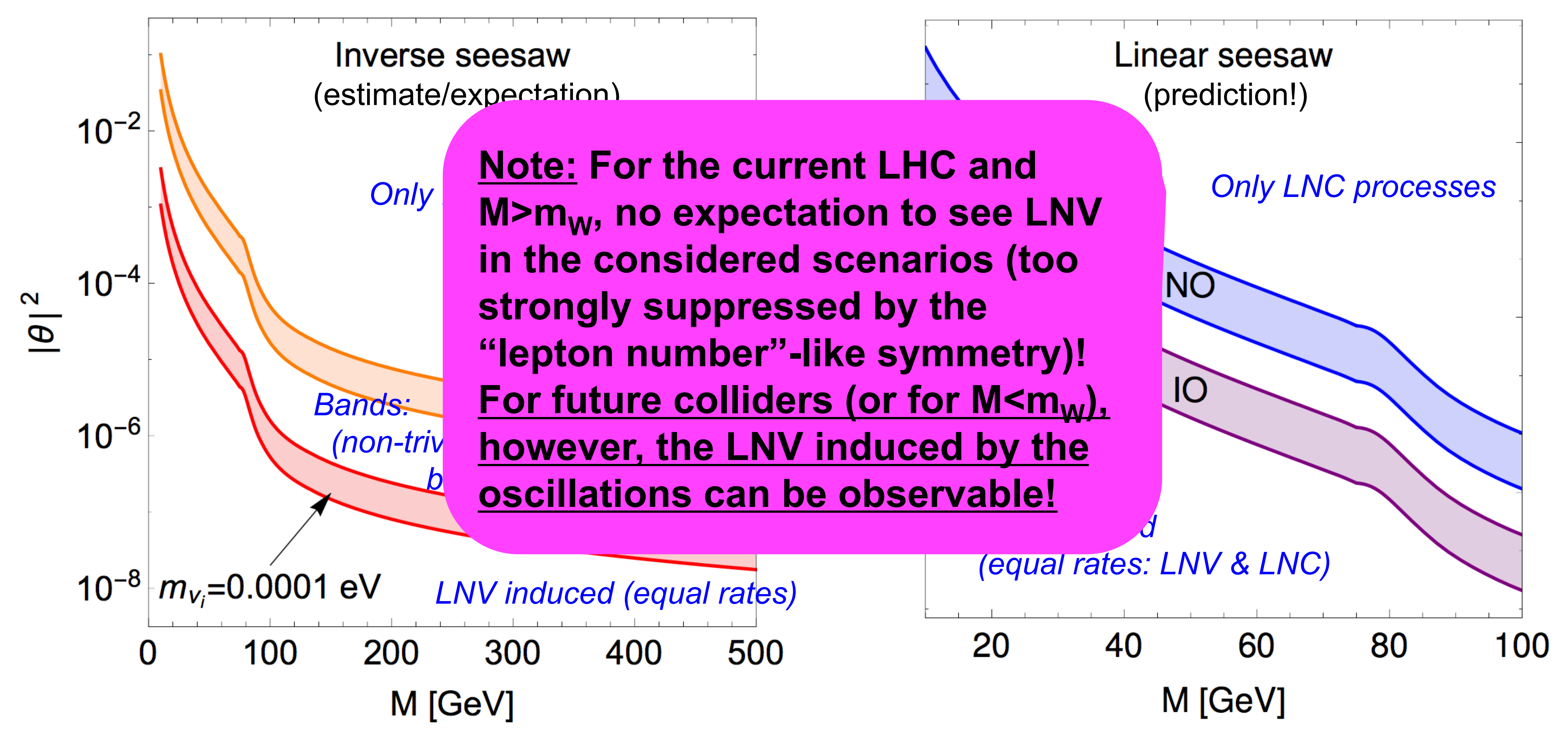


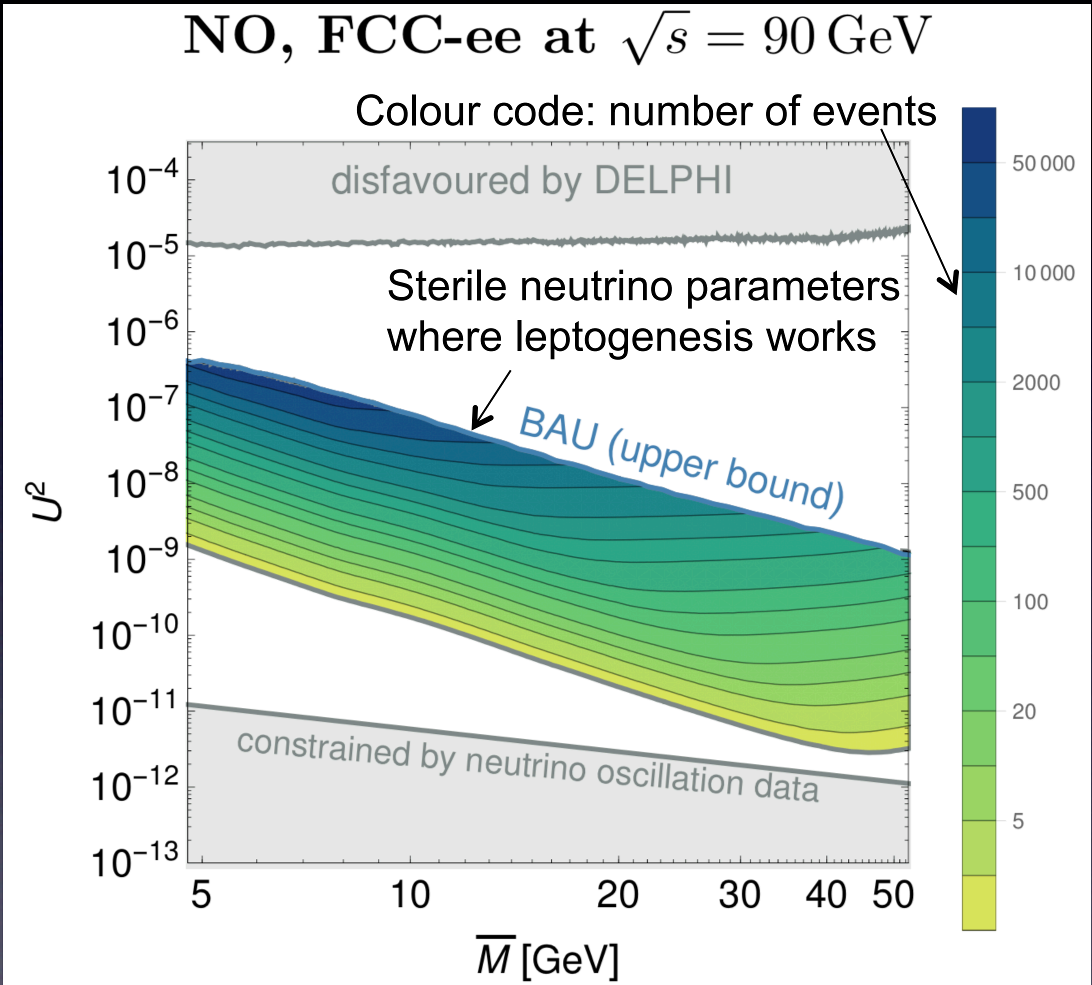
<u>Note:</u> For the current LHC and $M>m_W$, no expectation to see LNV in the considered scenarios (too strongly suppressed by the "lepton number"-like symmetry)!
<u>For future colliders (or for $M<m_W$), however, the LNV induced by the oscillations can be observable!</u>

See also: J. Gluza and T. Jelinski (2015), P. S. Bhupal Dev and R. N. Mohapatra (2015), G. Anamiati, M. Hirsch and E. Nardi, JHEP 1610 (2016),A. Das, P. S. B. Dev and R. N. Mohapatra (2017)

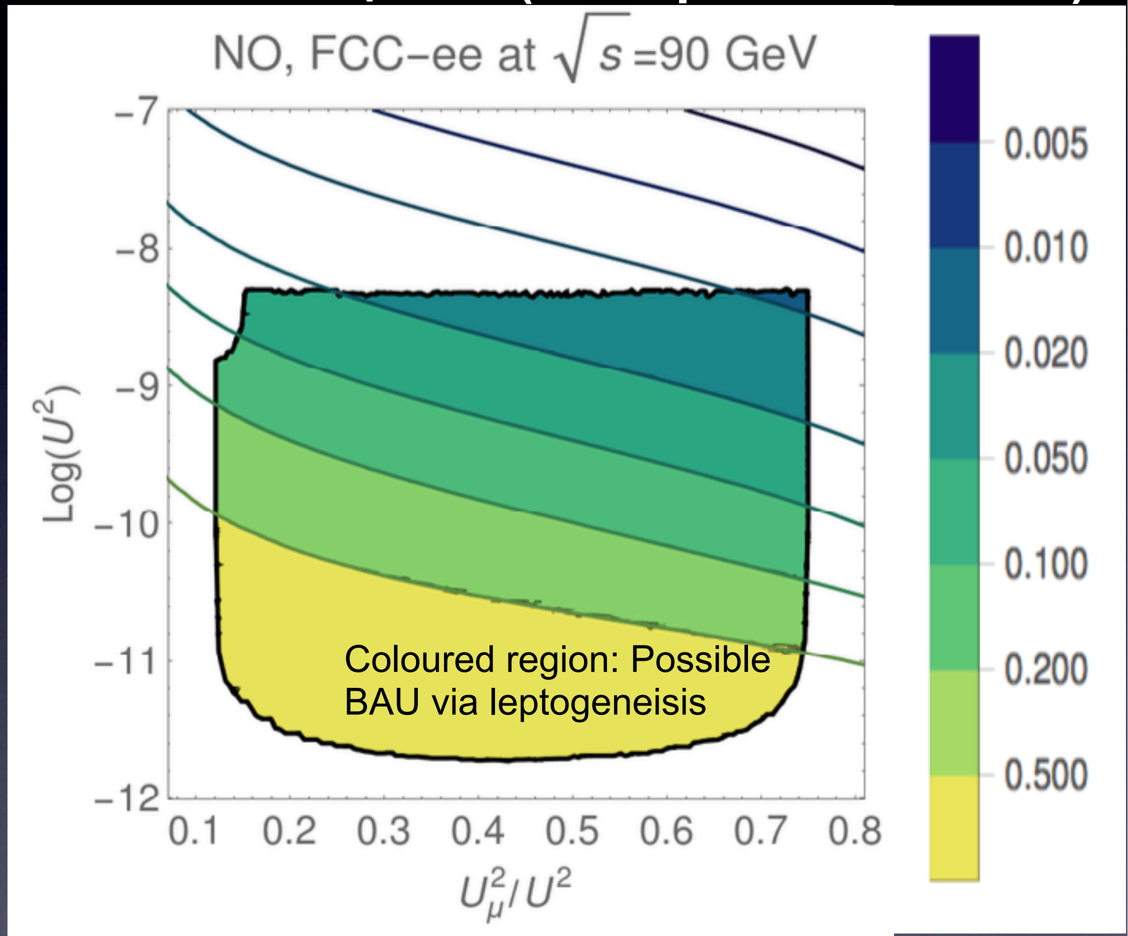
Towards measuring the flavor-dependent active-sterile mixing angles at future colliders … and probing leptogenesis

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

Probing Leptogenesis



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



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

Estimates from semi-leptonic heavy neutrino decays N → μ 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)

Sensitivity estimates for signatures at pp and ep colliders

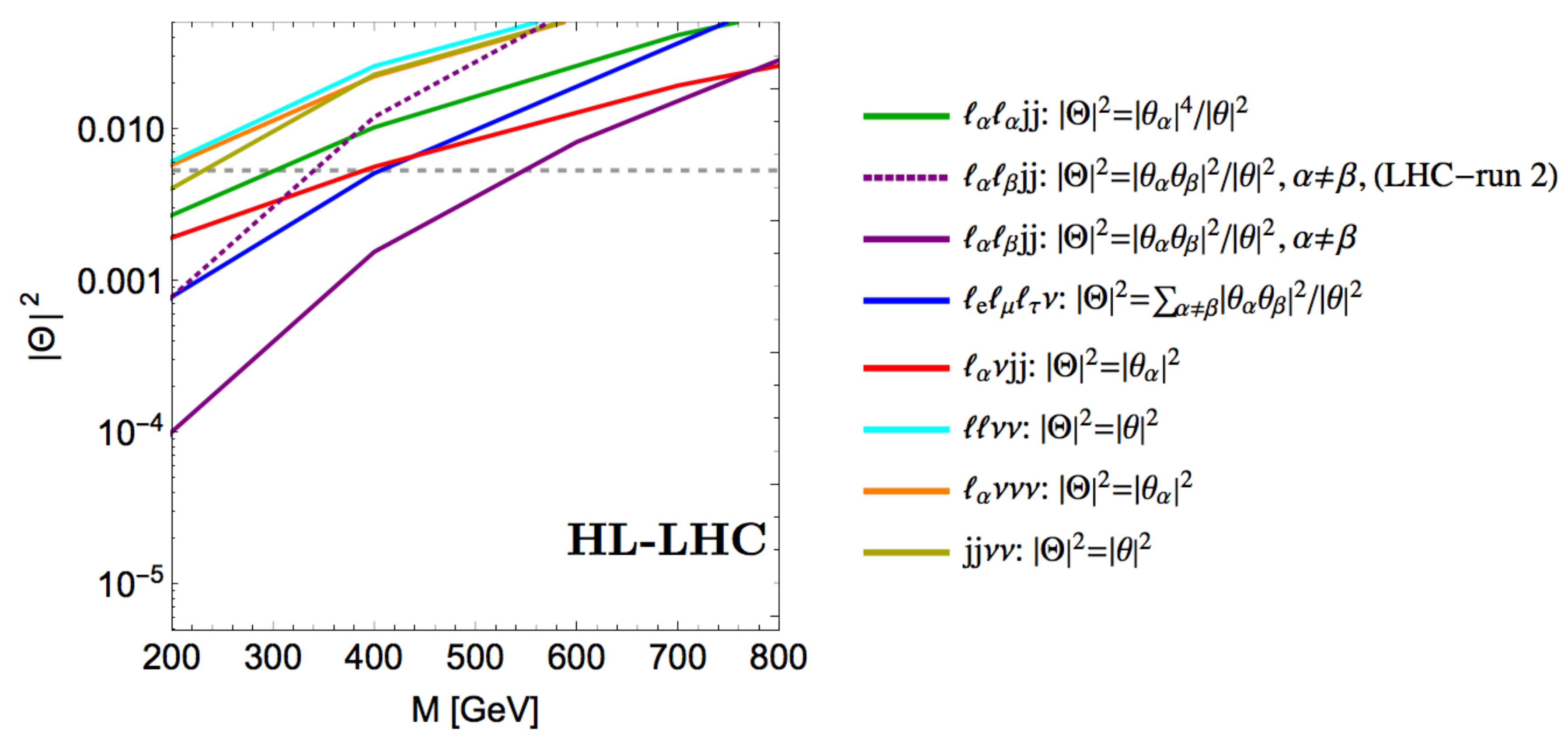
Sterile neutrino signatures at pp colliders

Name	Final State	Channel [production,decay]	$\lvert\theta_\alpha\rvert$ dependency	LNV/LFV
dilepton-dijet	$\ell_\alpha \ell_\beta jj$	$[\mathbf{W_s}, W]$	$\frac{\lvert\theta_\alpha\theta_\beta\rvert^2}{\theta^2}$	✓/✓
trilepton	$\ell_\alpha \ell_\beta \ell_\gamma \nu$	$[\mathbf{W_s}, \{W, Z(h)\}]$	$\left\{\frac{\lvert\theta_\alpha\theta_\beta\rvert^2}{\theta^2}^{(*)}, \lvert\theta_\alpha\rvert^{2(*)}\right\}$	×/✓
lepton-dijet	$\ell_\alpha \nu jj$	$[\mathbf{W_s}, Z(h)]$, $[\mathbf{Z_s}, W]$	$\lvert\theta_\alpha\rvert^2$	×
dilepton	$\ell_\alpha \ell_\beta \nu\nu$	$[\mathbf{Z_s}, \{W, Z(h)\}]$	$\left\{\lvert\theta_\alpha\rvert^{2(*)}, \lvert\theta\rvert^{2(*)}\right\}$	×
mono-lepton	$\ell_\alpha \nu\nu\nu$	$[\mathbf{W_s}, Z]$	$\lvert\theta_\alpha\rvert^2$	×
dijet	$\nu\nu jj$	$[\mathbf{Z_s}, Z(h)]$	$\lvert\theta\rvert^2$	×

Table 4: Signatures of sterile neutrinos at leading order for *pp* colliders with their corresponding final states, production and decay channels (cf. section 2.2), and their dependency on the active-sterile mixing parameters. A checkmark in the "LNV/LFV" column indicates that an unambiguous signal for LNV and/or LFV is possible (cf. discussion in sections 2.2.3 and 2.2.4).
$^{(*)}$: The dependency on the active-sterile mixing can be inferred when the origin of the charged leptons is known.

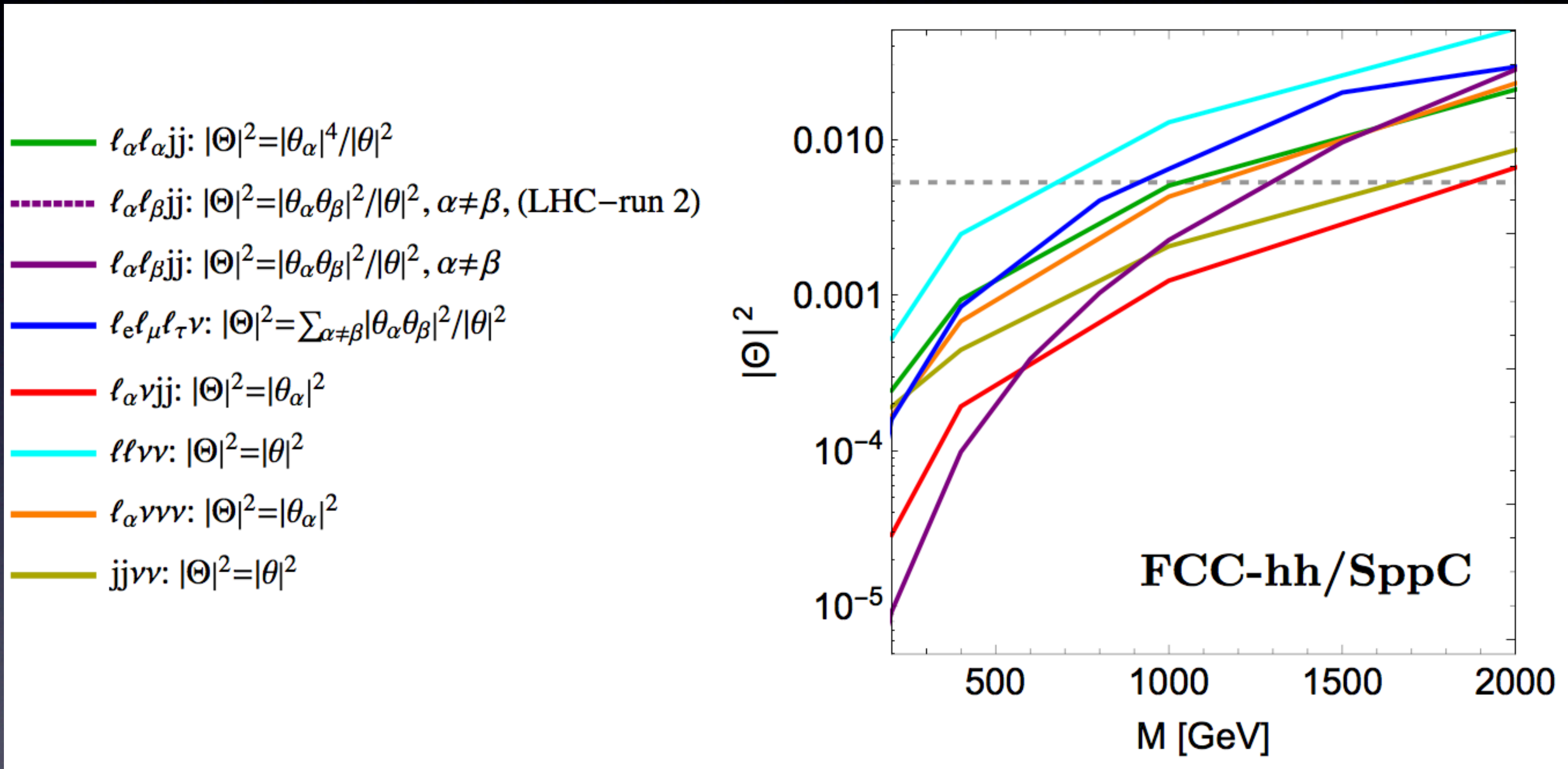
S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

Sensitivity estimates for sterile neutrino signatures at the HL-LHC



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

Sensitivity estimates for sterile neutrino signatures at the FCC-hh/SppC



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

Sterile neutrino signatures at e⁻p colliders

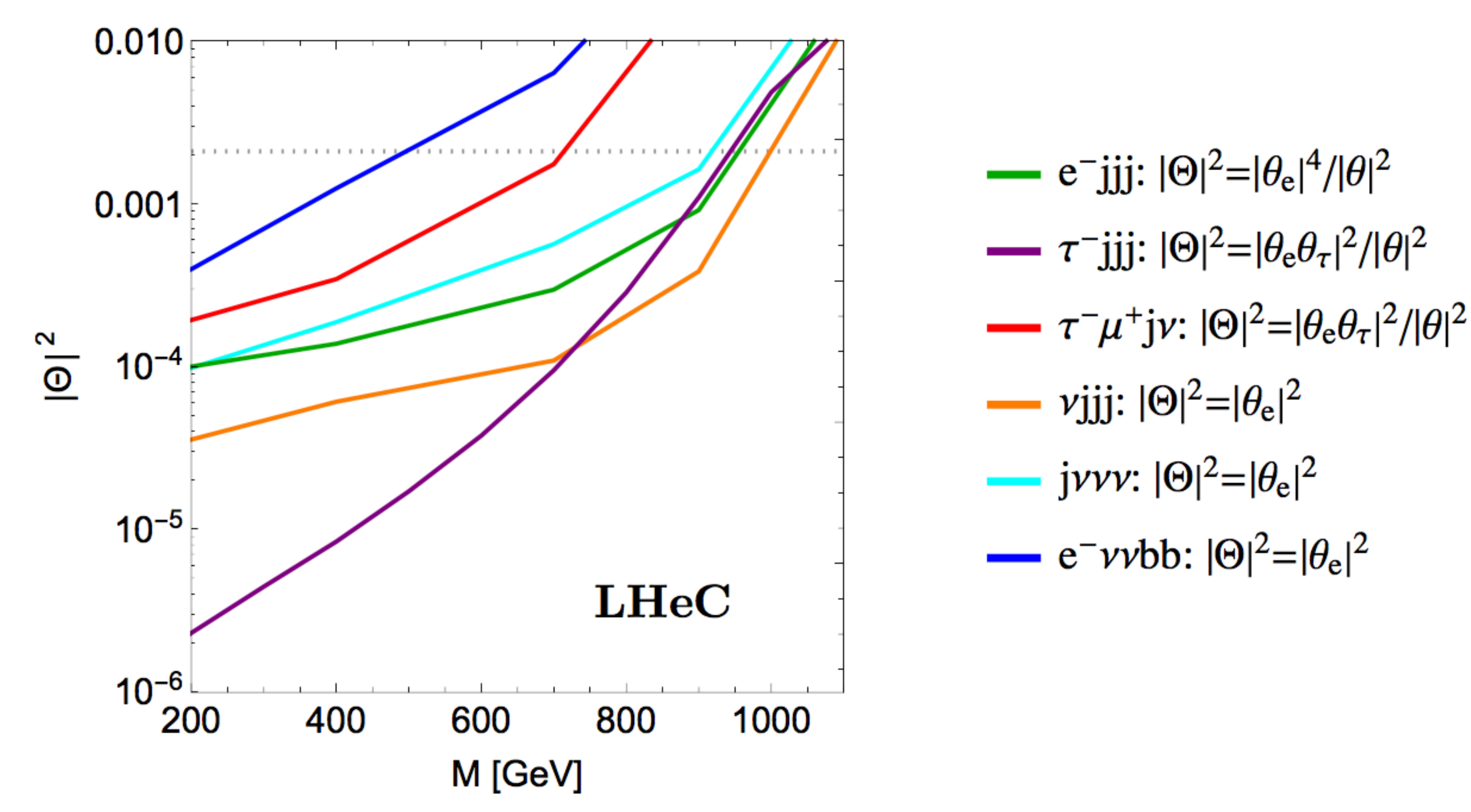
Name	Final State	Channel [production,decay]	$\lvert\theta_\alpha\rvert$ dependency	LNV/LFV
lepton-trijet	$jjj\ell_\alpha$	$[\mathbf{W_t}^{(q)}, W]$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓/✓
jet-dilepton	$j\ell_\alpha^\pm\ell_\beta^\mp\nu$	$[\mathbf{W_t}^{(q)}, \{W, Z(h)\}]$	$\left\{\frac{\lvert\theta_e\theta_\alpha\rvert^{2\,(*)}}{\theta^2}, \lvert\theta_e\rvert^{2(*)}\right\}$	×/✓
trijet	$jjj\nu$	$[\mathbf{W_t}^{(q)}, Z(h)]$	$\lvert\theta_e\rvert^2$	×
monojet	$j\nu\nu\nu$	$[\mathbf{W_t}^{(q)}, Z]$	$\lvert\theta_e\rvert^2$	×

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

lepton-quadrijet	$jjjj\ell_\alpha$	$[\mathbf{W_t}^{(\gamma)}, W]$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓/✓
dilepton-dijet	$\ell_\alpha\ell_\beta\nu jj$	$[\mathbf{W_t}^{(\gamma)}, \{W, Z(h)\}]$	$\left\{\frac{\lvert\theta_e\theta_\alpha\rvert^{2\,(*)}}{\theta^2}, \lvert\theta_e\rvert^{2(*)}\right\}$	×/✓
trilepton	$\ell_\alpha^-\ell_\beta^-\ell_\gamma^+\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, \{W, Z(h)\}]$	$\left\{\frac{\lvert\theta_e\theta_\alpha\rvert^{2\,(*)}}{\theta^2}, \lvert\theta_e\rvert^{2(*)}\right\}$	×/✓
quadrijet	$jjjj\nu$	$[\mathbf{W_t}^{(\gamma)}, Z(h)]$	$\lvert\theta_e\rvert^2$	×
lepton-dijet	$\ell_\alpha^- jj\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, Z(h)]$	$\lvert\theta_e\rvert^2$	×
dijet	$jj\nu\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, Z]$	$\lvert\theta_e\rvert^2$	×
monolepton	$\ell_\alpha^-\nu\nu\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, Z]$	$\lvert\theta_e\rvert^2$	×

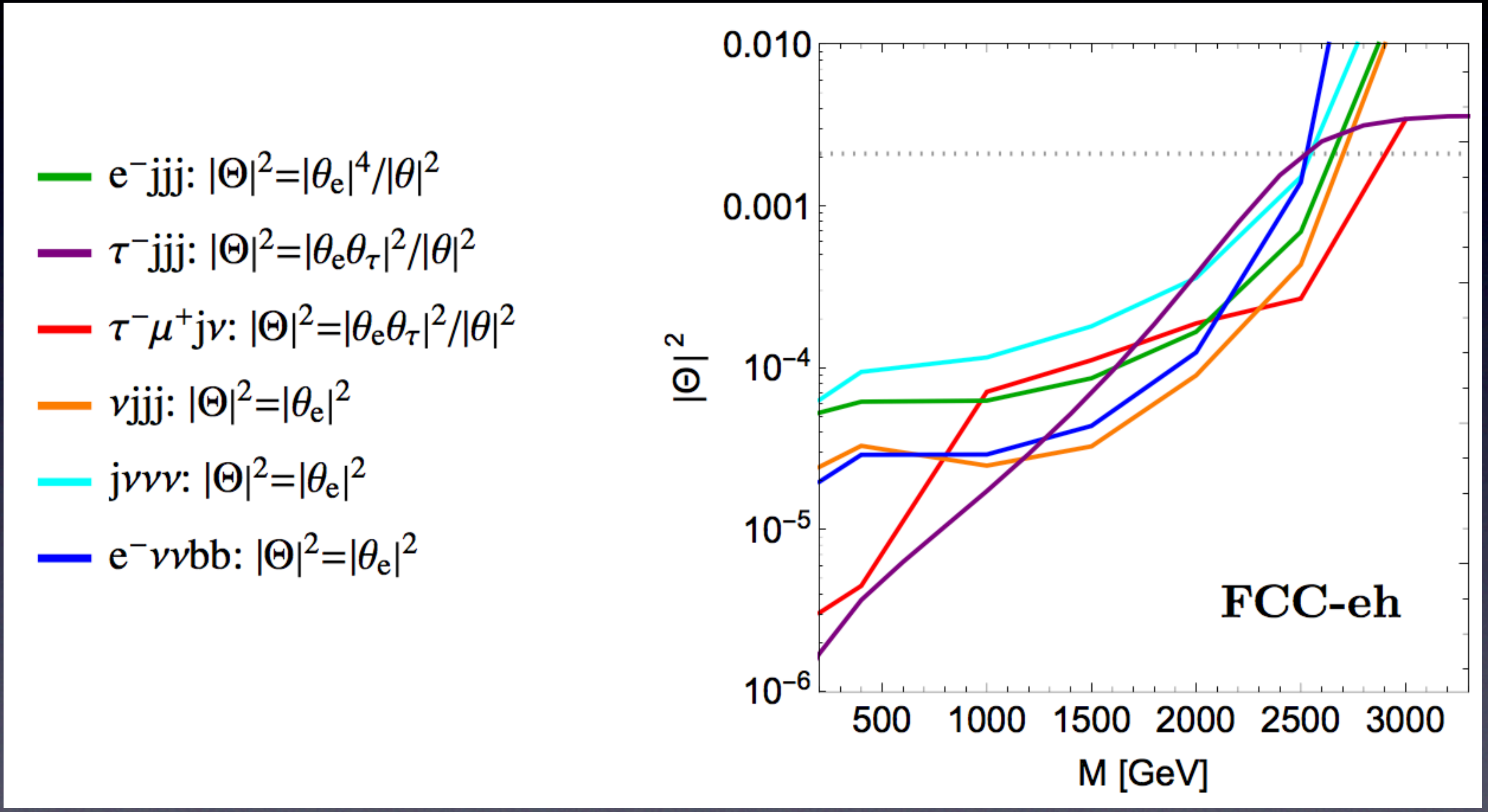
Table 5: Signatures of sterile neutrinos at leading order for e^-p colliders with their corresponding final states, production and decay channels (cf. section 2.2), and their dependency on the active-sterile mixing parameters. A checkmark in the "LNV/LFV" column indicates that an unambiguous signal for LNV and/or LFV is possible (cf. discussion in sections 2.2.3 and 2.2.4). The upper and lower part of the table contains signatures where the heavy neutrino is produced via electron-quark scattering ($\mathbf{W}_\mathbf{t}^{(\mathbf{q})}$) and $W\gamma$-fusion ($\mathbf{W}_\mathbf{t}^{(\gamma)}$), respectively.

Sensitivity estimates for sterile neutrino signatures at the LHeC



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

Sensitivity estimates for sterile neutrino signatures at the FCC-eh



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

Sensitivity forecasts for displaced vertex searches at the FCC-ee, hh and eh

General: Number of signal events from displaced vertices

N_{dv}: Number of signal events from displaced vertices

Production cross section σ

N_{xN}: Overall number of events from N decays

Br into desired final state

L: Integrated luminosity

$$N_{\mathrm{dv}}(\sqrt{s},\mathcal{L},M,|\theta|^2) = \sum_{\mathrm{x}=\nu,\ell^\pm} \overbrace{\sigma_{\mathrm{x}N}(\sqrt{s},M,|\theta|^2)\,\mathrm{Br}_{\mu jj}\,\mathcal{L}}^{N_{\mathrm{x}N}} \times$$

$$\int D_{\mathrm{x}N}(\vartheta,\gamma)\,P_{\mathrm{dv}}(x_{\mathrm{min}}(\vartheta),x_{\mathrm{max}}(\vartheta),\Delta x_{\mathrm{lab}}(\tau,\gamma))\,d\vartheta d\gamma\,.$$

D_{xN}: Probability distribution for producing N with certain θ and γ.

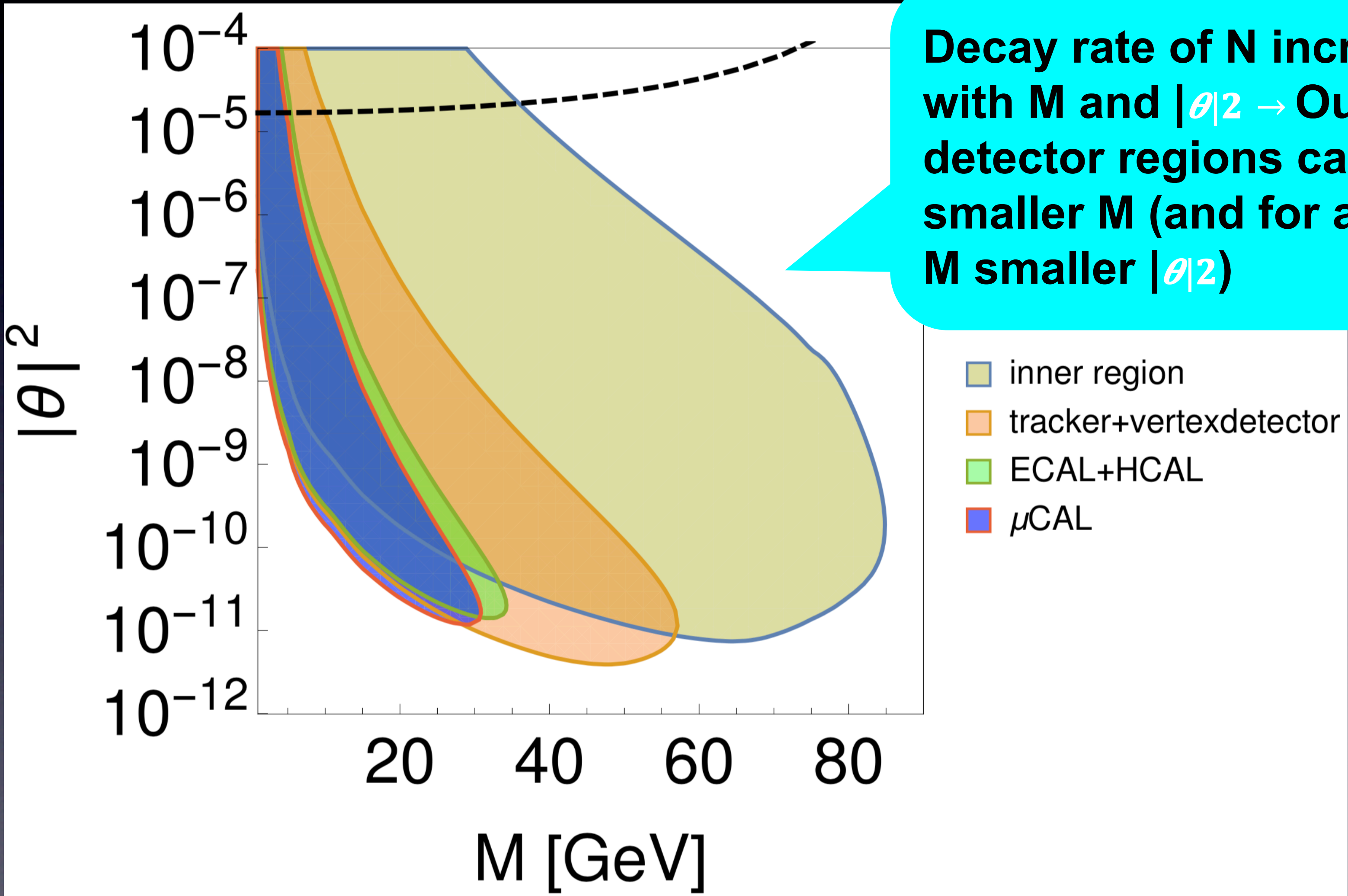
D_{xN}: Probability distribution for for the decay to occur within a certain detector part.

Now in addition one needs:
- Efficiencies for the various FCC detector regions, $\cdots$?
- Backgrounds when closer to primary vertex, cuts $\cdots$?

$\rightarrow$ **A lot of work to be done** $\cdots$

Parameter sensitivities of the different detector regions

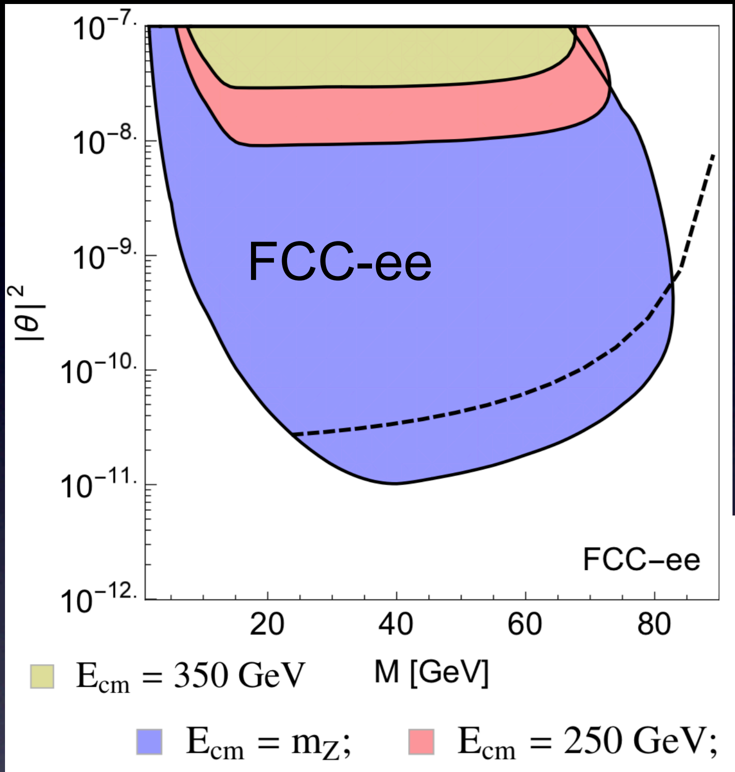
Example: FCC-ee, Z pole run, SiD-like detector



Decay rate of N increases with M and $|\theta|^2$ → Outer detector regions can probe smaller M (and for a given M smaller $|\theta|^2$)

Plot by Eros Cazzato

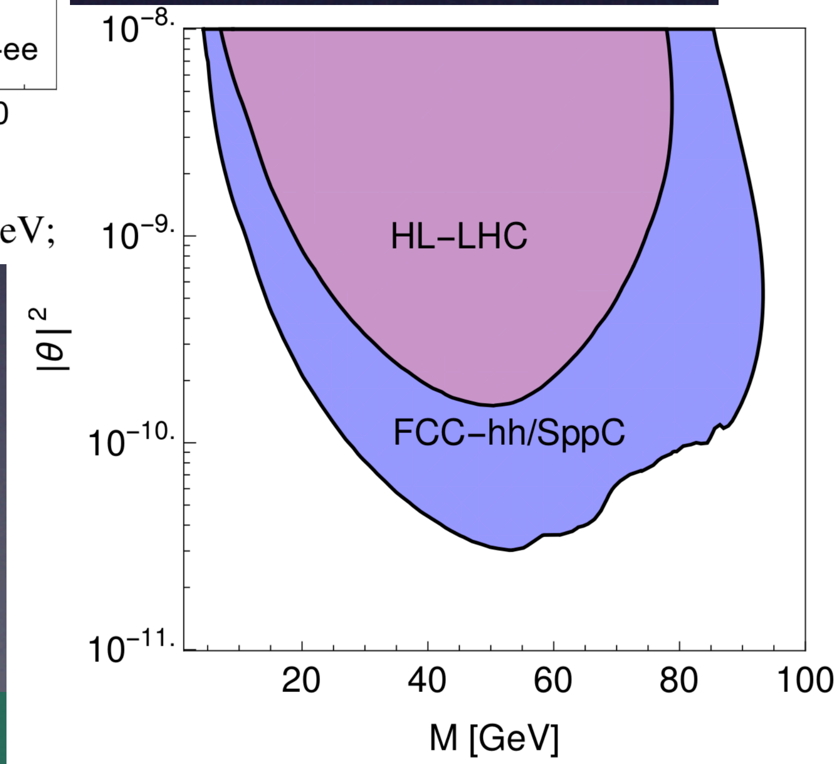
Estimated/“first look“ sensitivities via displaced vertices at FCC-ee, -hh and -eh

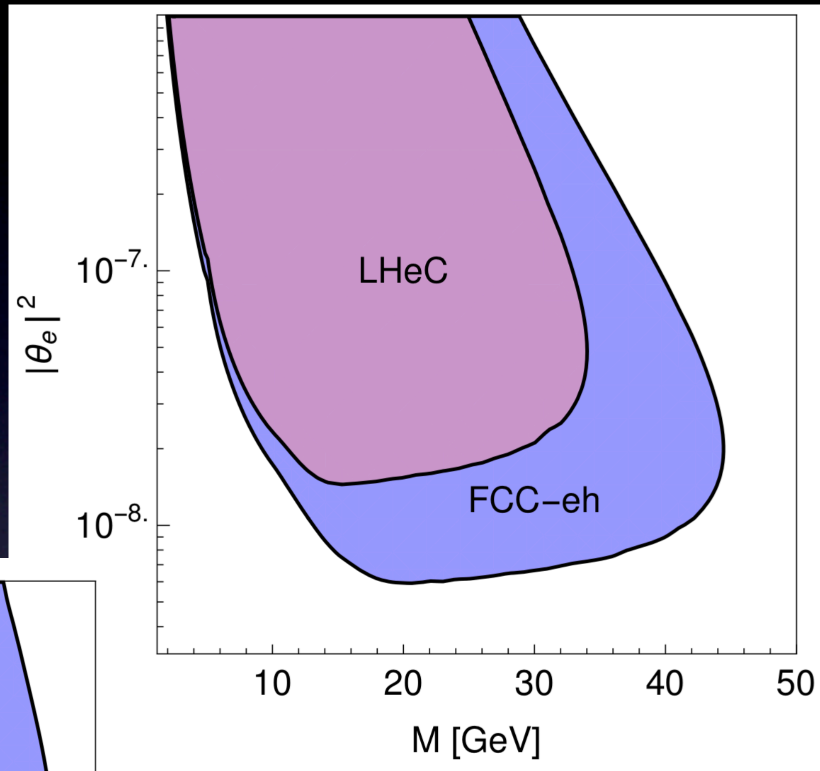


Estimate for FCC-ee [using SiD-like detector, L = 110 ab^{-1} at the Z pole]:
S.A., E. Cazzato, O. Fischer (arXiv:1604.02420)
See also:
Blondel, Graverini, Serra, Shaposhnikov (FCC study team, 2014)

“First look” result for FCC-hh:
S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

[Assumed for FCC-hh “first look”: x_{min} = 1mm, x_{max} = 1m, $\gamma_{average}$ = 40 (LH-LHC), 100 (FCC-hh), L= 20 ab^{-1}, 100% efficienty]



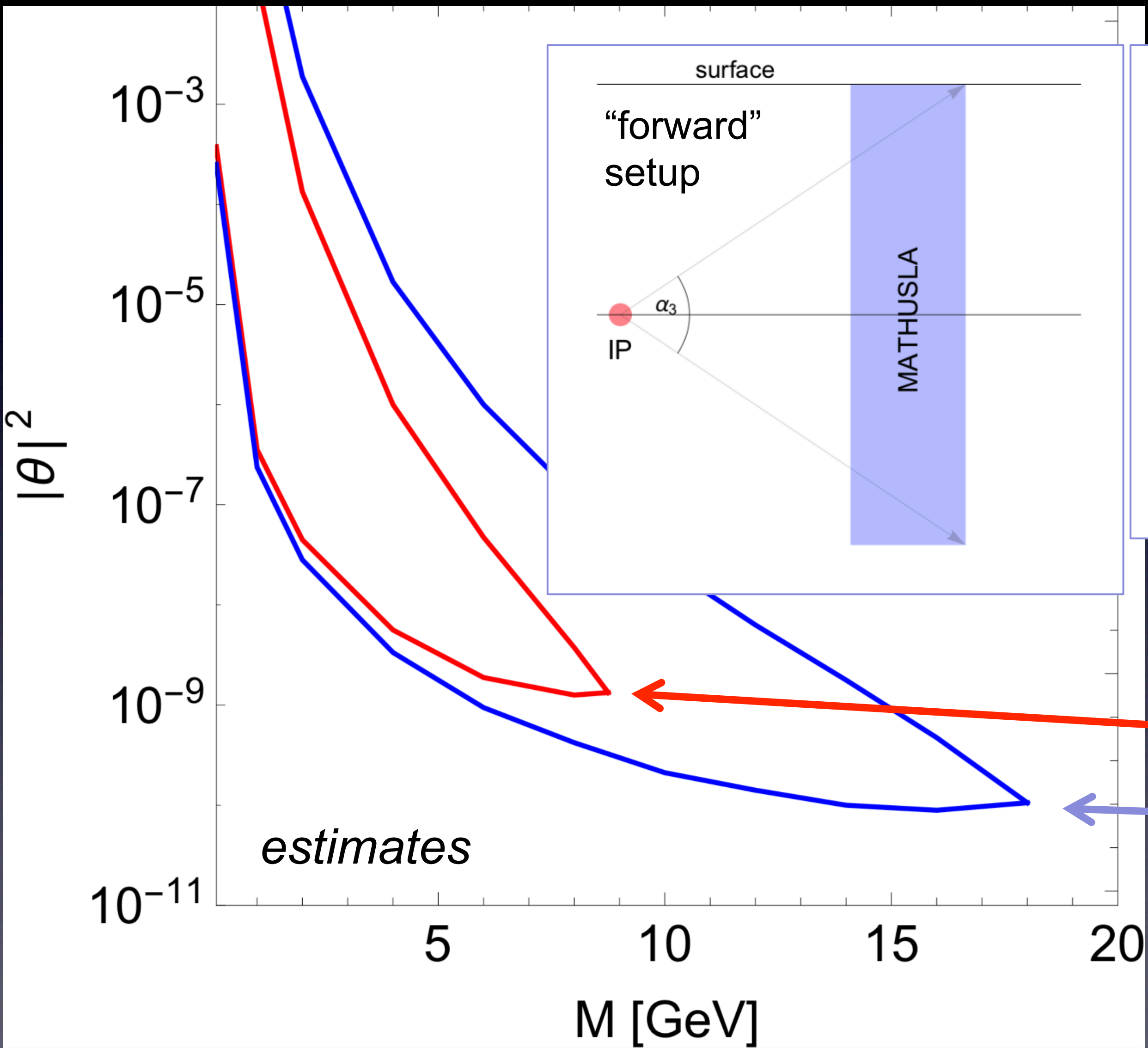


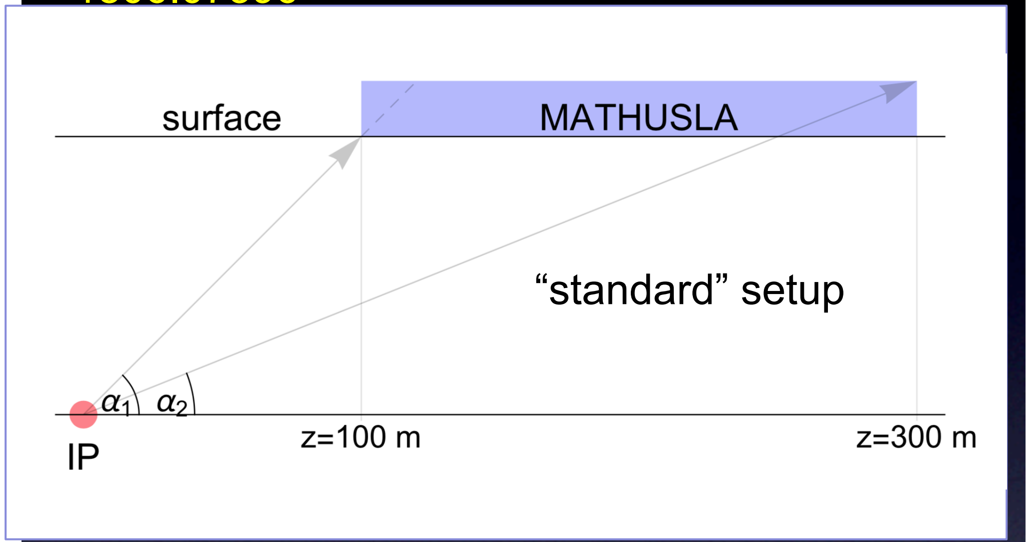
“First look” result for FCC-eh:
S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

[Assumed for FCC-eh “first look”: x_{min} = 1mm, x_{max} = 1m
$\gamma_{average}$ = 3 (LHeC), 5 (FCC-eh)
L= 1 ab^{-1}, 100% efficienty]

Probing lower M: Extra distant detector (e.g. MATHUSLA-type) with FCC-hh

See also MATHUSLA physics case: arXiv: 1806.07396





	z [m]	y [m]	x [m]
"standard"	[100,300]	[100, 120]	[-100, 100]
	z [m]	r [m]	ϕ [m]
"forward"	[20,40]	[5,30]	[0, 2π]

Table 1: Possible detector geometries for MATHUSLA at FCC-hh. The origin of the coordinate system is the IP, with $(z, y, x) = (0, 0, 0)$, with the z axis pointing along the direction of the beam, and y in the vertical and x in the horizontal direction. The "forward" detector variant is assumed to be symmetric in the angle ϕ (which rotates in the x-y plane) and with the fiducial detector volume starting outside of an inner circle with radius 5 m (to account for the beam pipe).