Long-Lived Sterile Neutrino Dark Sectors at the FCC

Stefan Antusch

University of Basel
Department of Physics

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

2nd FCC Physics Workshop, 2018, CERN

January 19, 2018

A sterile neutrino dark sector can be an answer to one of the big open questions in BSM physics:

What is the origin of the observed neutrinos masses?

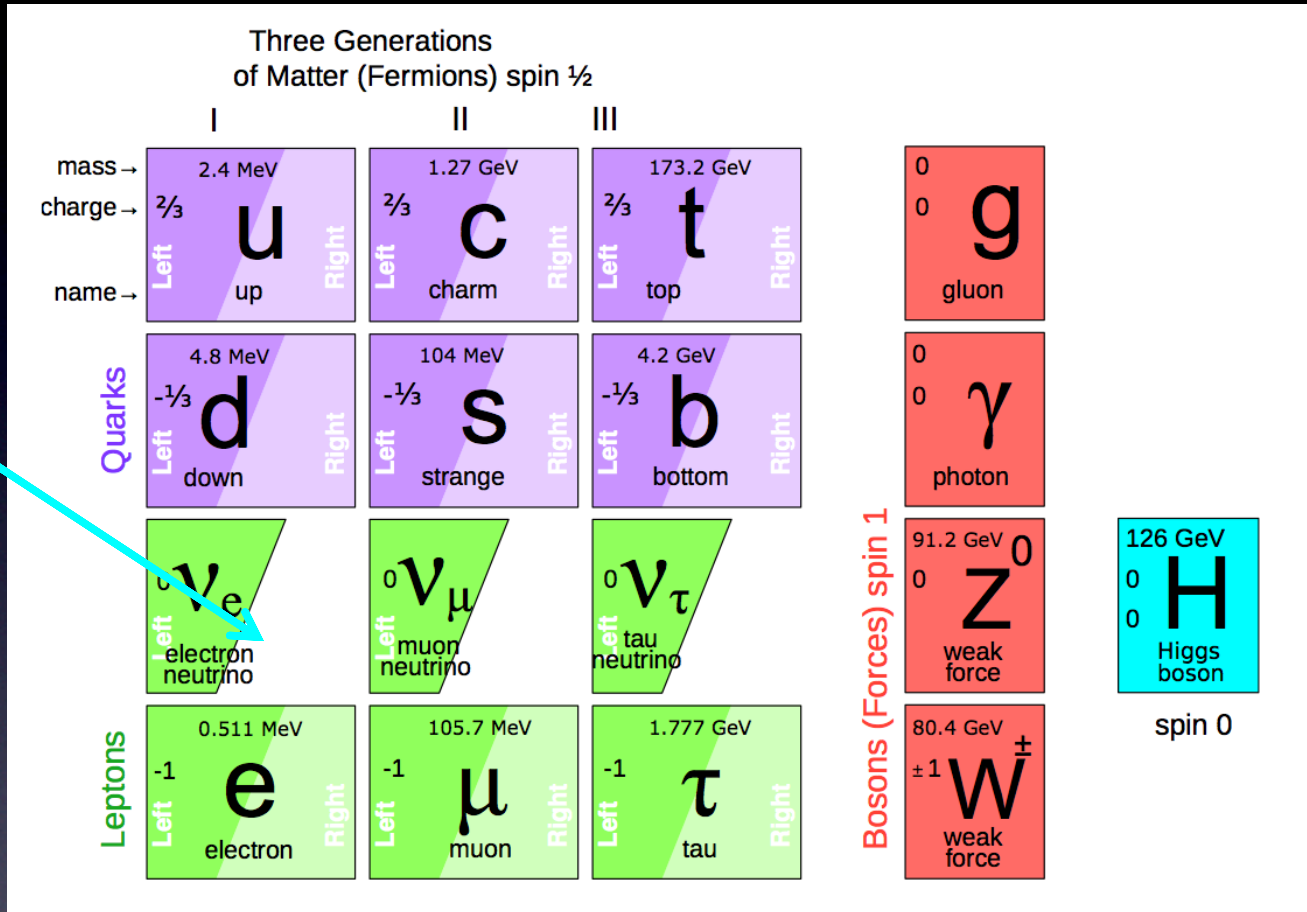
Main topic of my talk:

When the heavy (mainly “sterile”) neutrinos have masses $M \lesssim m_W$, they can be long-lived and probed with great precision at the FCC via displaced vertex searches!

A sterile neutrino "dark sector" – a 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:

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

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:

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

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

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 sterile neutrino parameters M, Y_ν?

What do we know about the sterile neutrino parameters?

Getting started: 1 ν_R, 1 ν_L

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

→ 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: $2\ \nu_R$, $2\ \nu_L$

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), …

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

Example of a small perturbation

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

➔ **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

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

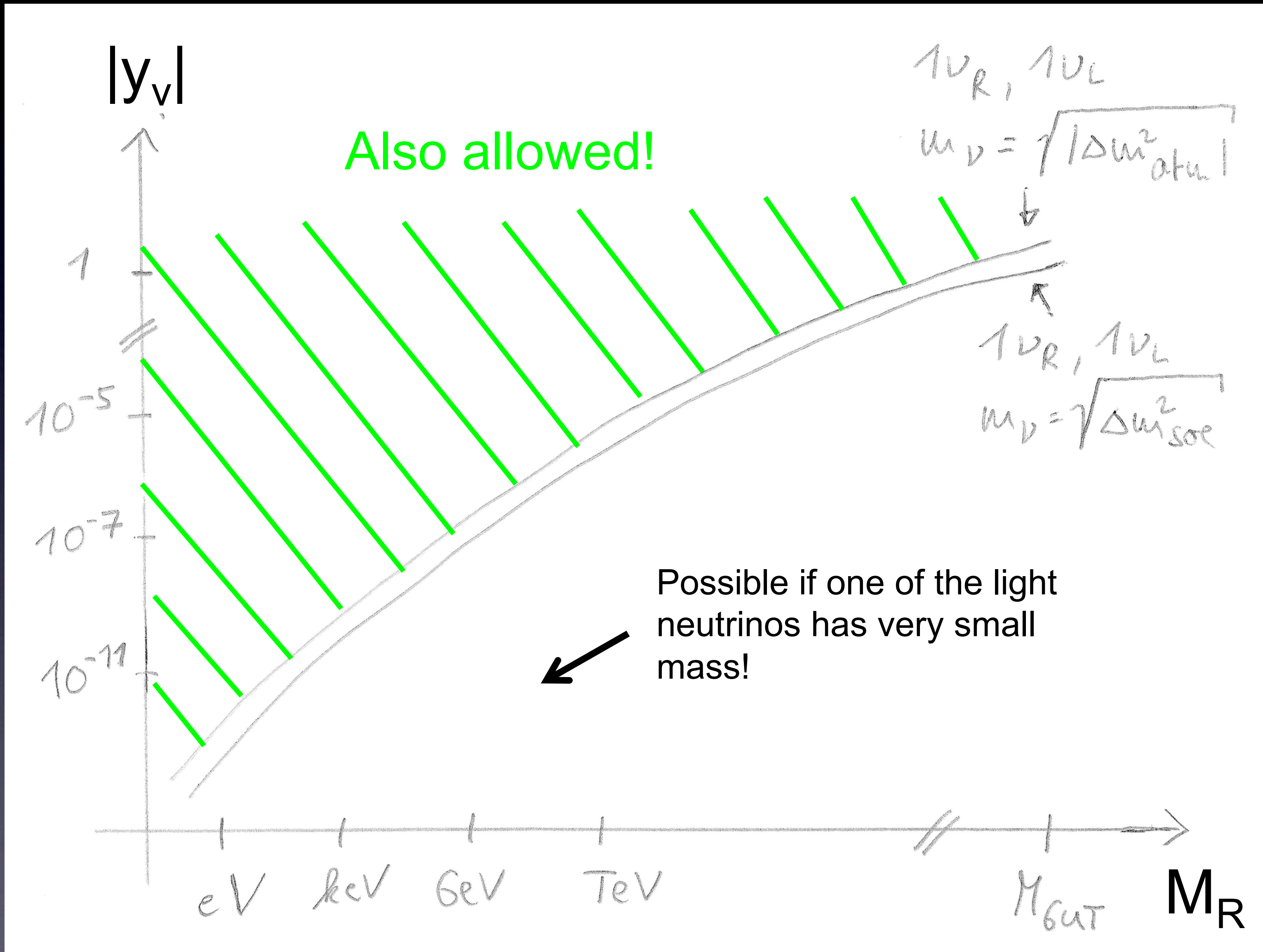
$$\Rightarrow \quad m_\nu = 0 + \varepsilon \frac{v_{EW}^2 \, \mathcal{O}(y_\nu^2)}{M_R^2}$$

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

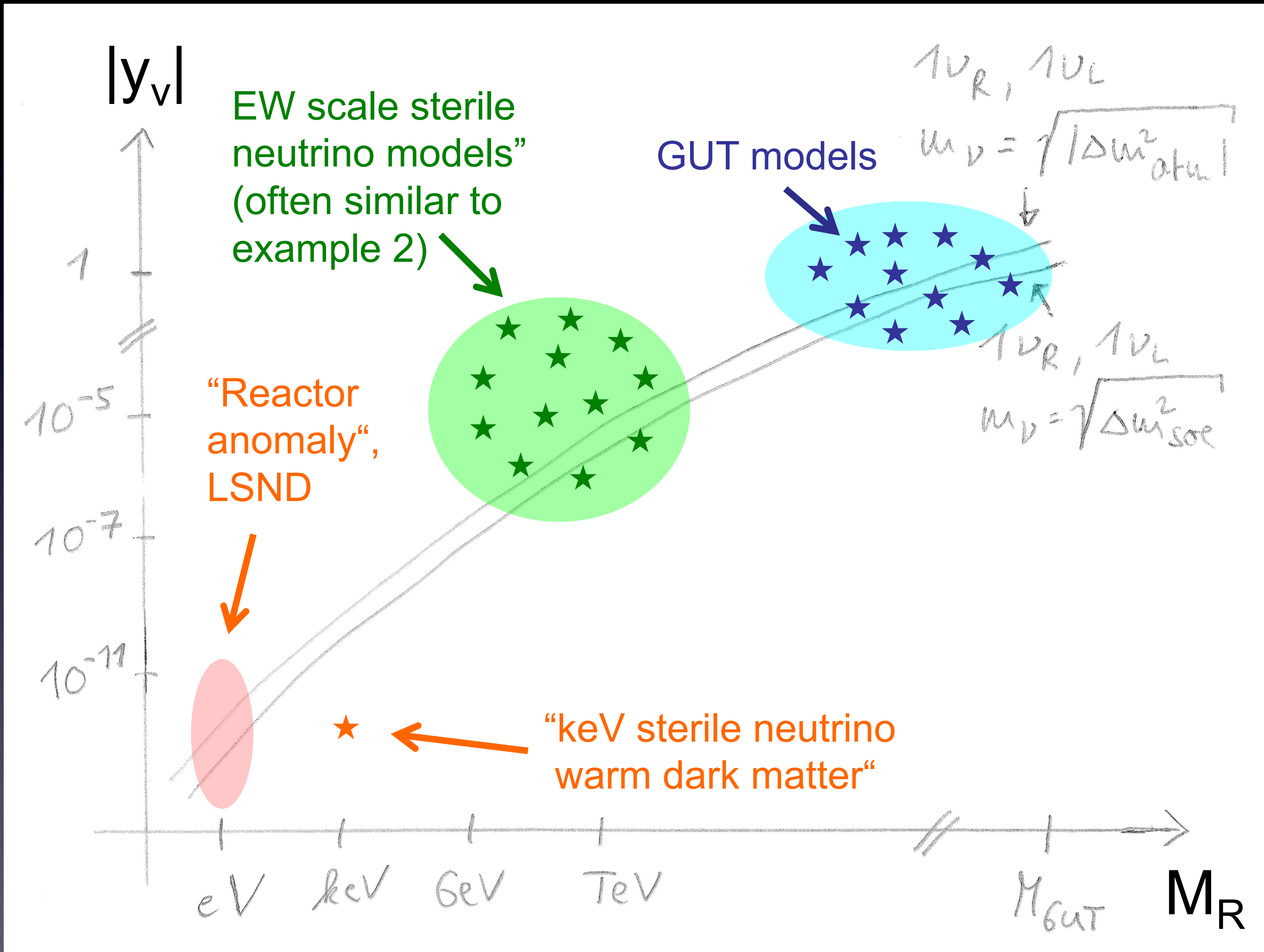
Possible values of M_R and y_ν



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)

$$Y_\nu = \begin{pmatrix} y_{\nu_e} & 0 \\ y_{\nu_\mu} & 0 \; \cdots \\ y_{\nu_\tau} & 0 \end{pmatrix}, \quad M = \left(\begin{array}{cc:cc} 0 & M_R & & \\ M_R & 0 & \multicolumn{2}{c}{0} \\ \hdashline & & * & * \; \cdots \\ \multicolumn{2}{c:}{0} & * & * \\ & & \vdots & \ddots \end{array}\right)$$

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

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).

Similar: "inverse" seesaw, "linear" seesaw

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

A benchmark model for EW scale sterile ν:

SPSS (Symmetry Protec[…]

Comment 1: In the symmetry limit, the two heavy neutrinos have both the same mass M. O(ε) perturbations induce small mass splitting ΔM!

Consider 2+n sterile neutrinos (plus the thre[…] the steriles as in example 2 due to some generic "[…]umber"-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

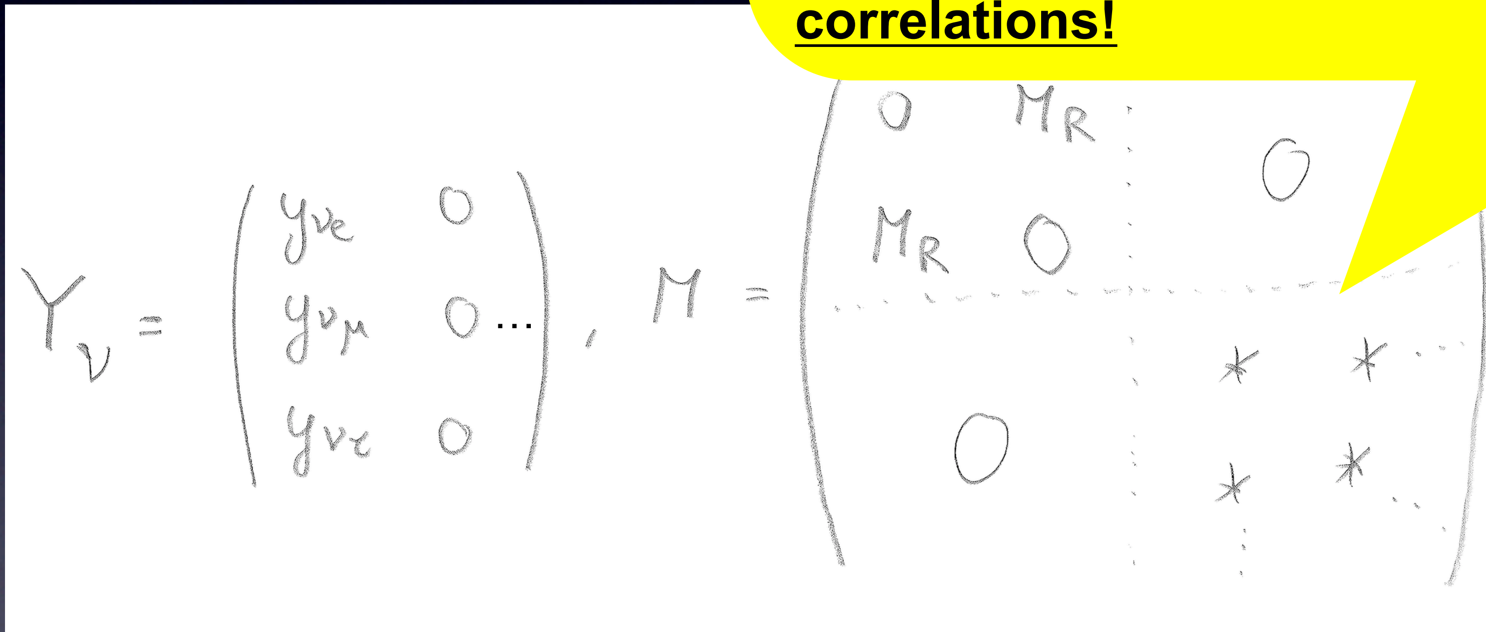
For details on the SPSS, see:
S.A., O. Fischer (arXiv:1502.05915)

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 2: 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
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

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).

What are the observable effects of EW scale heavy neutrinos?

(This part we neglect the O(ε) effects; will be discussed later ...)

As example: SPSS (Symmetry Protected Seesaw Scenario)

In the symmetry limit:

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

$+ \ldots$ (terms from additional sterile vs)

As example: SPSS (Symmetry Protected Seesaw Scenario)

In the symmetry limit:

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

4 Parameters:
M, y_α, (α=e,μ,τ)

As example: SPSS (Symmetry Protected Seesaw Scenario)

In the symmetry limit:

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

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

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

"**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:

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

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

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

- 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, ($\alpha=e,\mu,\tau$)

Observable effects of the sterile neutrinos: M >> Λ_{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 >> Λ_{EW}: "Leptonic non-unitary"

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

➔ *See talk by O. Fischer*

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

Non-unitarity parameters:

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

⇒ U_{PMNS} ≡ N is non-unitary

⇒ various obs. effects!

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

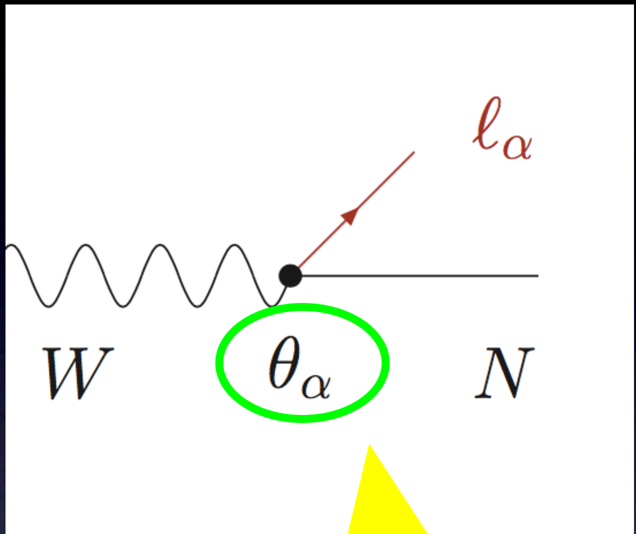
In addition for $M \cong \Lambda_{EW}$: Effects from on-shell heavy neutrinos

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

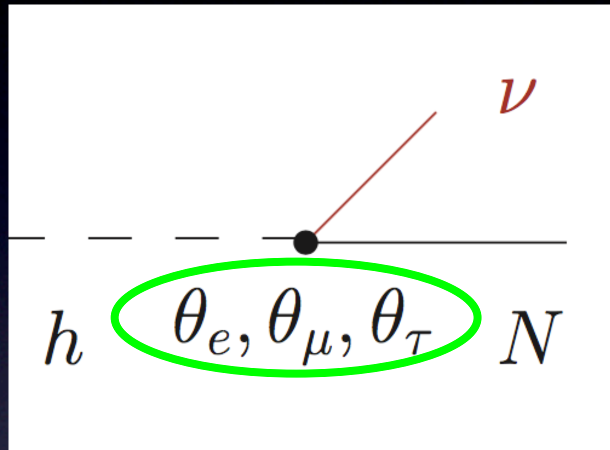
$$U = \begin{pmatrix} \mathcal{N}_{1e} & \mathcal{N}_{1\mu} & \mathcal{N}_{1\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{2e} & \mathcal{N}_{2\mu} & \mathcal{N}_{2\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{3e}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

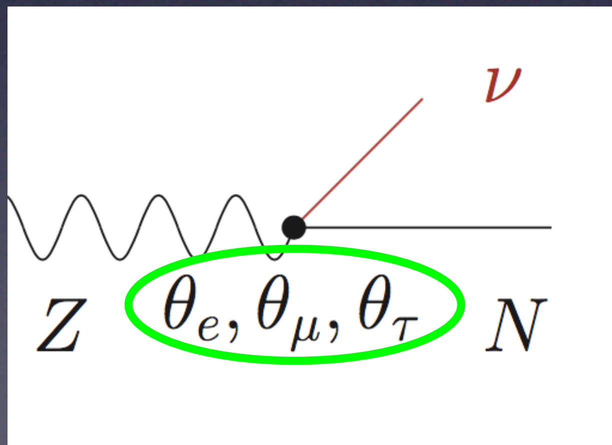
$\Rightarrow$ heavy neutrinos can get produced also in weak interaction processes!

Heavy neutrino interactions



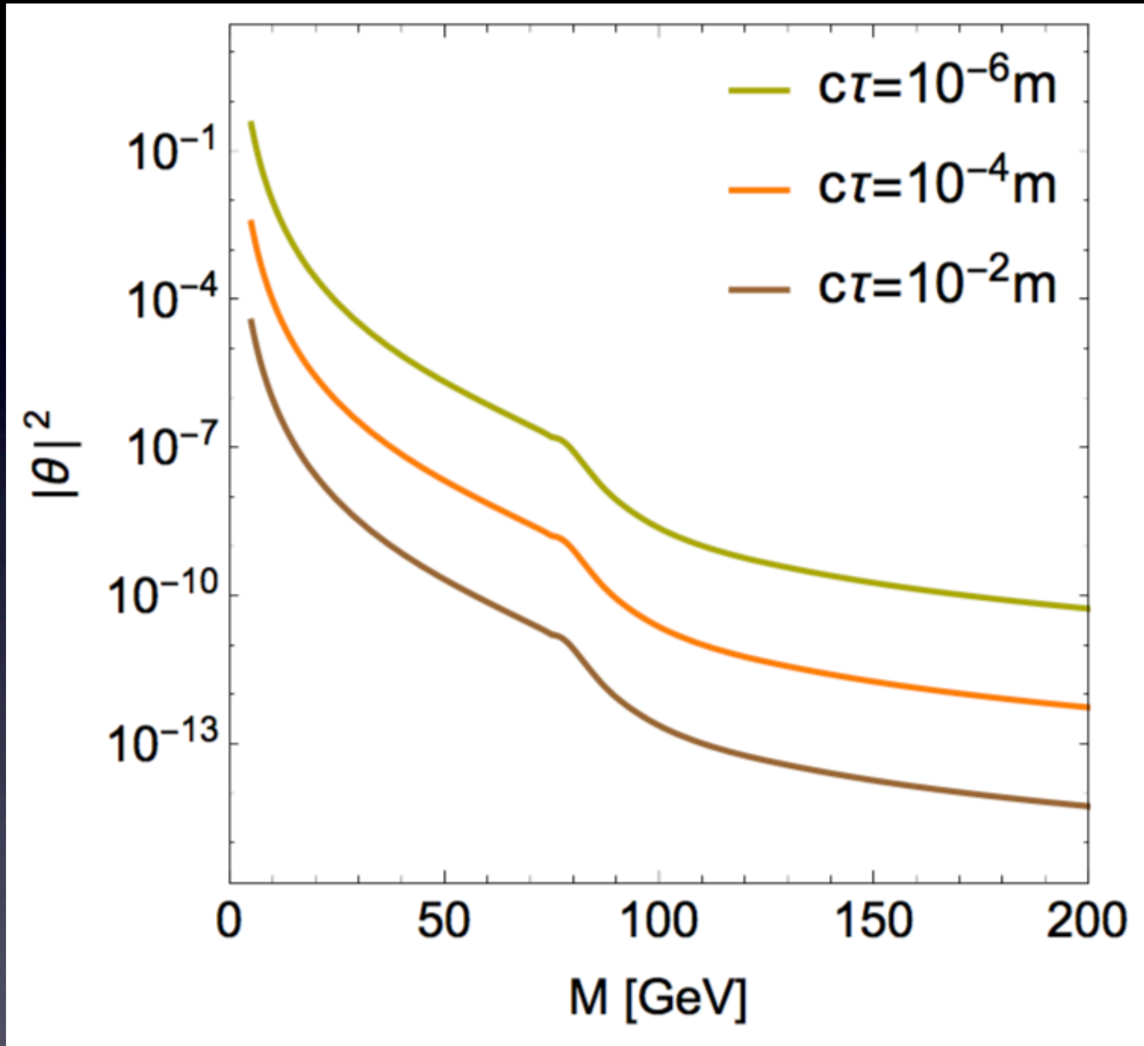
When W bosons are involved, there is a possible sensitivity to the flavour-dependent θ_α





Many works by many autors on possible collider signatures …

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

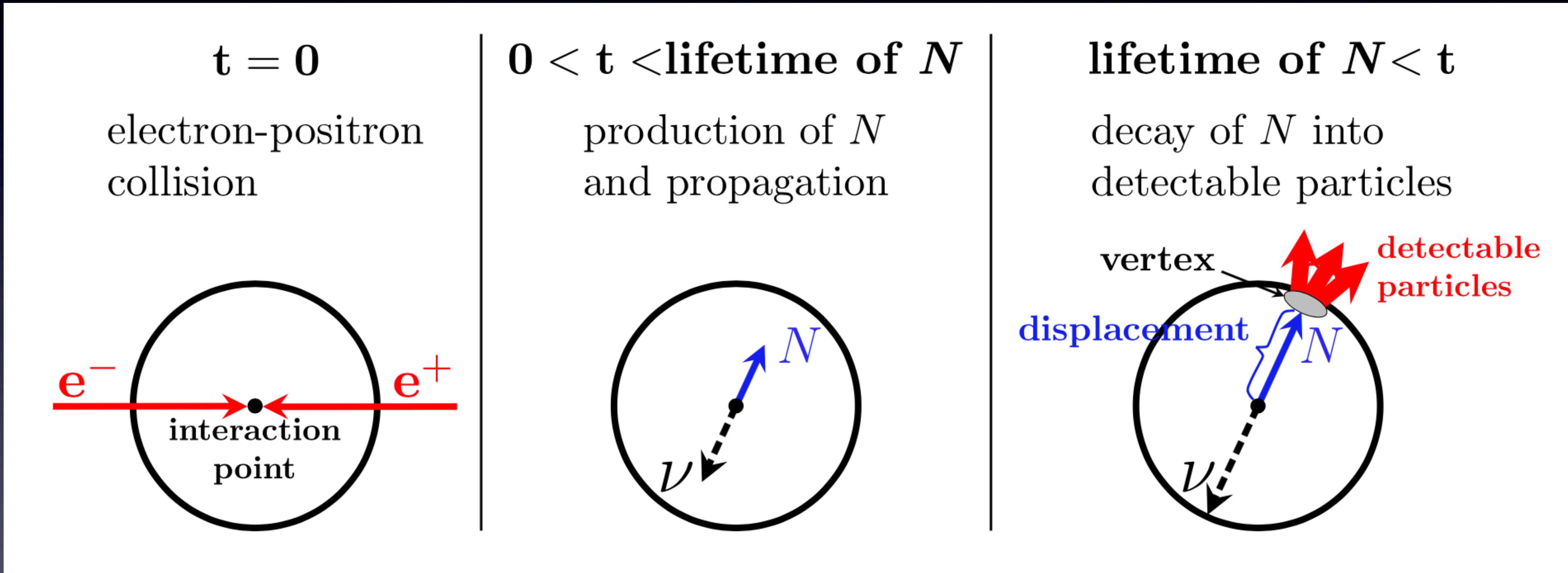


cf. S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

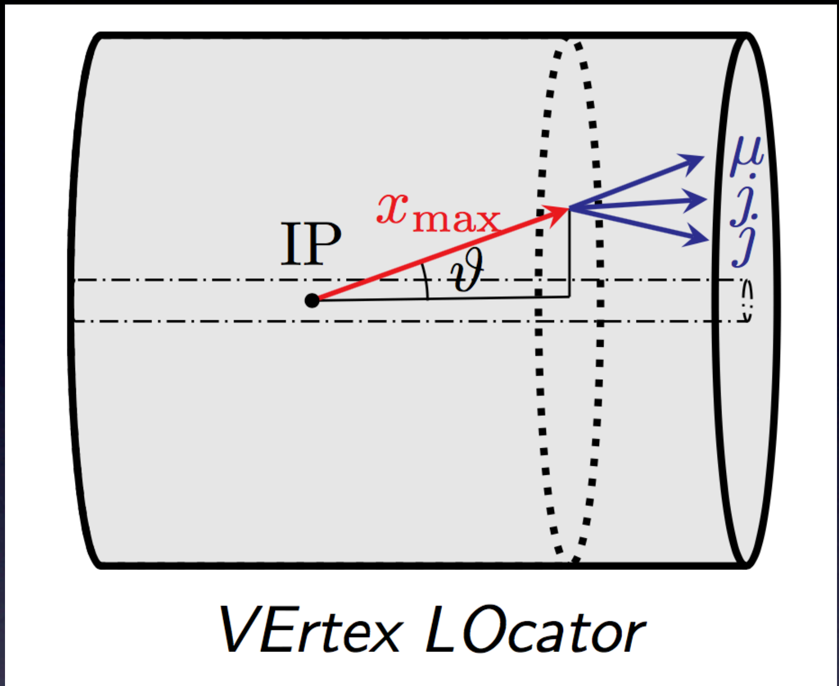
Note: Decay length in the laboratory frame is: $c\tau\sqrt{\gamma^2 - 1}$

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

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



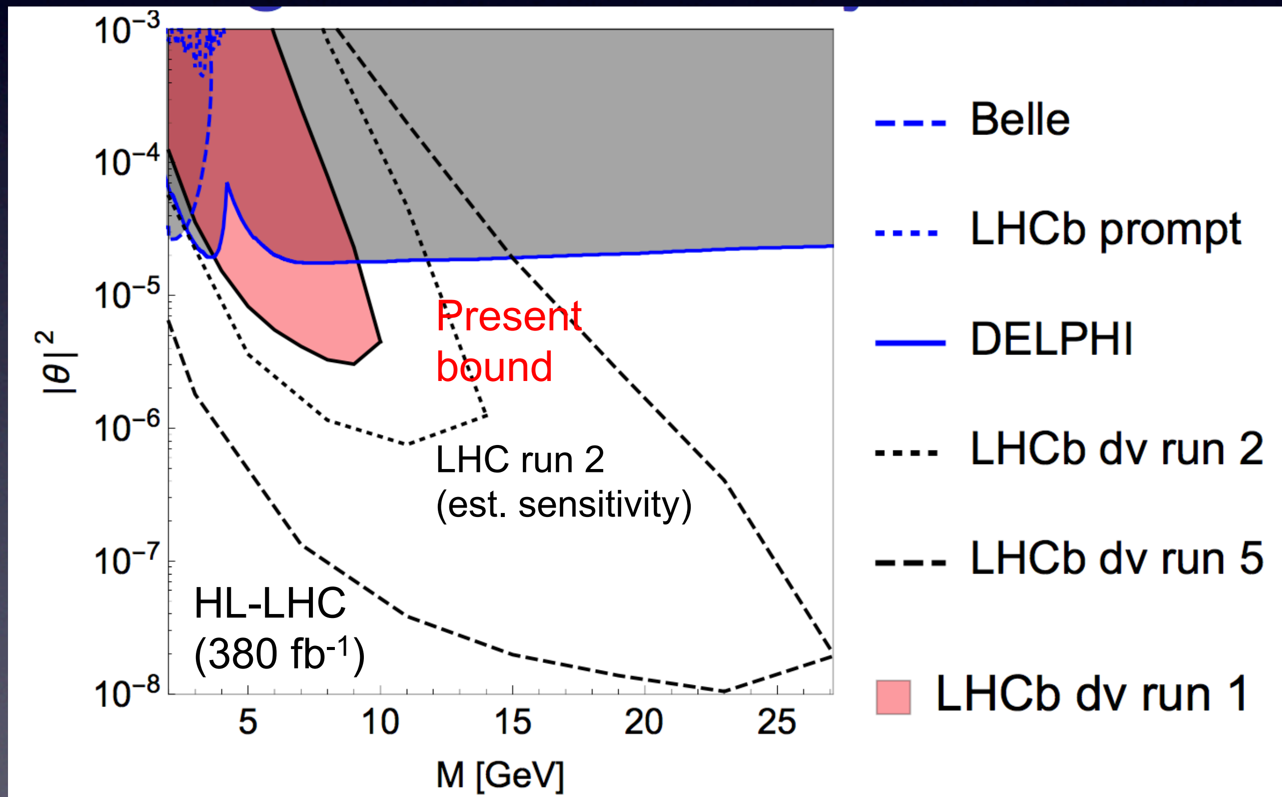
Present bounds (& estim. future sensitivities) from displaced vertex searches at LHCb



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 $\theta_e = \theta_\tau = 0$):



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

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

Sensitivity forecasts for 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

$$N_{\rm dv}(\sqrt{s},\mathcal{L},M,|\theta|^2) = \sum_{\rm x=\nu,\ell^\pm} \overbrace{\sigma_{{\rm x}N}(\sqrt{s},M,|\theta|^2)\,{\rm Br}_{\mu jj}\,\mathcal{L}}^{N_{{\rm x}N}} \times$$
$$\int D_{{\rm x}N}(\vartheta,\gamma)\,P_{\rm dv}(x_{\rm min}(\vartheta),x_{\rm max}(\vartheta),\Delta x_{\rm lab}(\tau,\gamma))\,d\vartheta d\gamma\,.$$

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

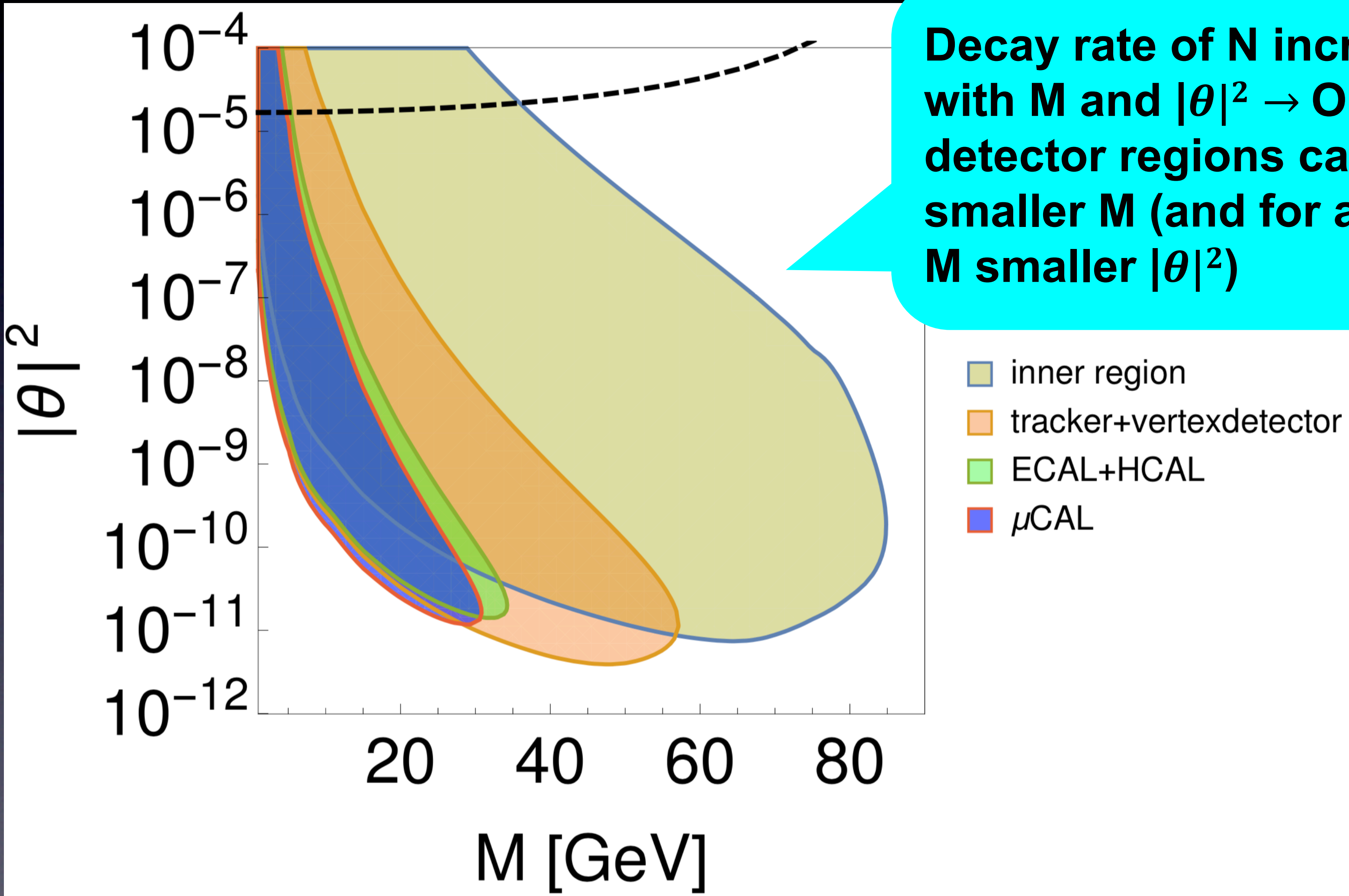
D_{xN}: Probability distribution for for the decay to occur within a certain detector part.

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

→ **A lot of work to be done …**

Parameter sensitivities of the different detector regions

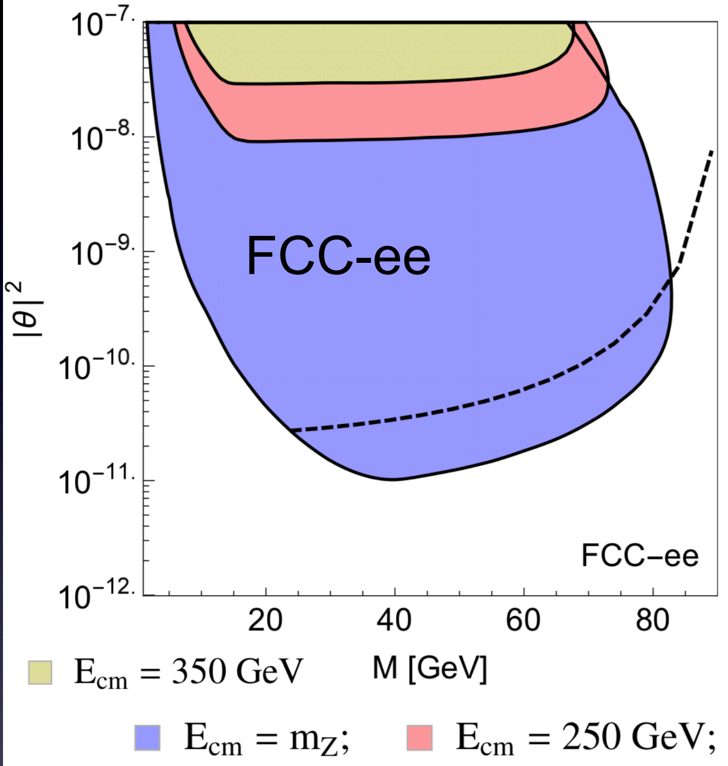
Example: FCC-ee, Z pole run, SiD-like detector



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

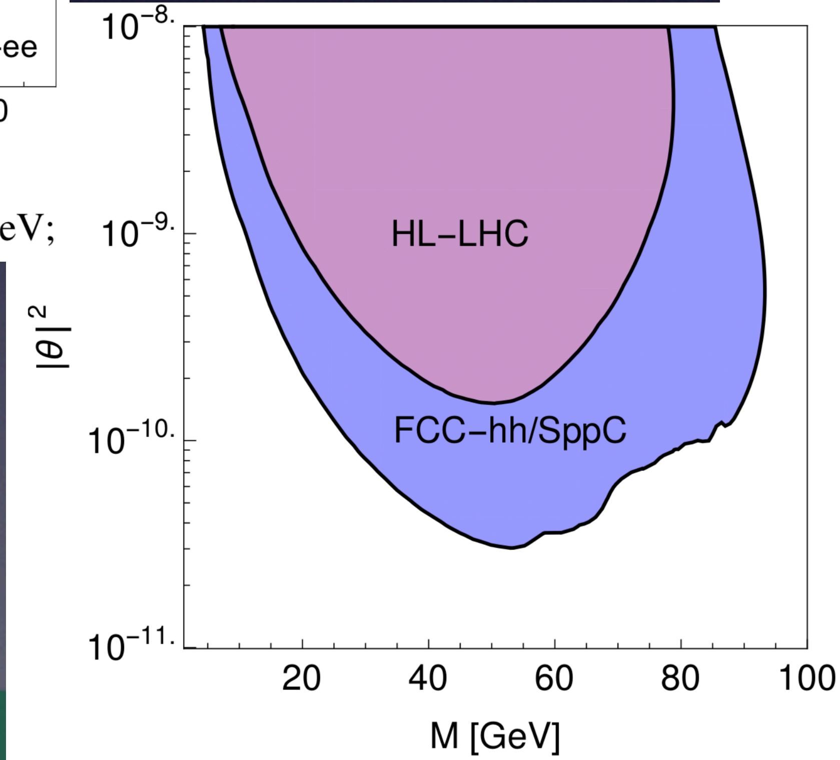
Estimated/“first look“ sensitivities via displaced vertices at FCC-ee, -hh and -eh

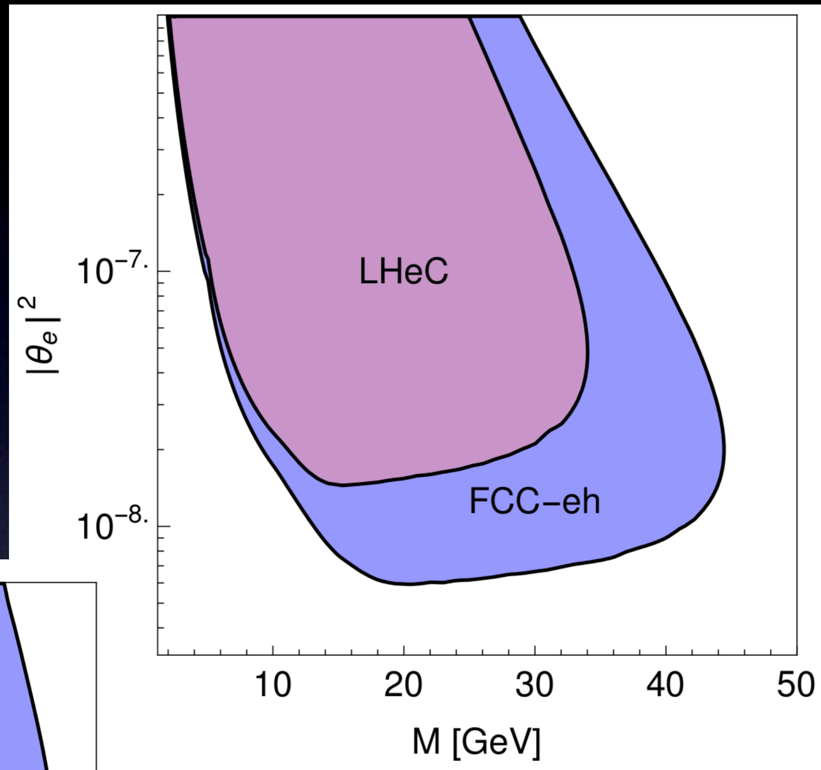


Estimate for FCC-ee [using SiD-like detector, L = 110 ab^{-1} at the Z pole]:
S.A., E. Cazzato, O. Fischer (arXiv:1604.02420)
See also:
Blondel, Graverini, Serra, Shaposhnikov (FCC study team, 2014)

“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]



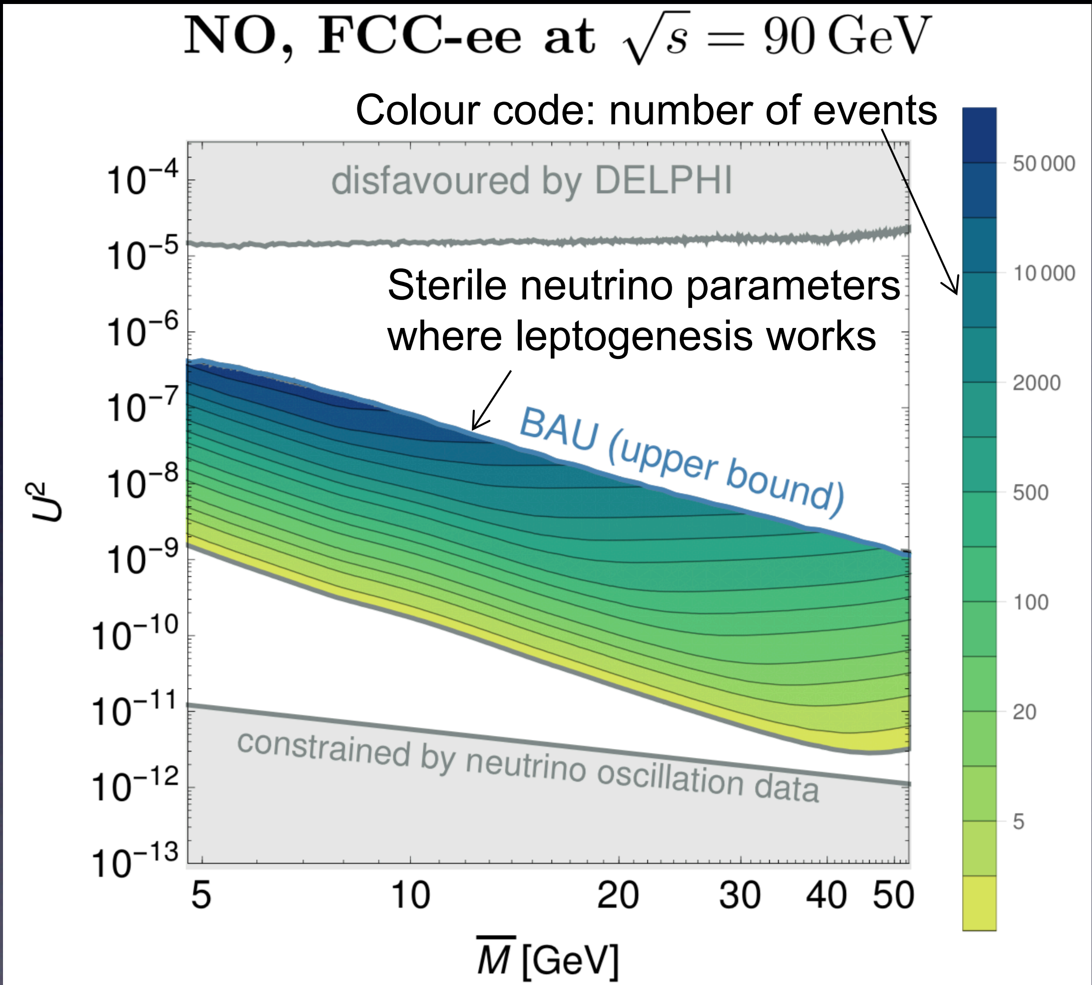


“First look” result for FCC-eh:
S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

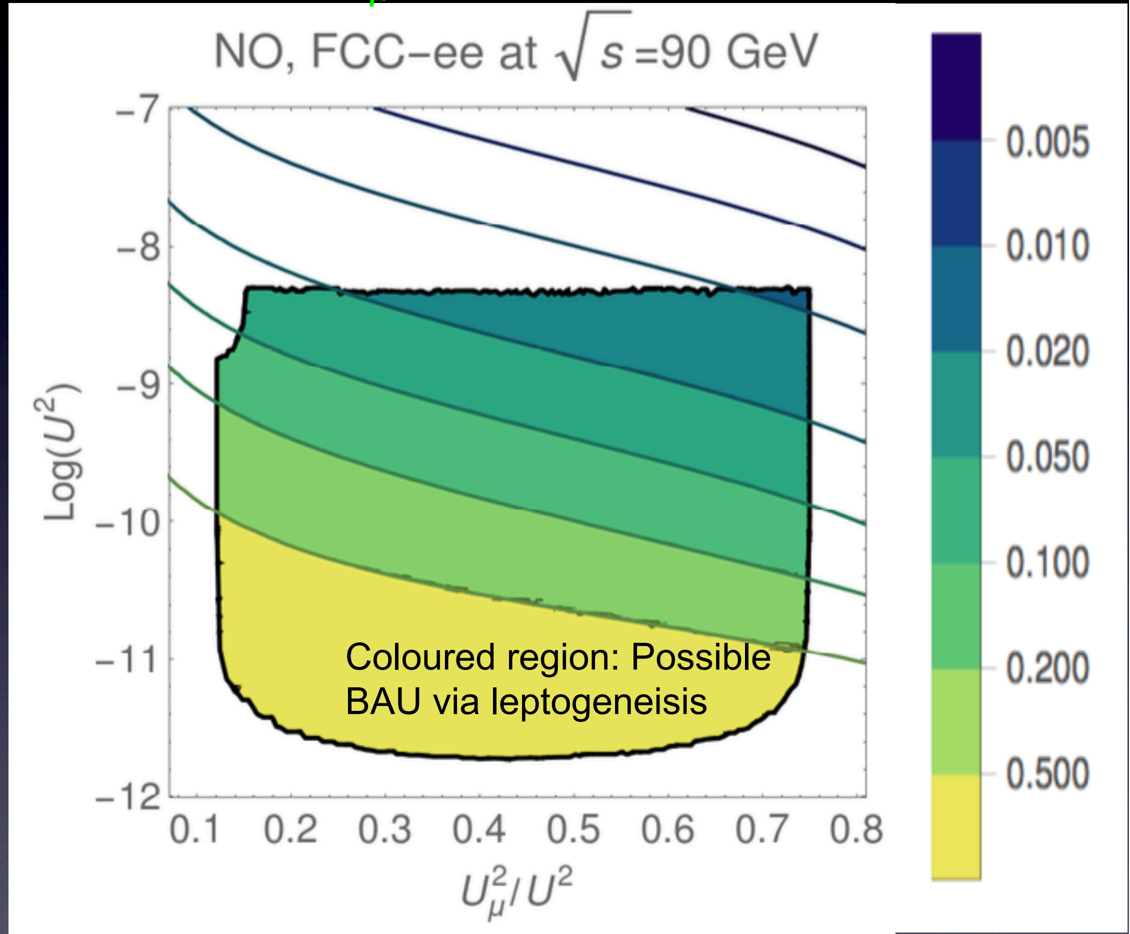
[Assumed for FCC-eh “first look”: x_{min} = 1mm, x_{max} = 1m
$\gamma_{average}$ = 3 (LHeC), 5 (FCC-eh)
L= 1 ab^{-1}, 100% efficienty]

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

Probing Leptogenesis



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



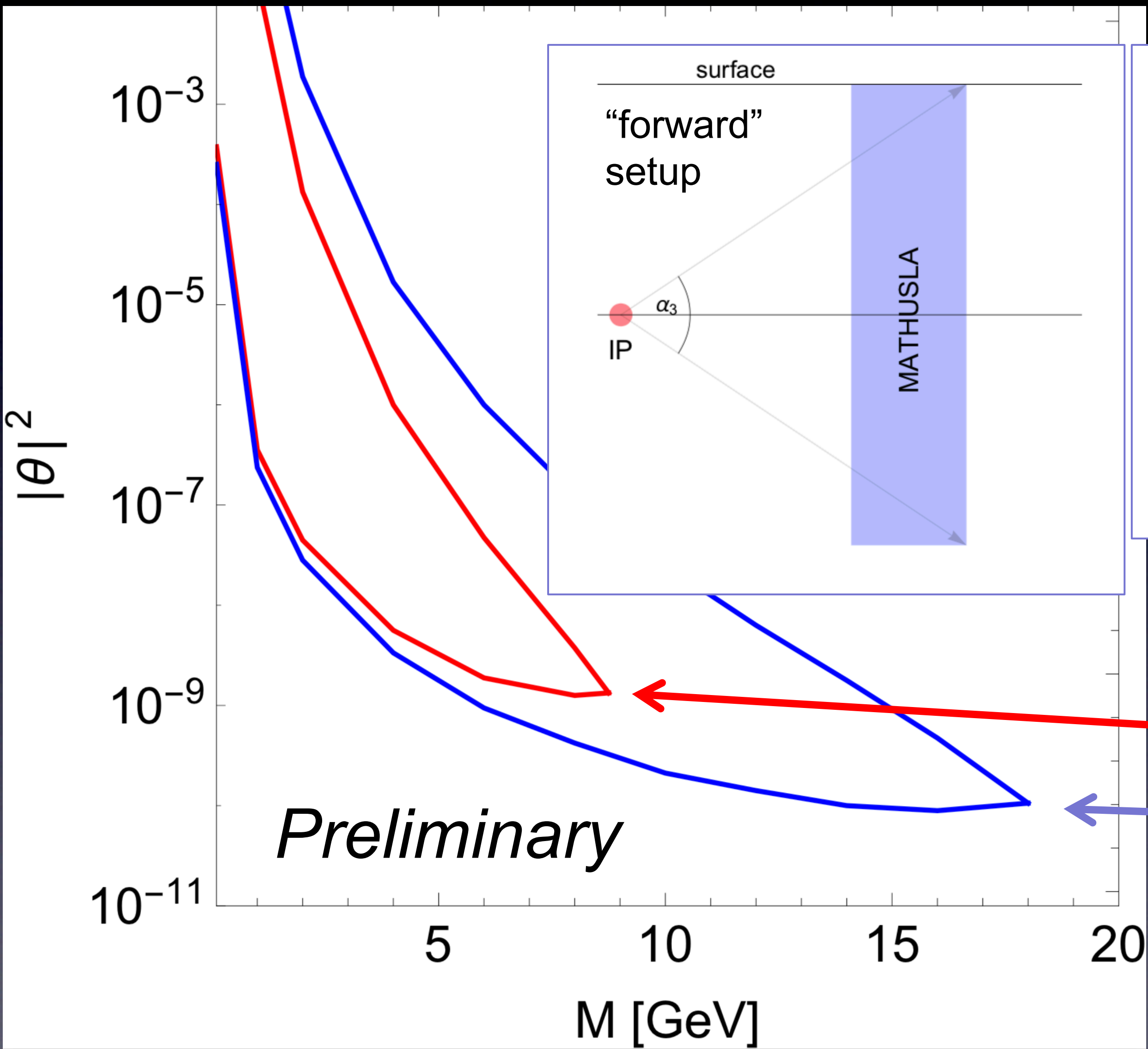
With: $U^2 = |\theta|^2$ and, for example, $U_\mu^2 = |\theta_\mu|^2$
(NO = normal light neutrino mass ordering)

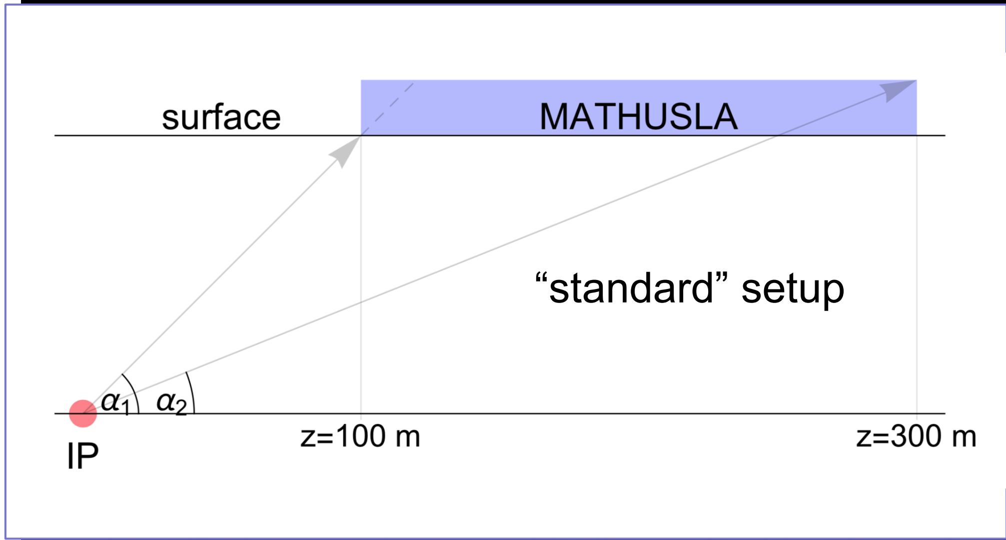
Estimates from semi-leptonic heavy neutrino decays N → μ jj, measurements also possible for the other flavours e and τ!

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

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

MATHUSLA Theory White Paper, to appear 2018



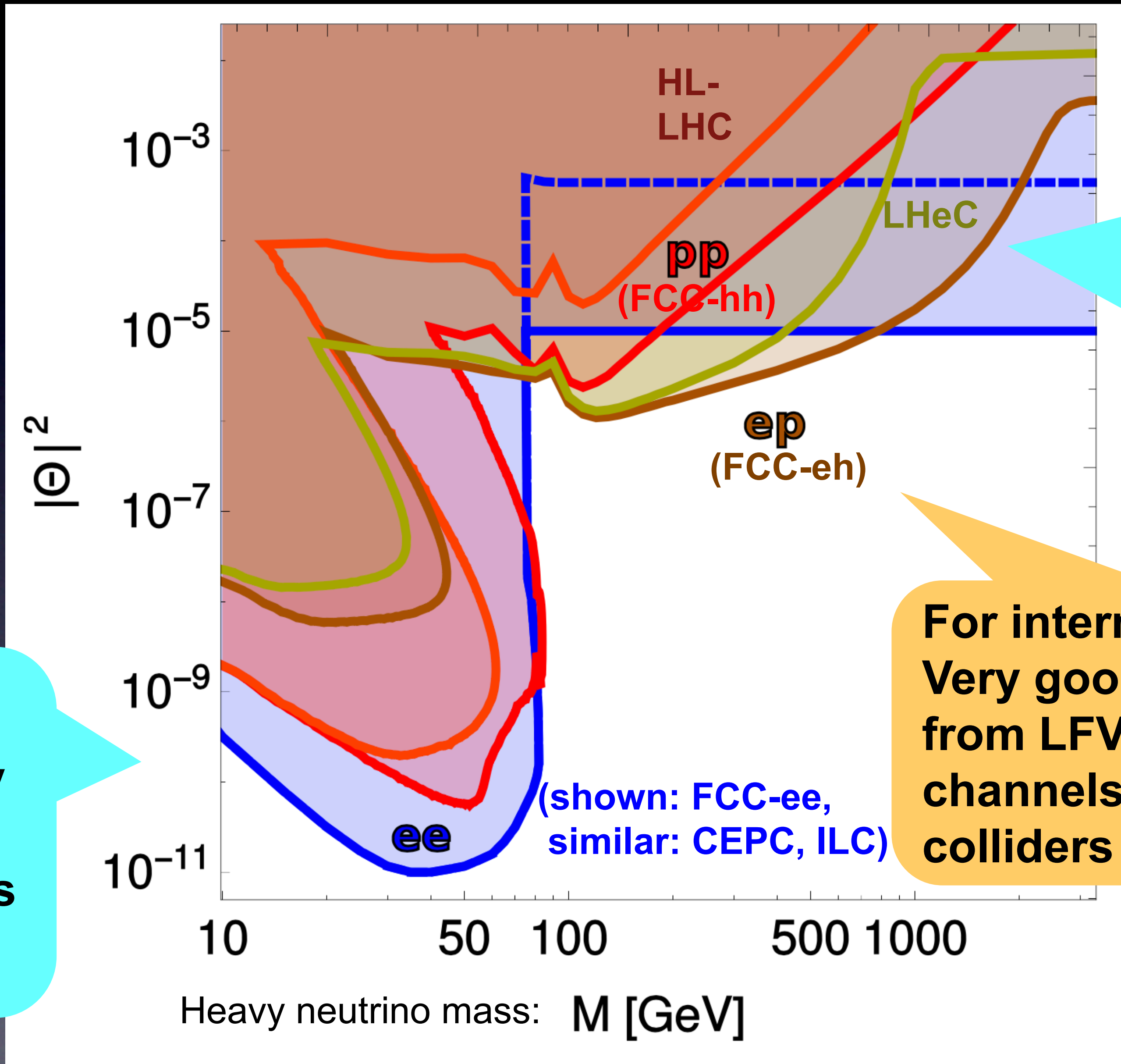


➔ *See also talk by K. Deshpande*

	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).

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



For M >> O(TeV): Best sensitivity from EWPO measurements at FCC-ee (also: cLFV)

➔ *See talk by O. Fischer*

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

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

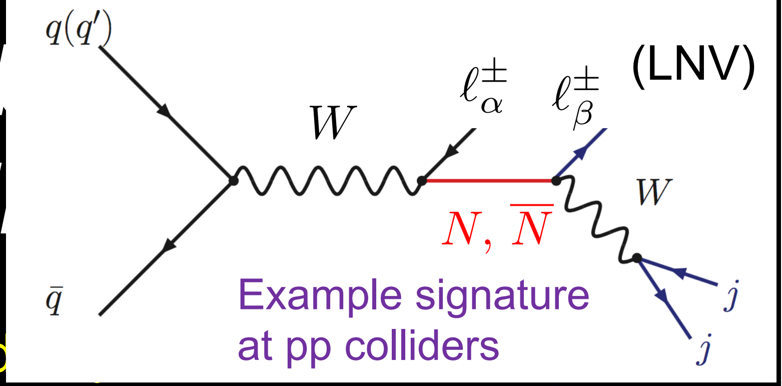
Plot from: S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

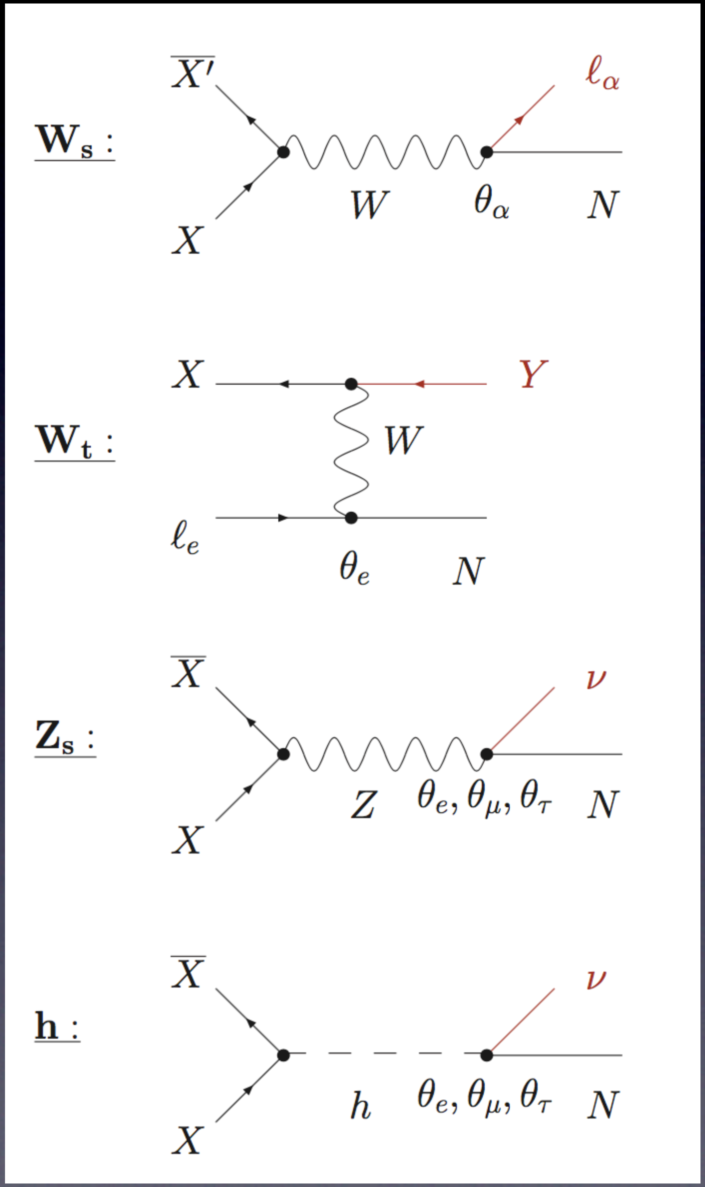
Can we observe Lepton Number violation (LNV) at colliders?

$\rightarrow$ A comment and a recent result

(Here we have to include the $O(\varepsilon)$ effects!)

Signatures for lepton numb[er violation] from sterile neutri[nos]





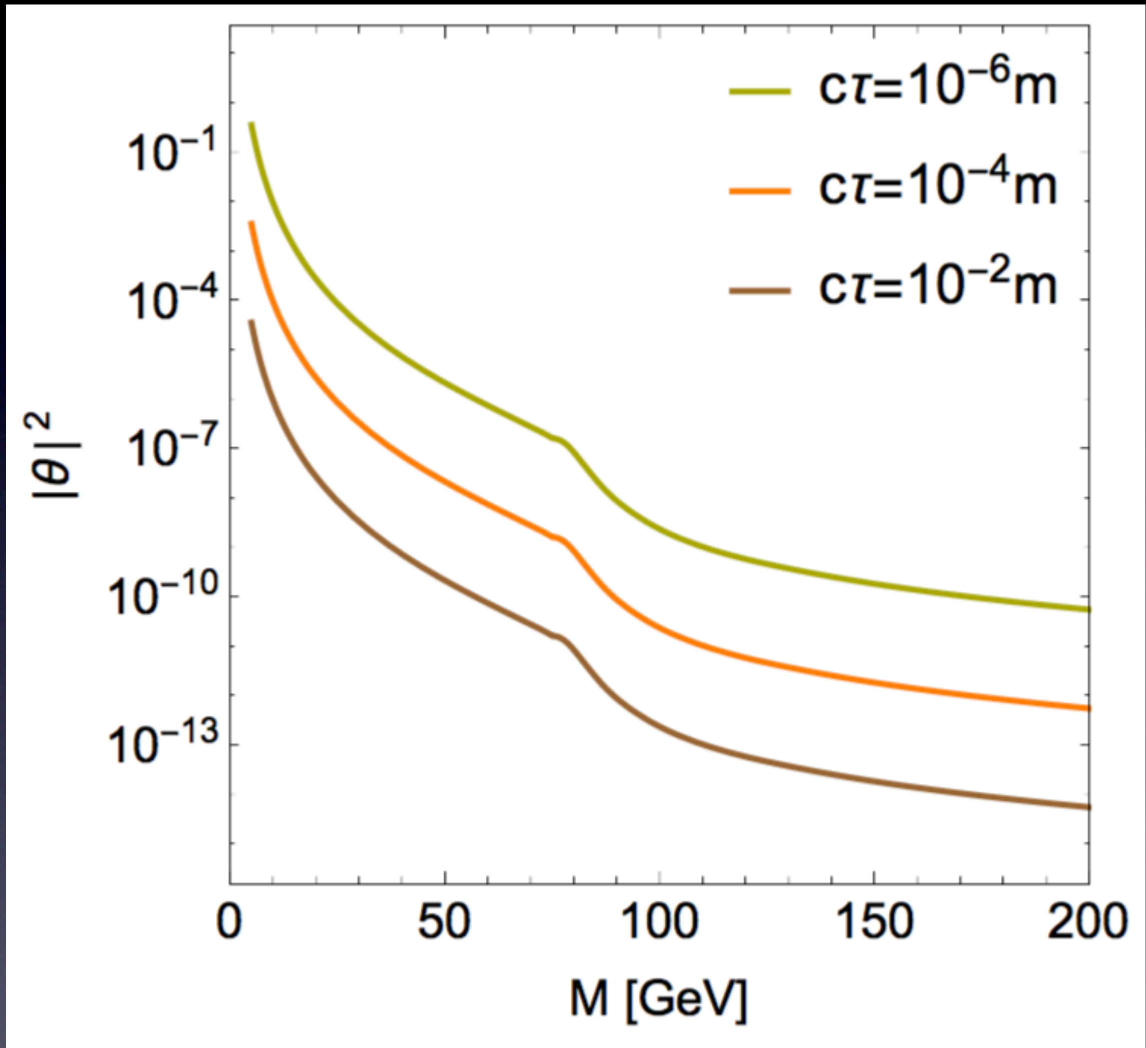
Different collid[ers ...] different production channels:

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

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

However: LNV can get induced by <u>heavy neutrino-antineutrino oscillations!</u>

As shown earlier: Lifetime and decay length of heavy neutrinos



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

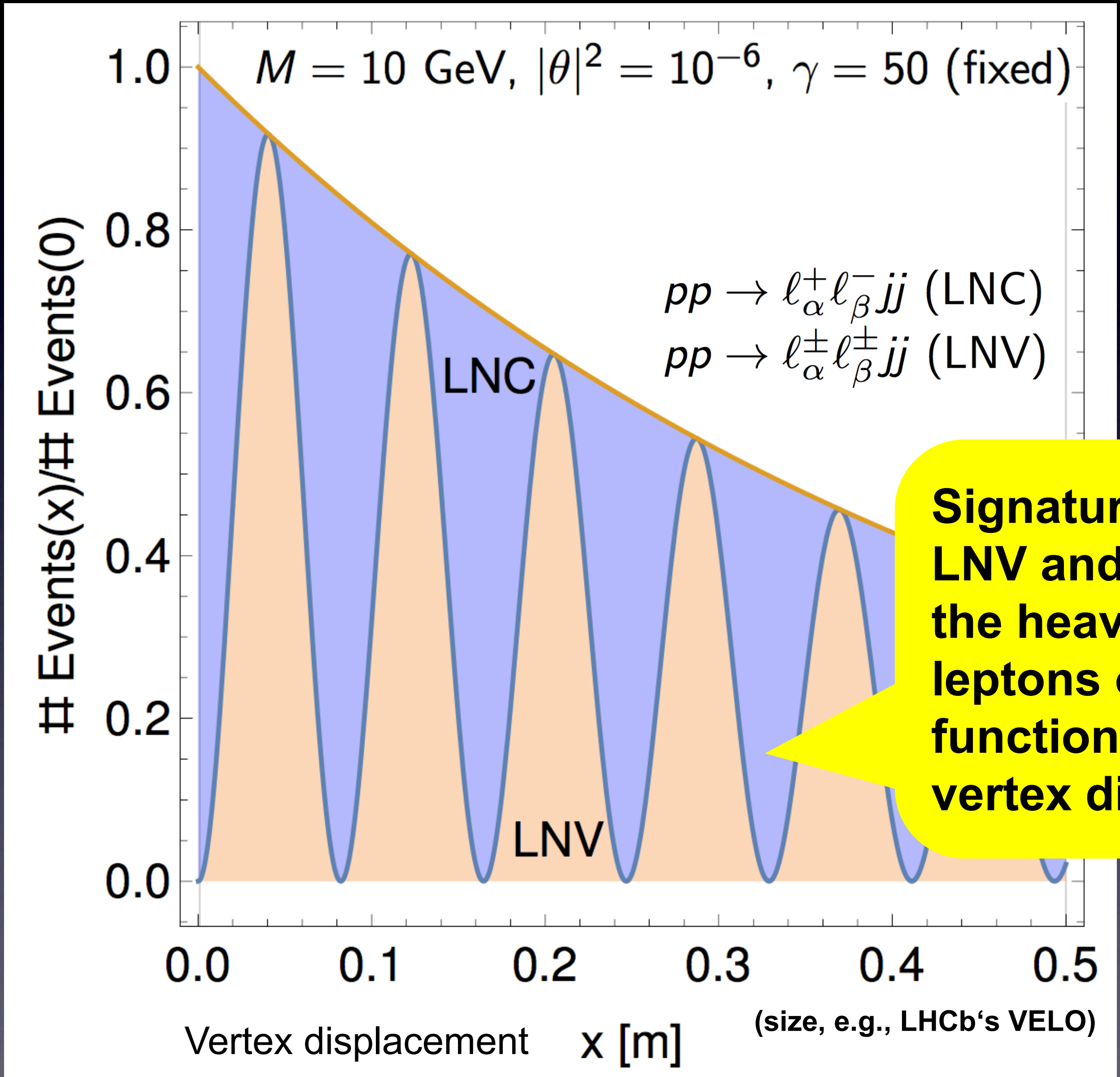
Note: Decay length in the laboratory frame is: $c\tau\sqrt{\gamma^2 - 1}$

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)

➔ *Mre details and Refs in the extra slides ...*



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

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

Summary

- A sterile neutrino dark sector is a well-motivated extension of the SM towards explaining the origin of the masses of the light neutrinos.
- With protective "lepton number"-like symmetry, "large y_ν" and EW scale masses of the sterile neutrinos are possible (& technically "natural")!
- When the masses of the sterile neutrinos are around the EW scale (and in particular when they are $\lesssim m_W$), the FCC experiments can have fantastic discovery prospects for a sterile neutrino dark sector via displaced vertex searches.

Thanks for your attention!

Extra Slides

Predictions of specific low scale seesaw models: Examples

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)

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

+ 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**):

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

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

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

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

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

... more about this later in my talk!

Resolvable heavy neutrino-antineutrino oscillations at colliders: definitions and more information …

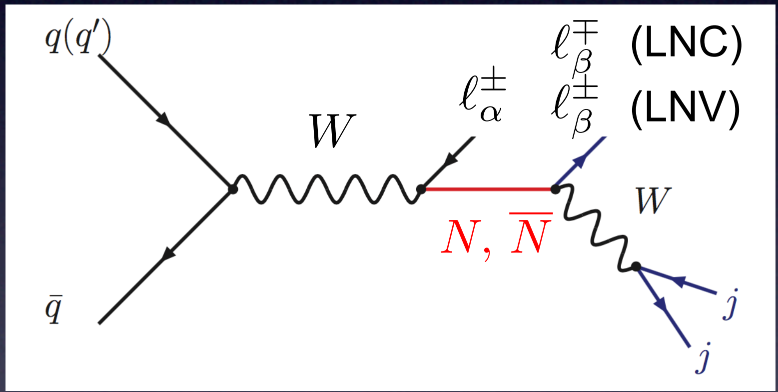
Heavy neutrino-antineutrino oscillations at colliders

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 ➔ $l_\alpha\, l_\beta$ 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)

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

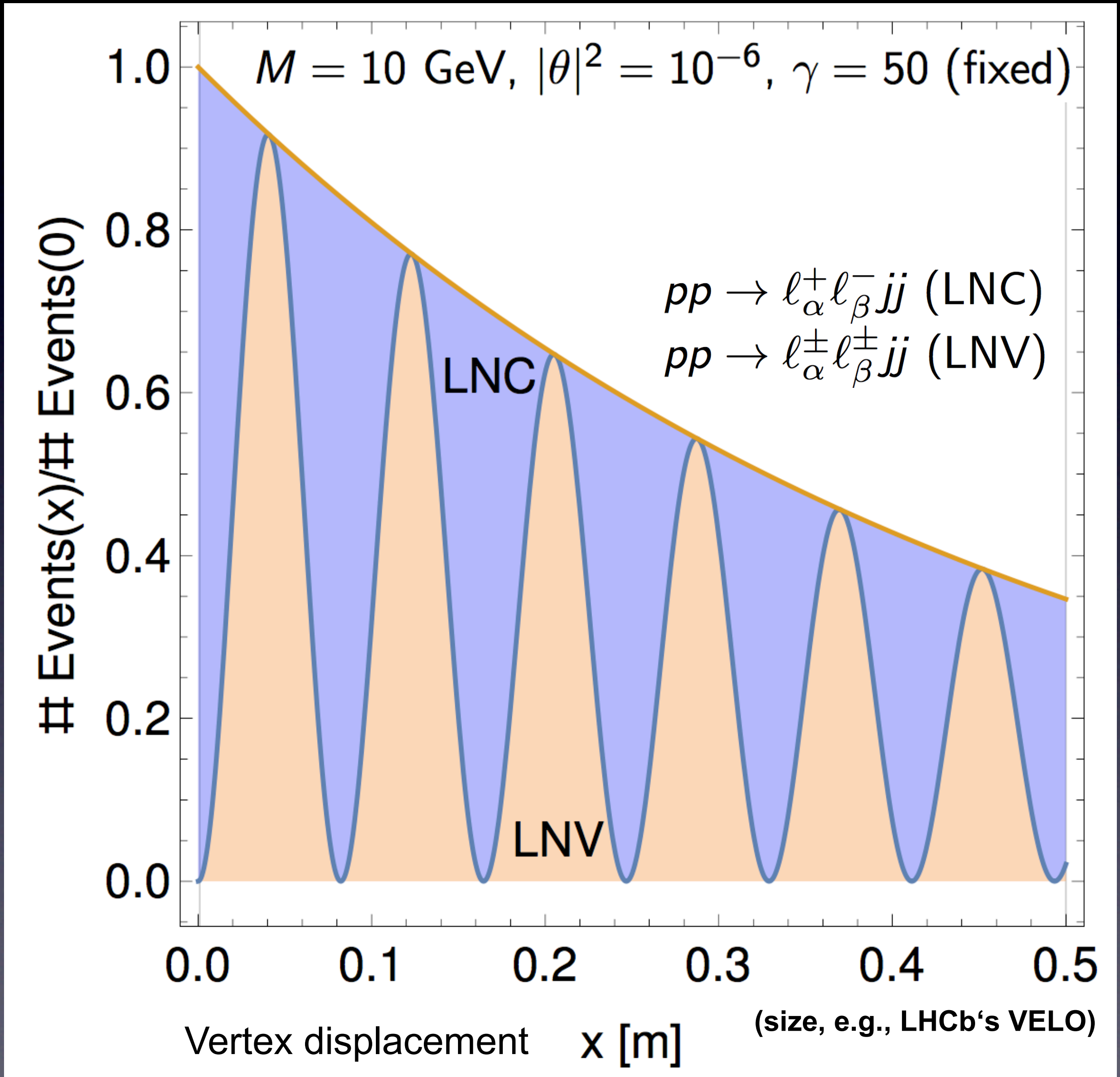
J. Gluza and T. Jelinski (2015), G. Anamiati, M. Hirsch and E. Nardi (2016), S.A., E. Cazzato, O. Fischer (2017), A. Das, P. S. B. Dev and R. N. Mohapatra (2017)

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

Heavy neutrino-antineutrino oscillations at colliders can be resolvable

Example:
Linear seesaw (inverse mass ordering)

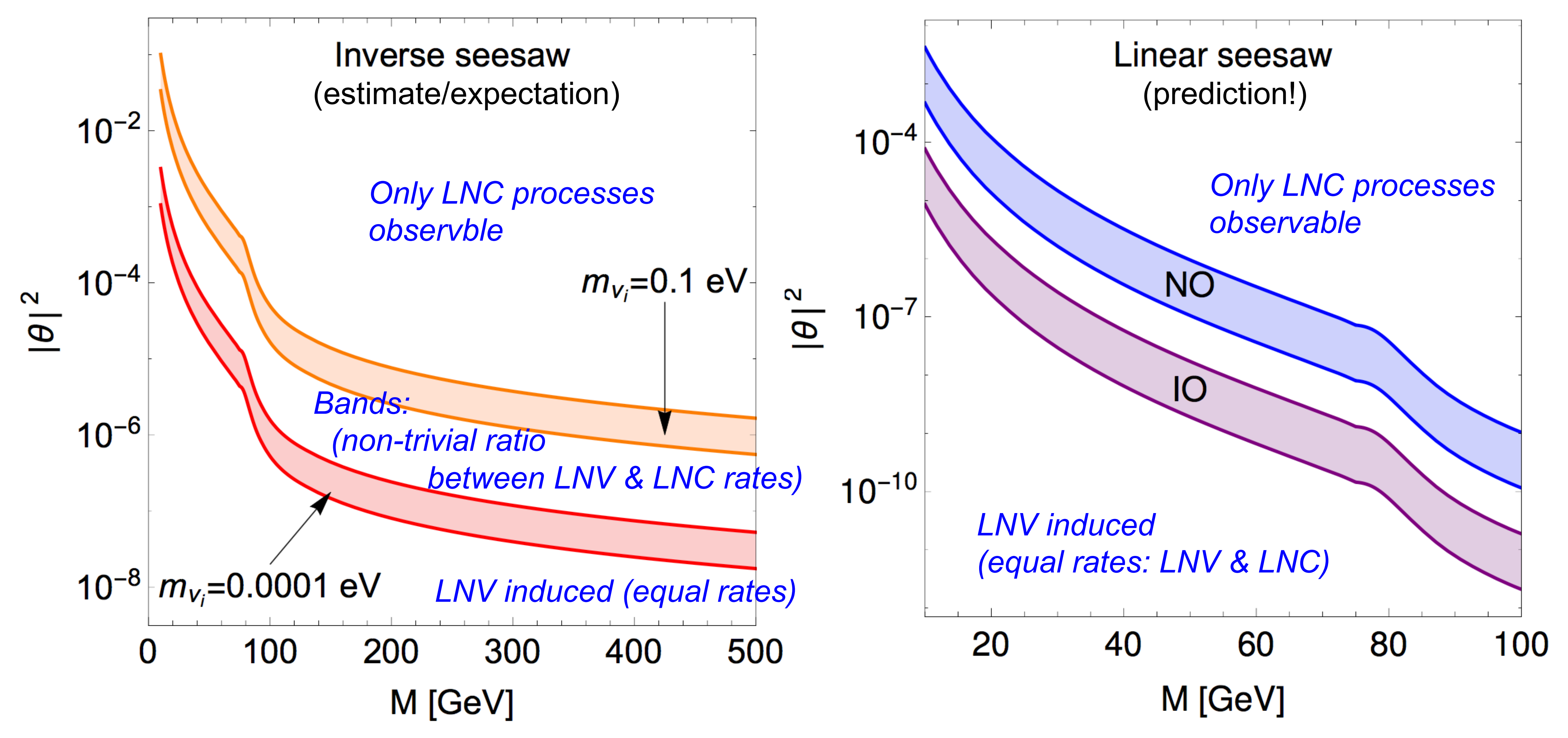
(using the prediction for ΔM in the minimal linear seesaw model for inverse neutrino mass ordering)



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

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)