Collider tests of low scale seesaw models: some aspects

Stefan Antusch

University of Basel, Department of Physics

UNI BASEL

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One of the big open questions in BSM physics:

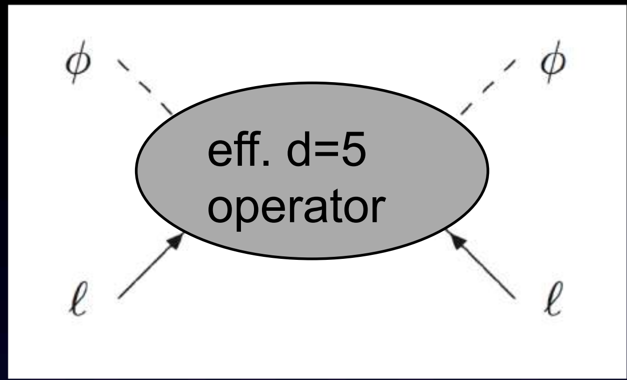
What is the origin of the observed neutrinos masses?

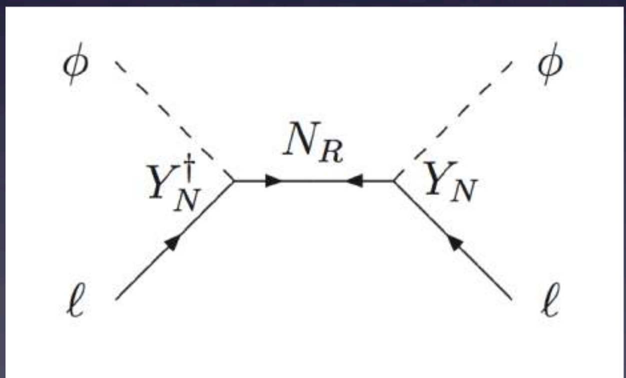
Topic of my talk:

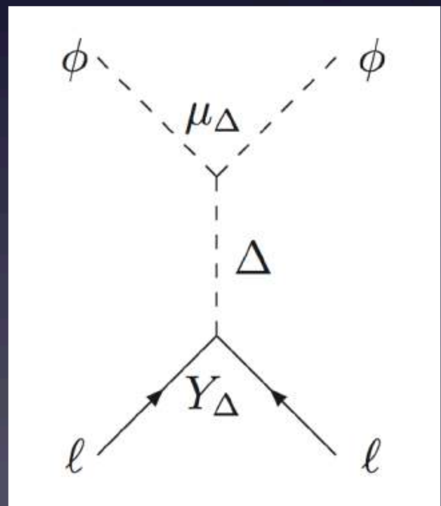
Collider phenomenology with neutrino mass generation around the EW/TeV scale

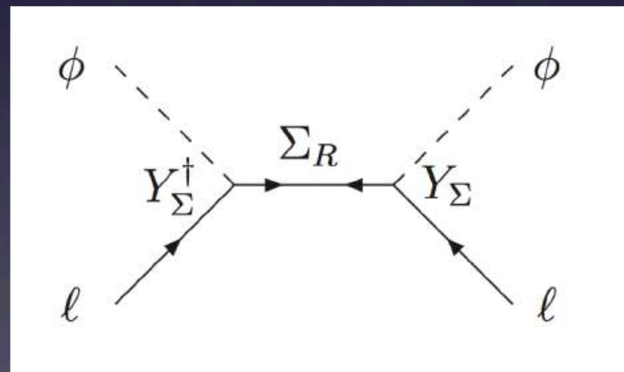
Seesaw models type I, II and III

Classification as tree-level realisations of the dim=5 neutrino mass operator:









<u>Type I Seesaw</u>

SM + r.h. neutrinos N_i in $(1,1)_1$ of G_{SM}

<u>Type II Seesaw</u>

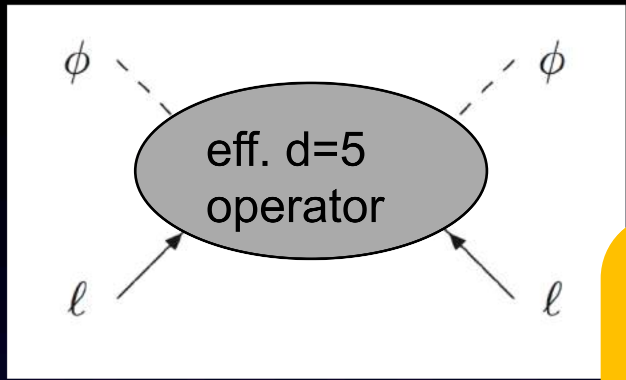
SM + scalar triplet Δ in $(1,3)_1$ of G_{SM}

<u>Type III Seesaw</u>

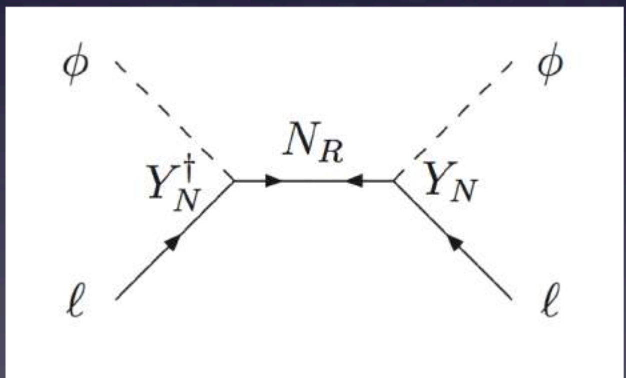
SM + fermionic triplets Σ in $(1,3)_0$ of G_{SM}

Seesaw models type I, II and III

Classification as tree-level realisations of the dim=5 neutrino mass operator:



We have no experimental hint so far which mechanism is the right one! → part of BSM quest



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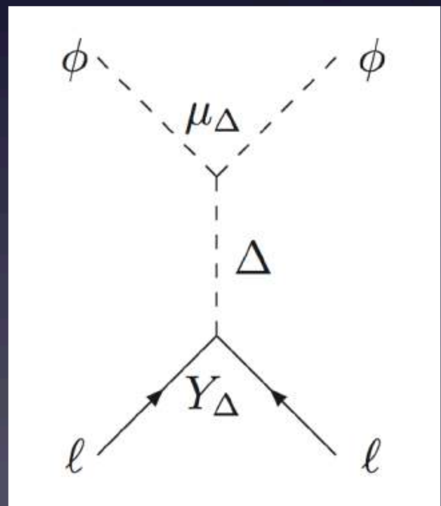
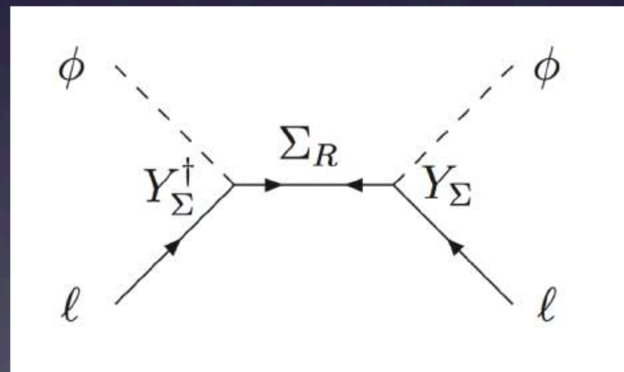


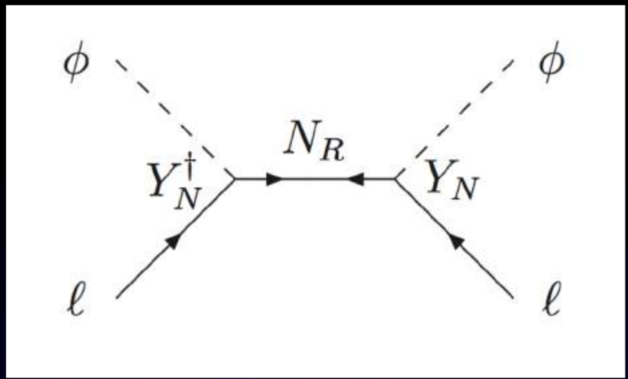
Type II Seesaw

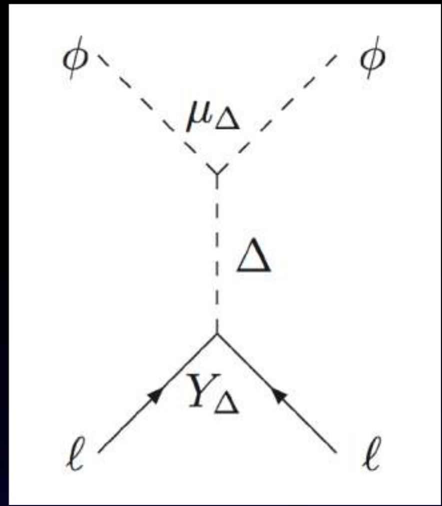
SM + scalar triplet Δ in $(1,3)_1$ of G_{SM}

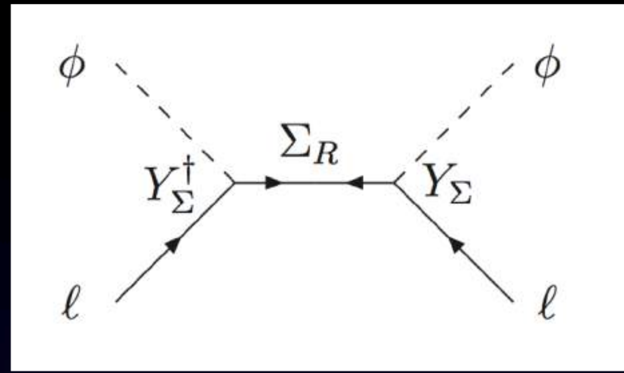


Type III Seesaw

SM + fermionic triplets Σ in $(1,3)_0$ of G_{SM}







Type I Seesaw

SM + r.h. neutrinos N_i in $(1,1)_1$ of G_{SM}

Type II Seesaw

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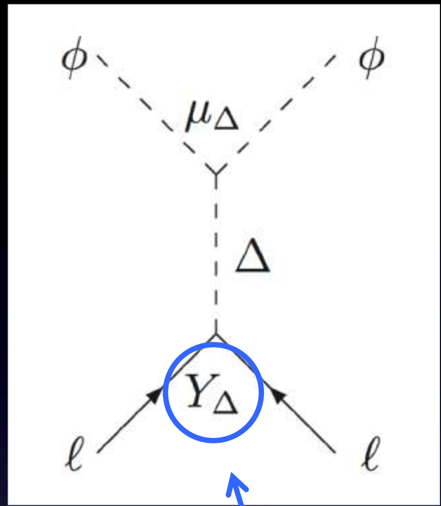
SM + fermionic triplets Σ in $(1,3)_0$ of G_{SM}

Also unknown: At which scale?

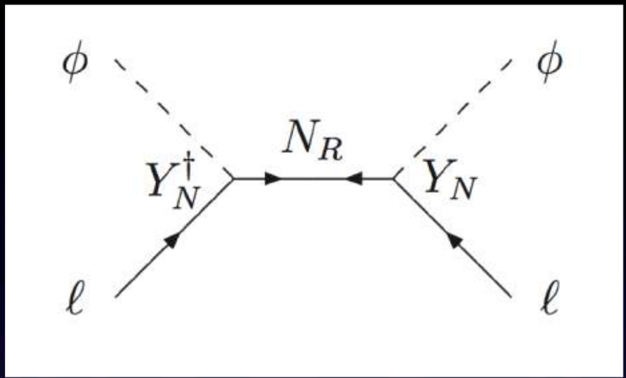
(A) At very high scale (~ M_{GUT})
(B) At EW/TeV scale (→ colliders, ...)
for Type I seesaw also:
(C) At keV scale (→ sterile ν DM)
(D) At eV scale (→ oscillations & sterile ν's)

Neutrino masses:
At TeV energies?

Type II Seesaw

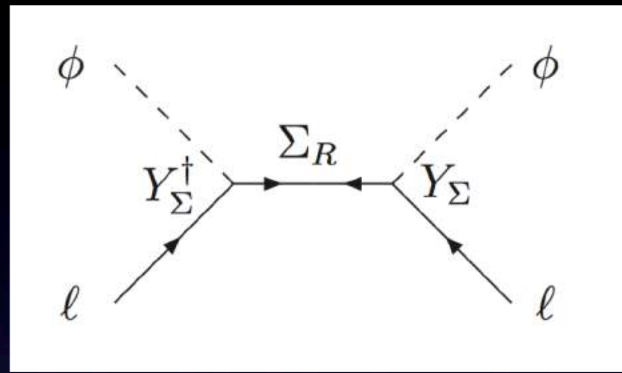


Type I Seesaw



$$M_N = \begin{pmatrix} 0 & M \\ M & \mu \end{pmatrix}$$

Type III Seesaw

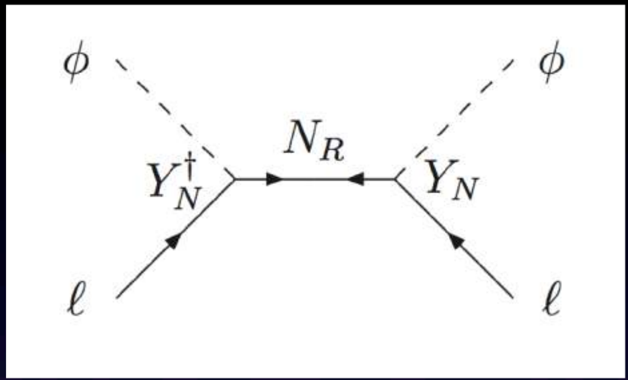


$$M_\Sigma = \begin{pmatrix} 0 & M \\ M & \mu \end{pmatrix}$$

With an approximate “lepton number”-like symmetry
→ all three types of seesaw mechanisms can operate “naturally” at EW/TeV energies
→ Low scale seesaw models

Neutrino masses:
At TeV energies?

Type I Seesaw



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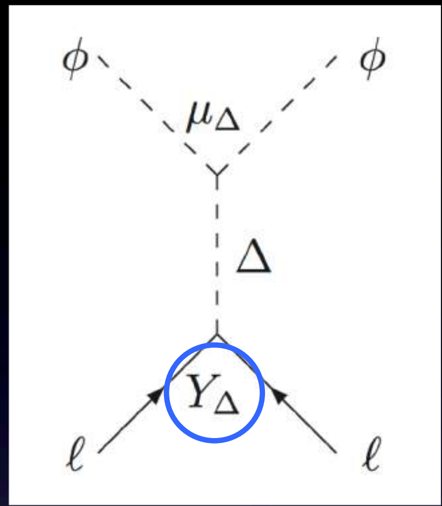
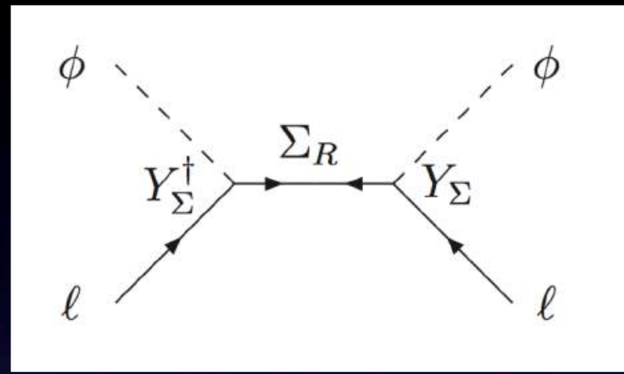


Type III Seesaw



$$M_\Sigma = \begin{pmatrix} 0 & M \\ M & \mu \end{pmatrix}$$

Forbidden if symmetry was exact!

E.g. in the type I seesaw: Example for protective "lepton number"-like symmetry:

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

→ **Note: "Symmetry protection" requires pairs of sterile (right-handed) neutrinos)!**

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), …

Content of my talk: Some collider aspects of low scale type I and II seesaw scenarios.

Part 1:

Collider signatures of sterile neutrinos (from a low scale type I seesaw mechanism)

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)

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

+ O(ε) perturbations which generate the light neutrino masss and a ΔM of heavy neutrinos (and 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 (for most cases in my talk) 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 sterile neutrinos?

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

As example: SPSS (Symmetry Protected Seesaw Scenario)

In the symmetry limit:

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

As example: SPSS (Symmetry Protected Seesaw Scenario)

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$+$ … (terms from additional sterile νs)

4 Parameters:
M, y_α, (α=e,μ,τ)

As example: SPSS (Symmetry Protected Seesaw Scenario)

In the symmetry limit:

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

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

Mass eigenstates:

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

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

with:

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

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

This defines the 5x5 mixing matrix U.

We consider the SPSS: Instead of the y_α, we use the active sterile mixing angles θ_α, (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:

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

- Active-sterile neutrino mixing parameters:

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

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

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

Main effect for $M >> \Lambda_{EW}$: "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), …

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:

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

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

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: $M \cong \Lambda_{EW}$

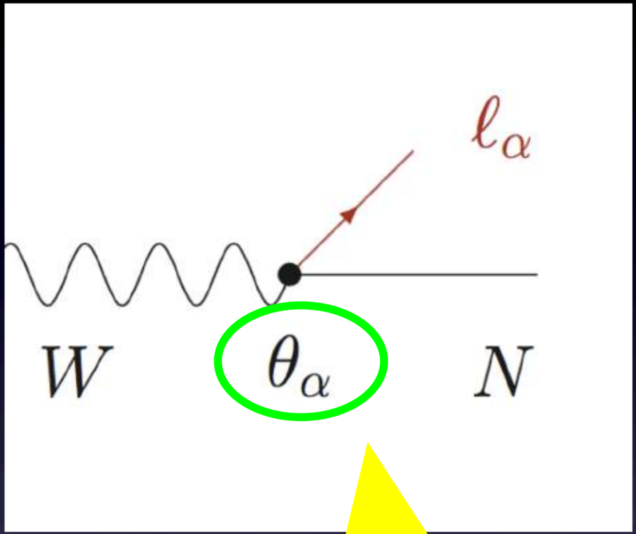
In addition for $M \cong \Lambda_{EW}$: Effects from on-shell heavy neutrinos

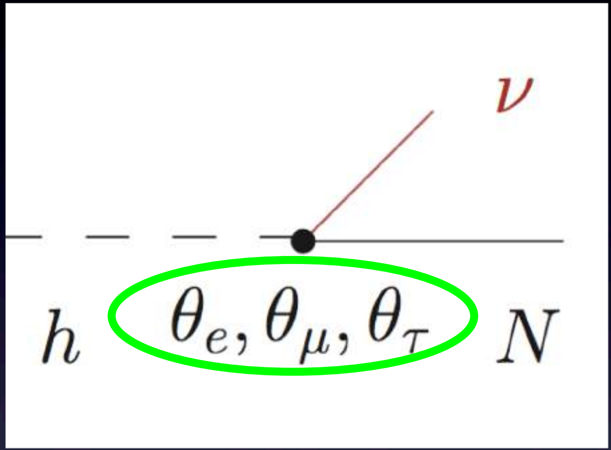
Sterile neutrinos mix with the active ones ➔ the heavy neutrinos (= mass eigenstates) participate in weak interactions!

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

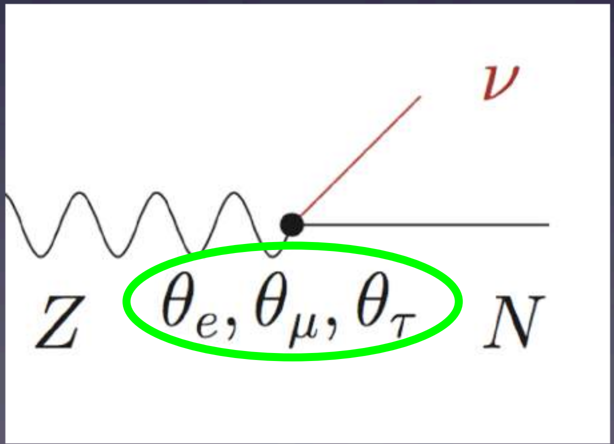
⇒ heavy neutrinos can get produced also in weak interaction processes!

Heavy neutrino interactions



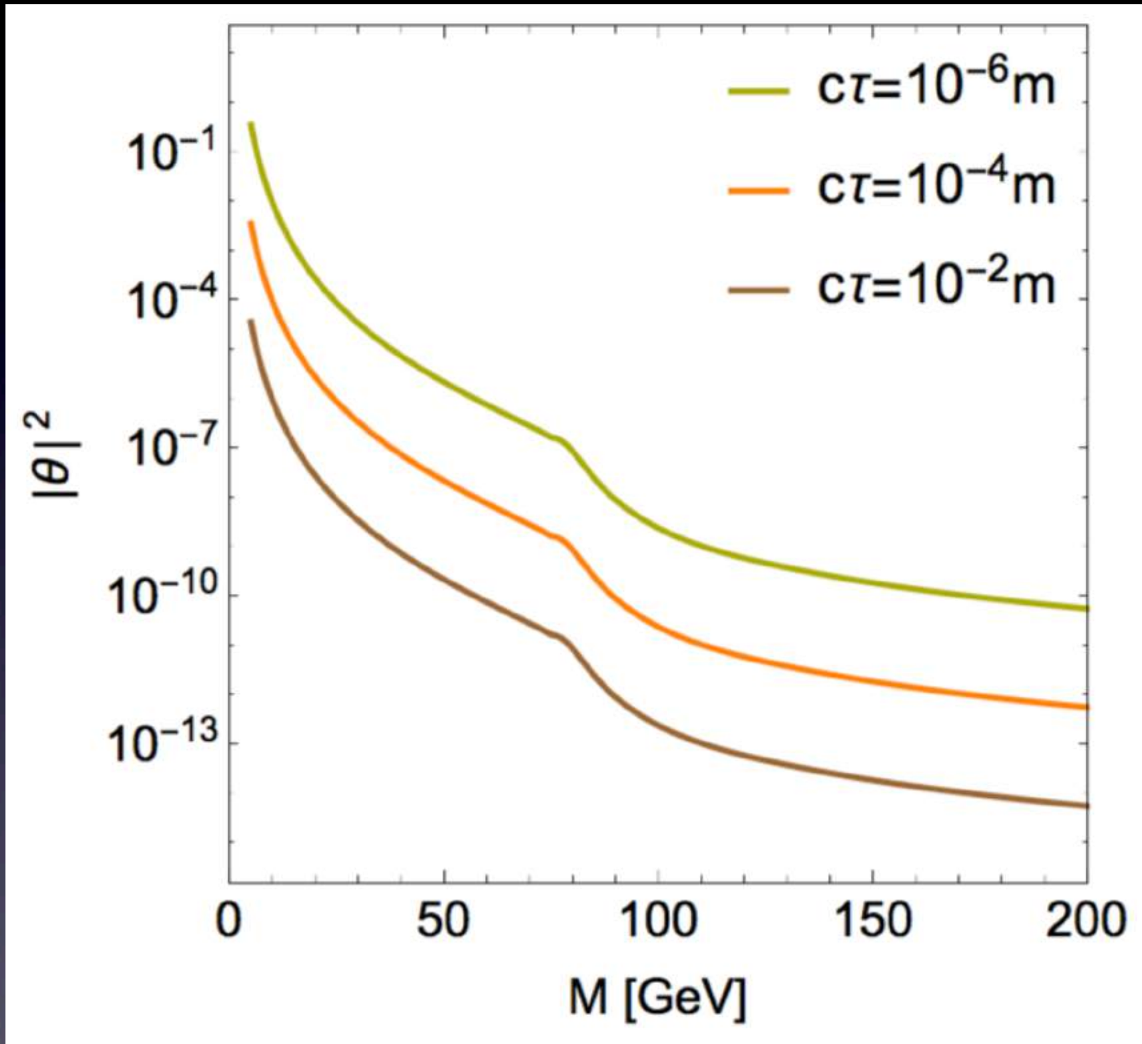


When W bosons are involved, there is a possible sensitivity to the flavour-dependent θ_α



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

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

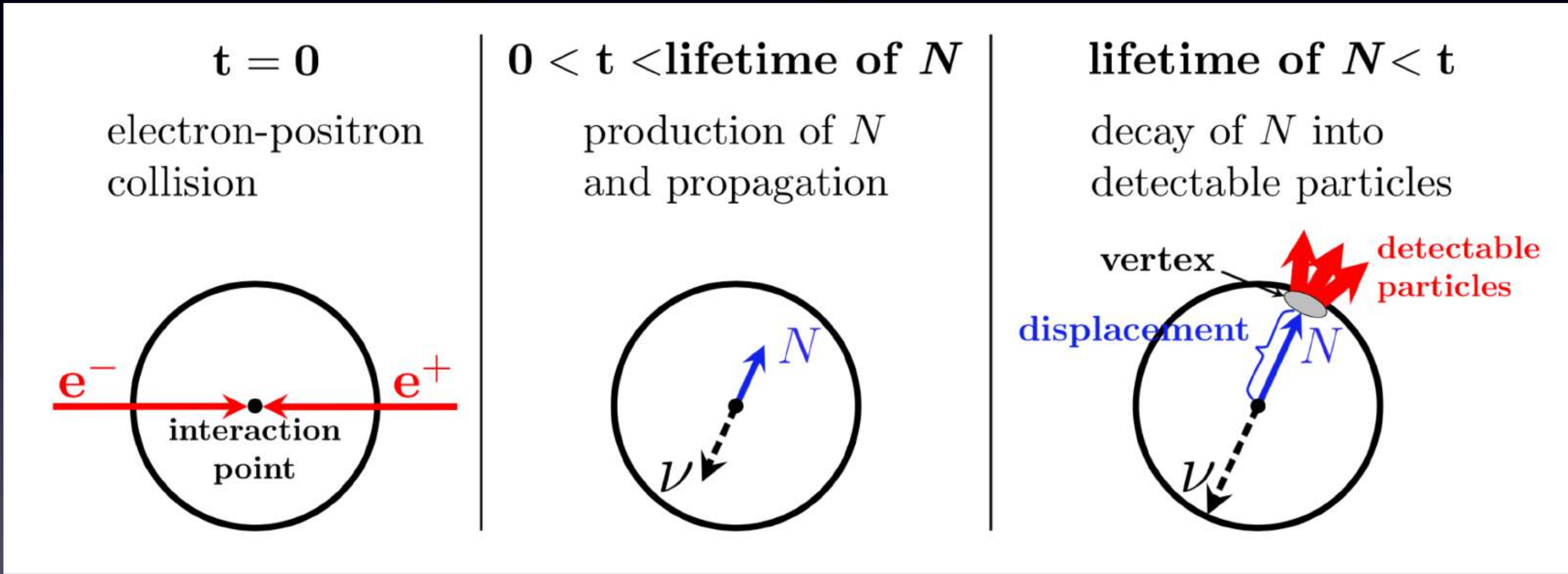


cf. S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

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

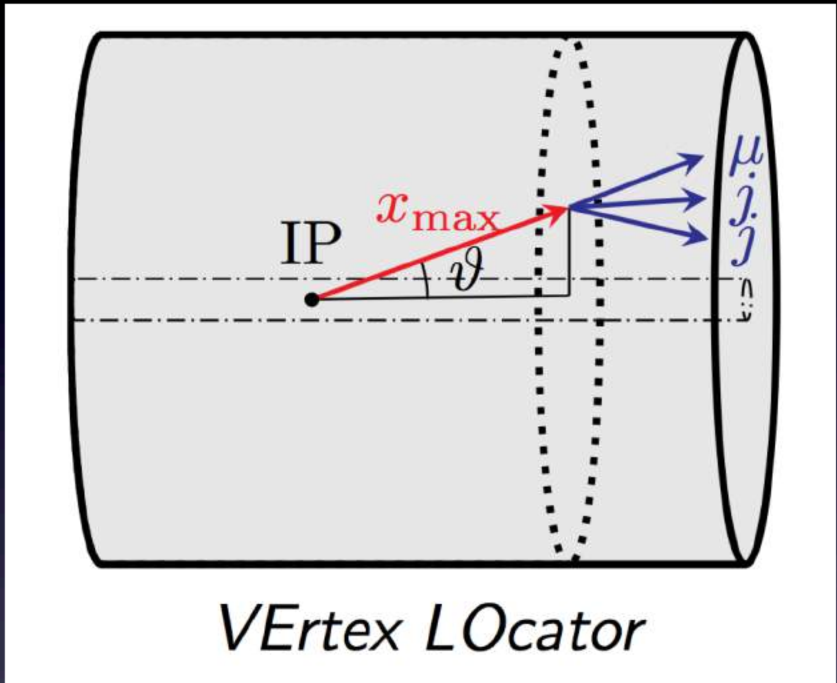
Very sensitive searches possible for $M<m_W$ via "displaced vertices"

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



Present constraints on heavy (mainly sterile) neutrino parameters

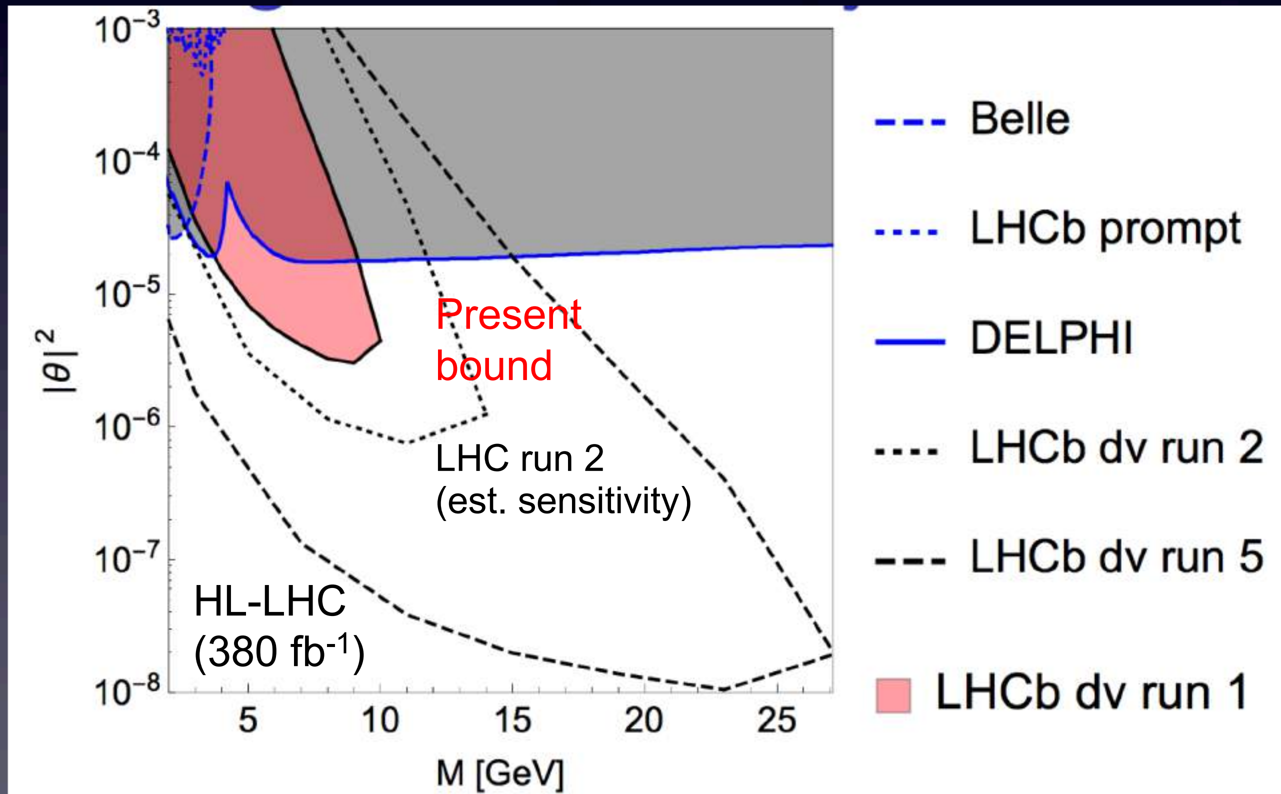
Present bounds (& estim. future sensitivities) from displaced vertex searches at LHCb



LHCb analysis exists for LHC run 1 data:

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

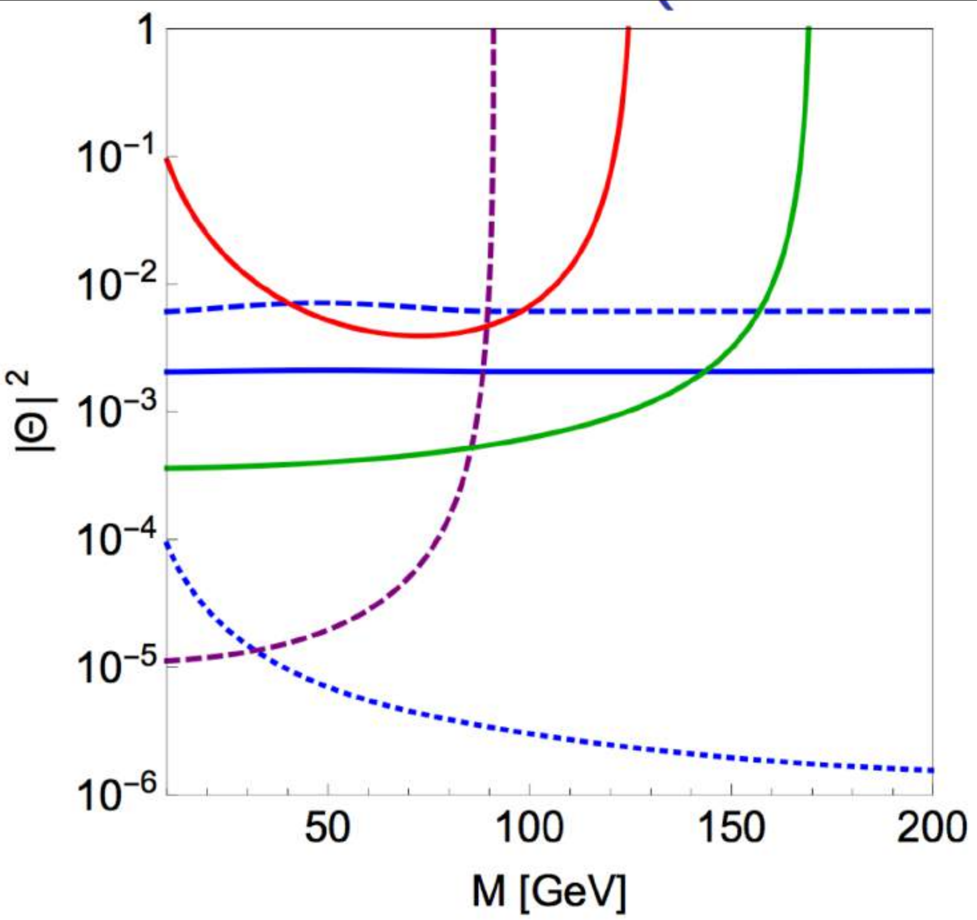
The results can be translated into bounds on $|\theta|^2$ (here for $\theta_e = \theta_\tau = 0$):



Remark 1: Recent ATLAS analysis found similar (somewhat stronger) bound:
E. Izaguirre, B. Shuve (arXiv:1905.09787)

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

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



(global constraints, including EWPO and cLFV)

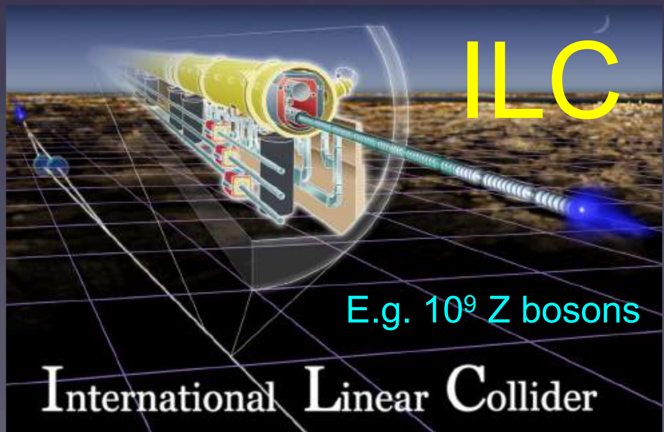
with: $|\theta|^2 := \sum_\alpha |\theta_\alpha|^2$

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)

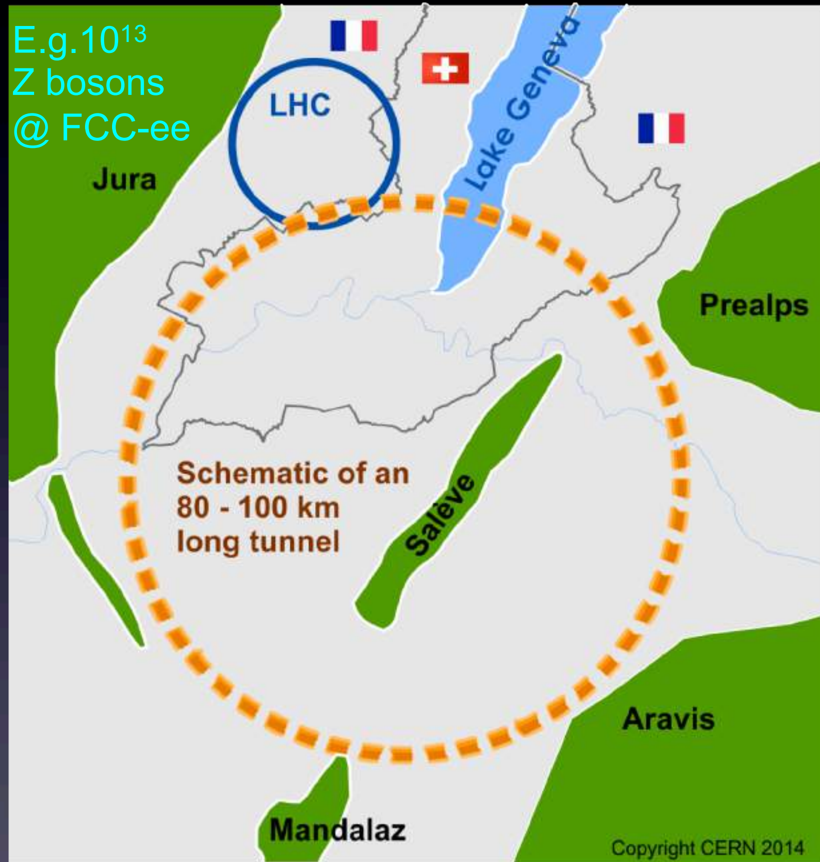
What are the prospects for discovering such heavy neutrinos at future experiments?

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

Ambitious plans for future colliders …

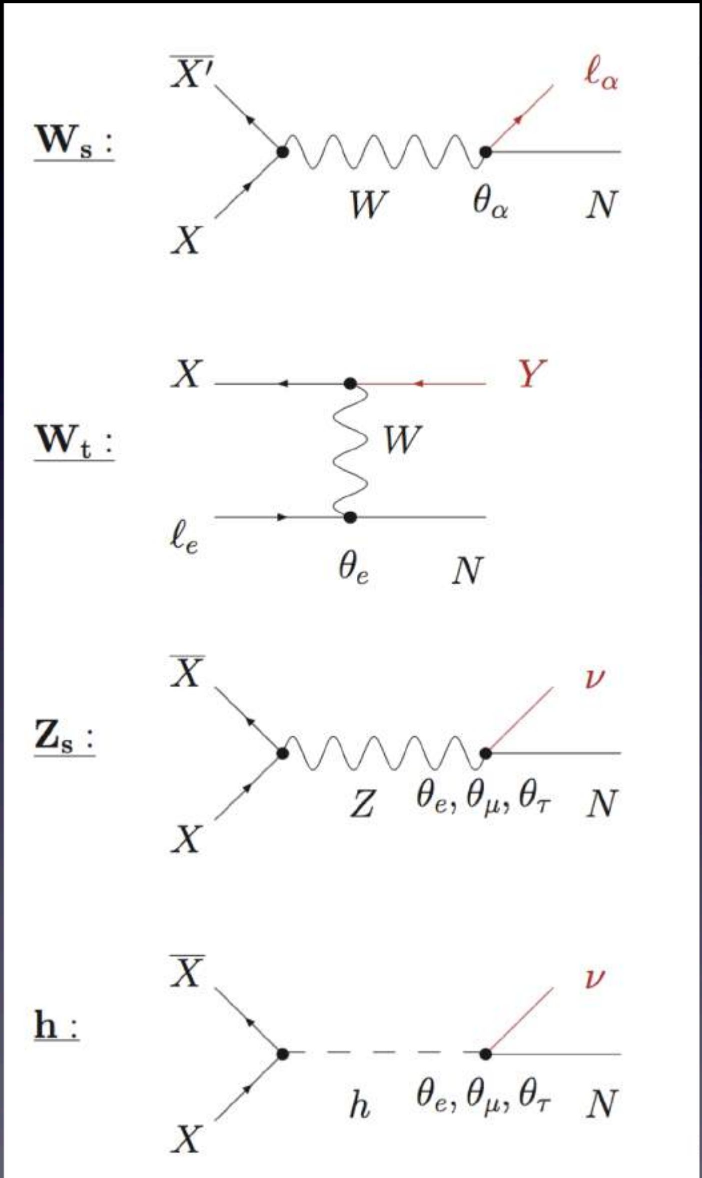


FCC (-ee, -hh, -eh)



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



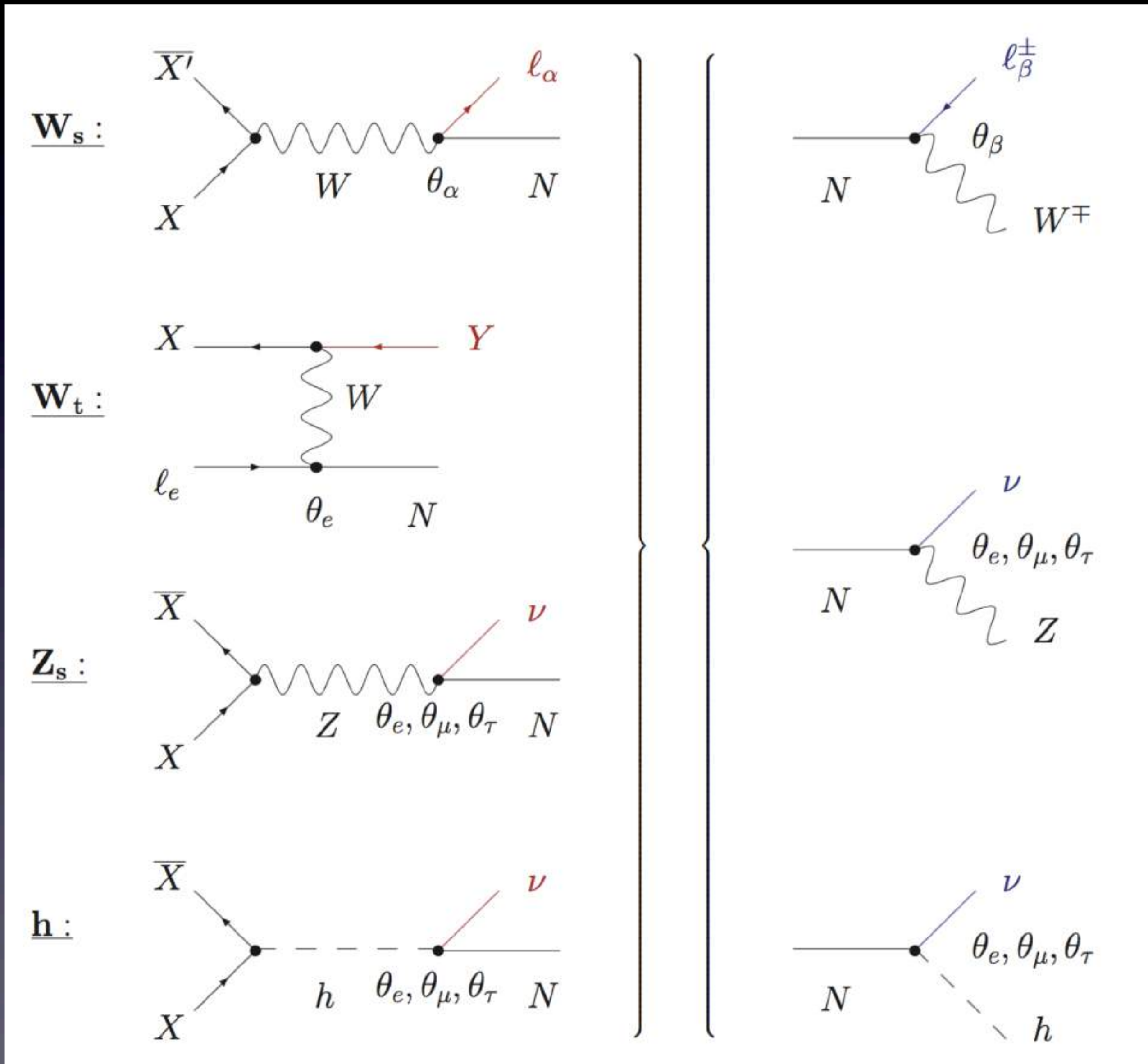
S.A., E. Cazzato, O. Fischer (arXiv:1612.02728),
See also many other works by many authors ...

Different collider types feature different production channels …

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

Systematic assessment of signatures of sterile neutrinos at colliders

(at LO)

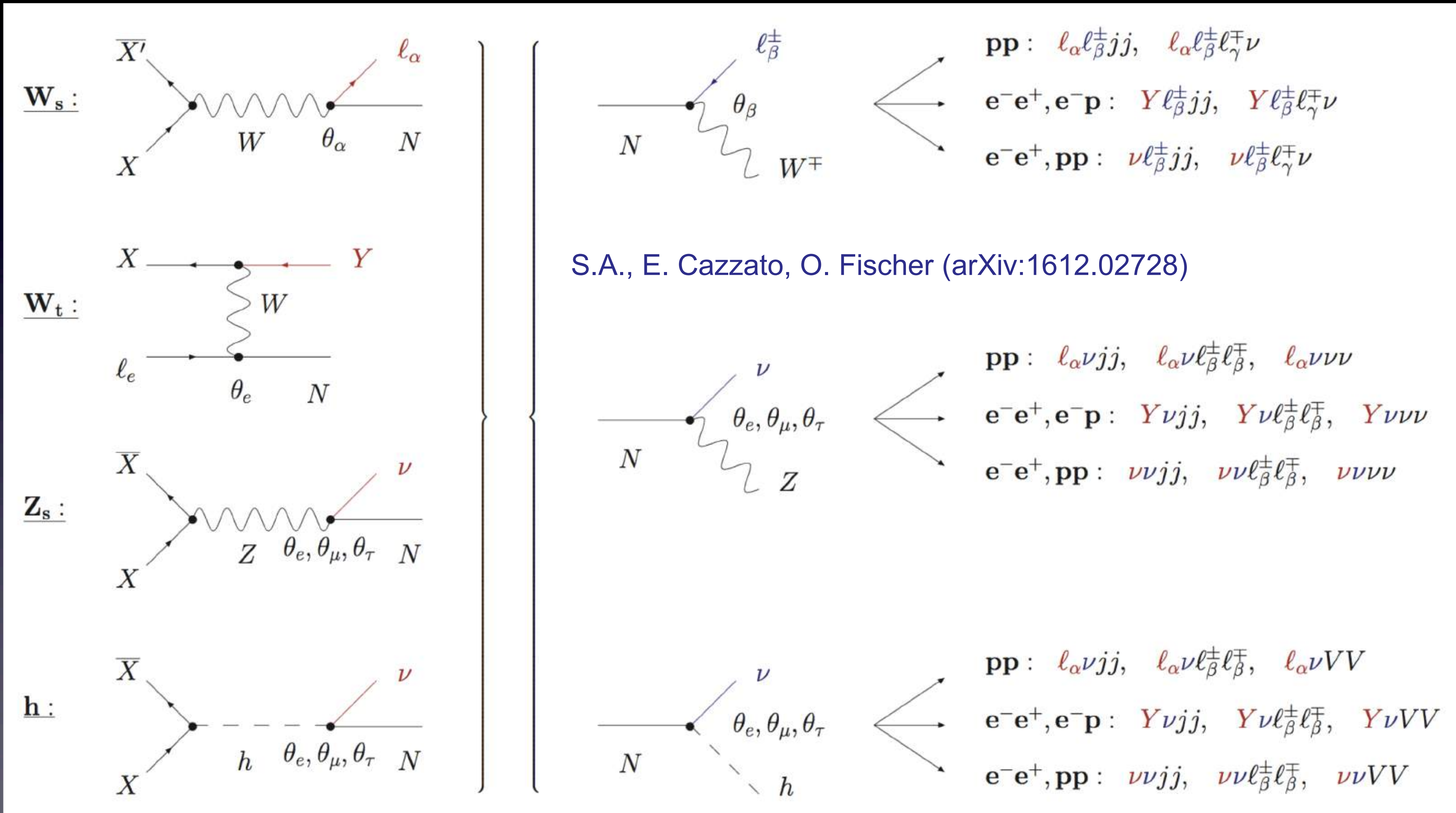


… and, including the possible decay channels, sensitivity to different combinations of active-sterile mixing parameters:

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

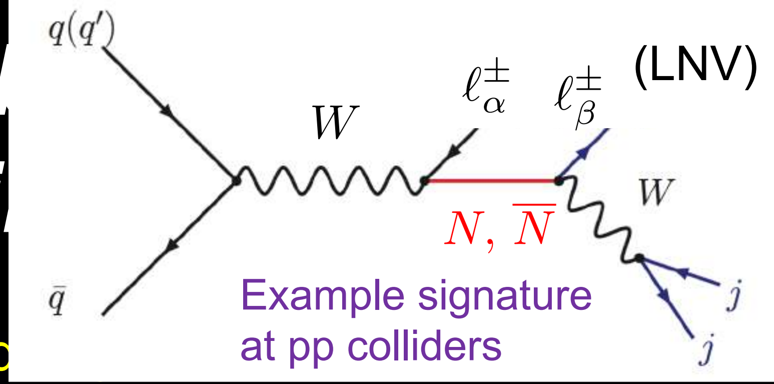
Systematic assessment of signatures of sterile neutrinos at colliders

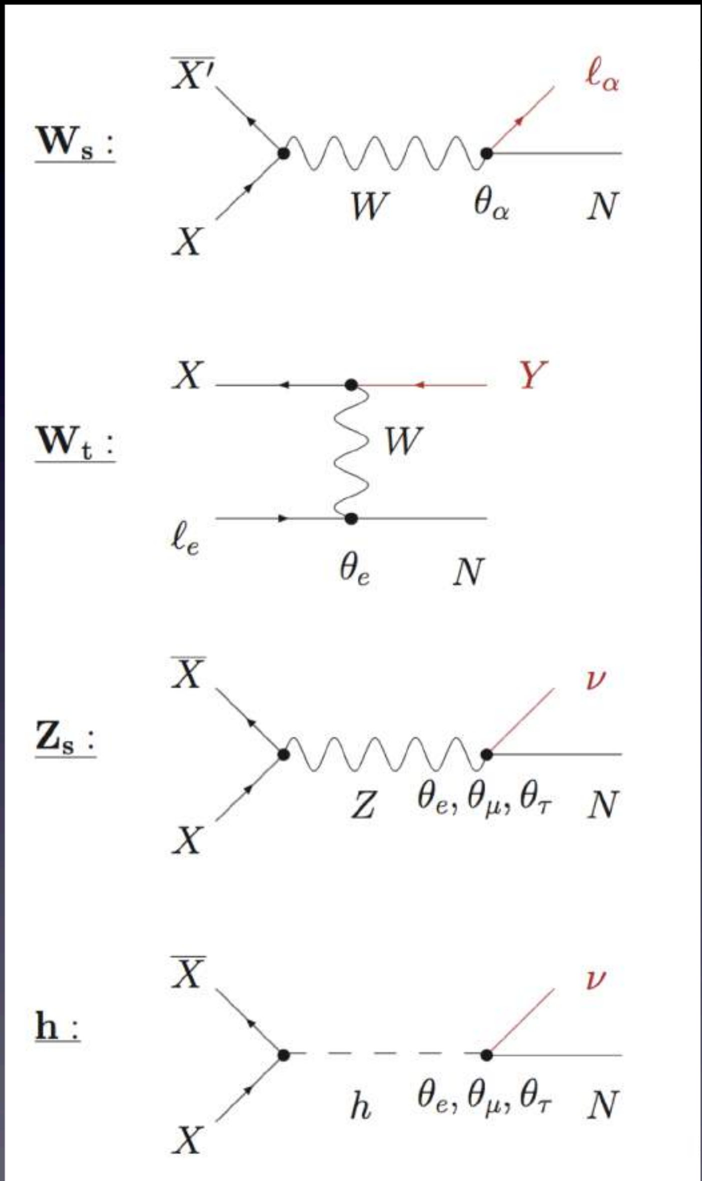
(at LO)



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

Signatures for lepton num… from sterile neutri…





Different collid… different production channels:

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

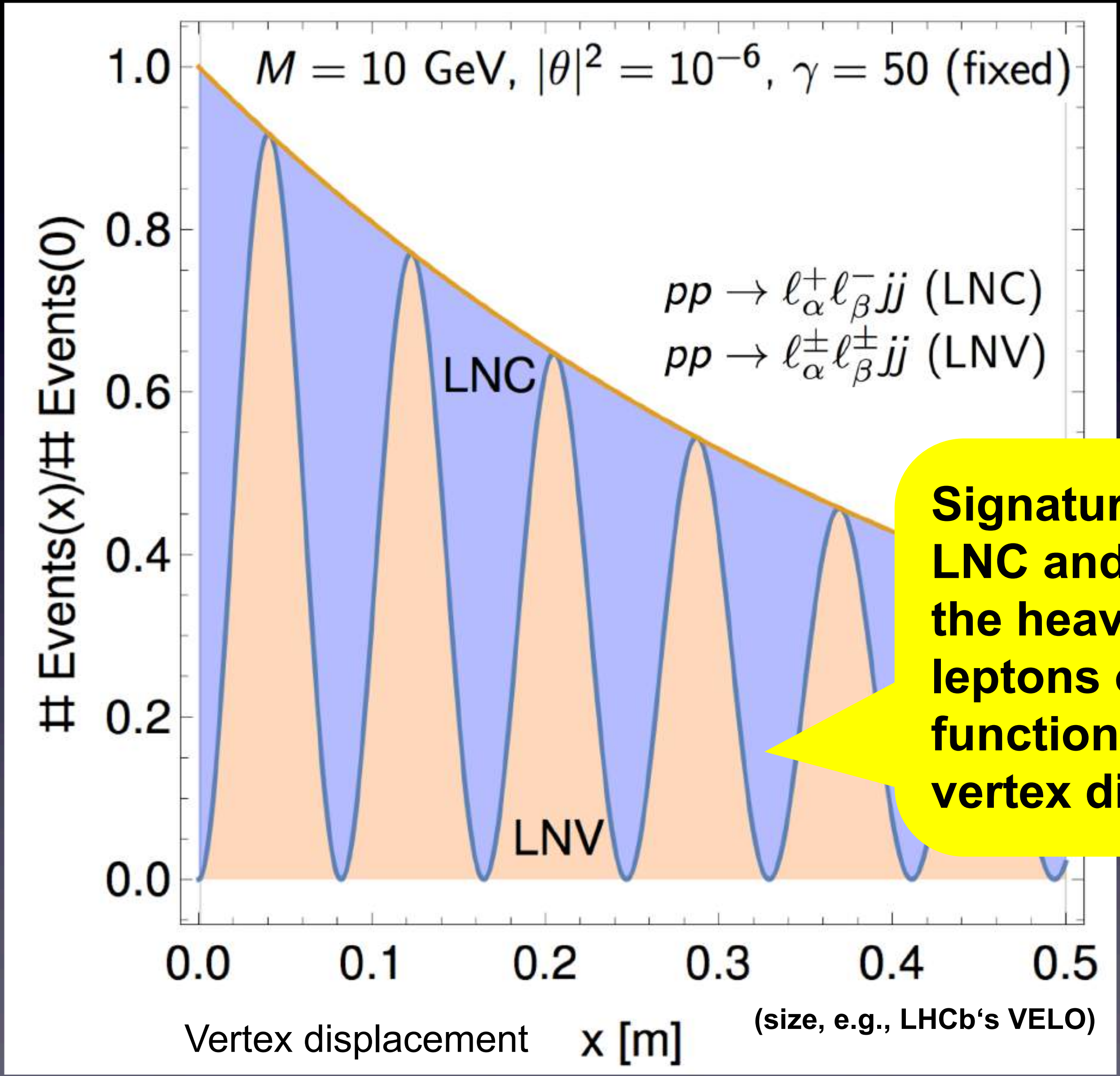
Lepton-number violating (LNV) signatures possible (with no SM background at parton level) but expected to be suppressed by the (approximate) protective "lepton number"-like symmetry!

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 adding 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)



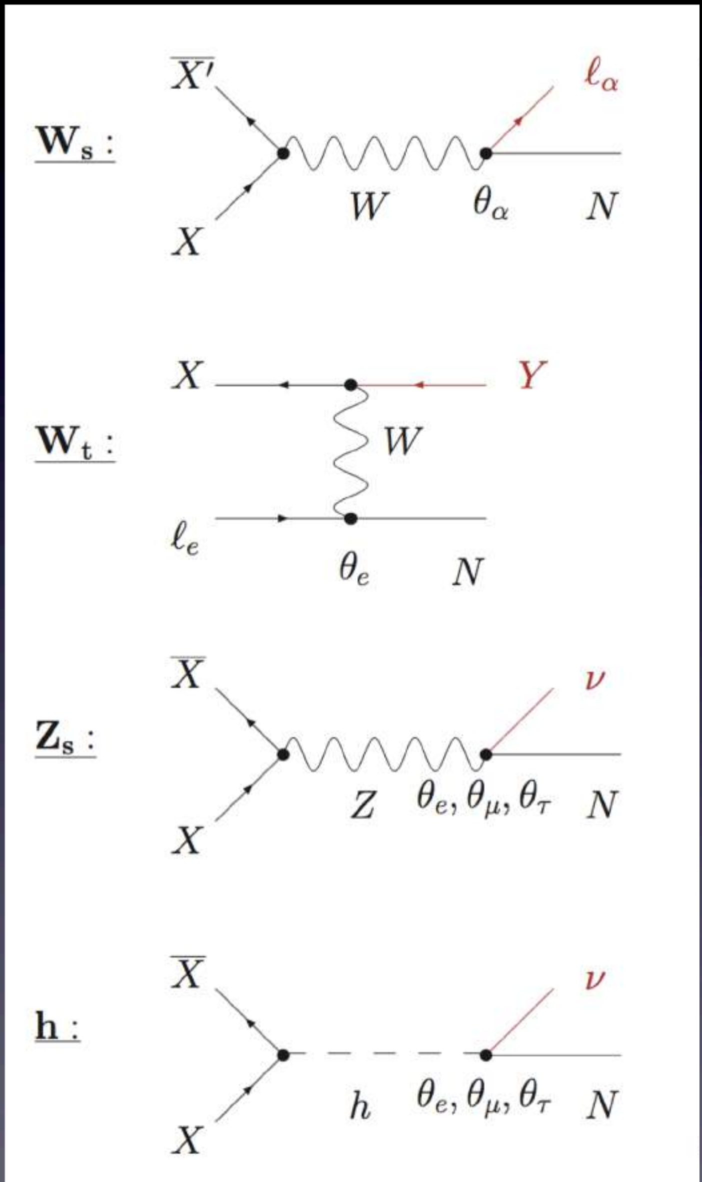
S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

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
W_s	×	✓+LNV/LFV	×
W_t	✓	×	✓ +LNV/LFV
Z_s	✓	✓	×
h	(✓)	(✓)	(✓)

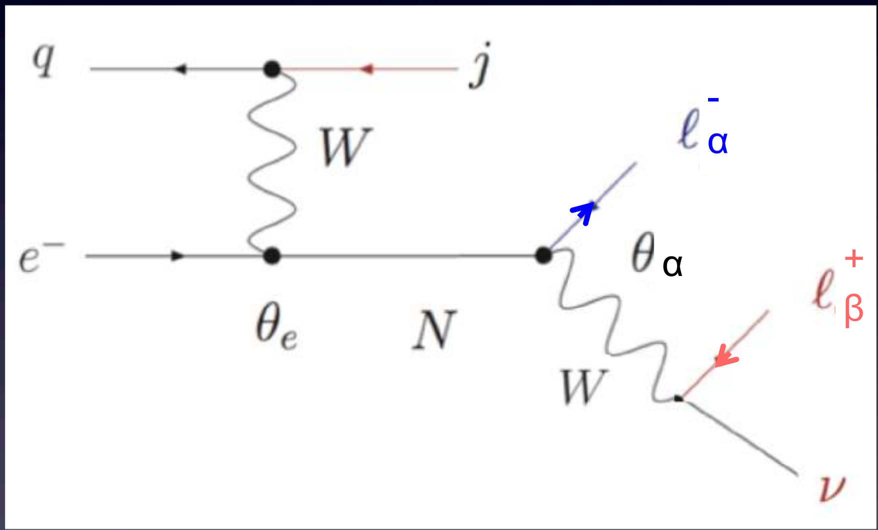
<u>Lepton flavour violating LFV</u> (and lepton number conserving LNC) signatures possible (with no SM background at parton level*). <u>Promising for future searches!</u>

*) 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

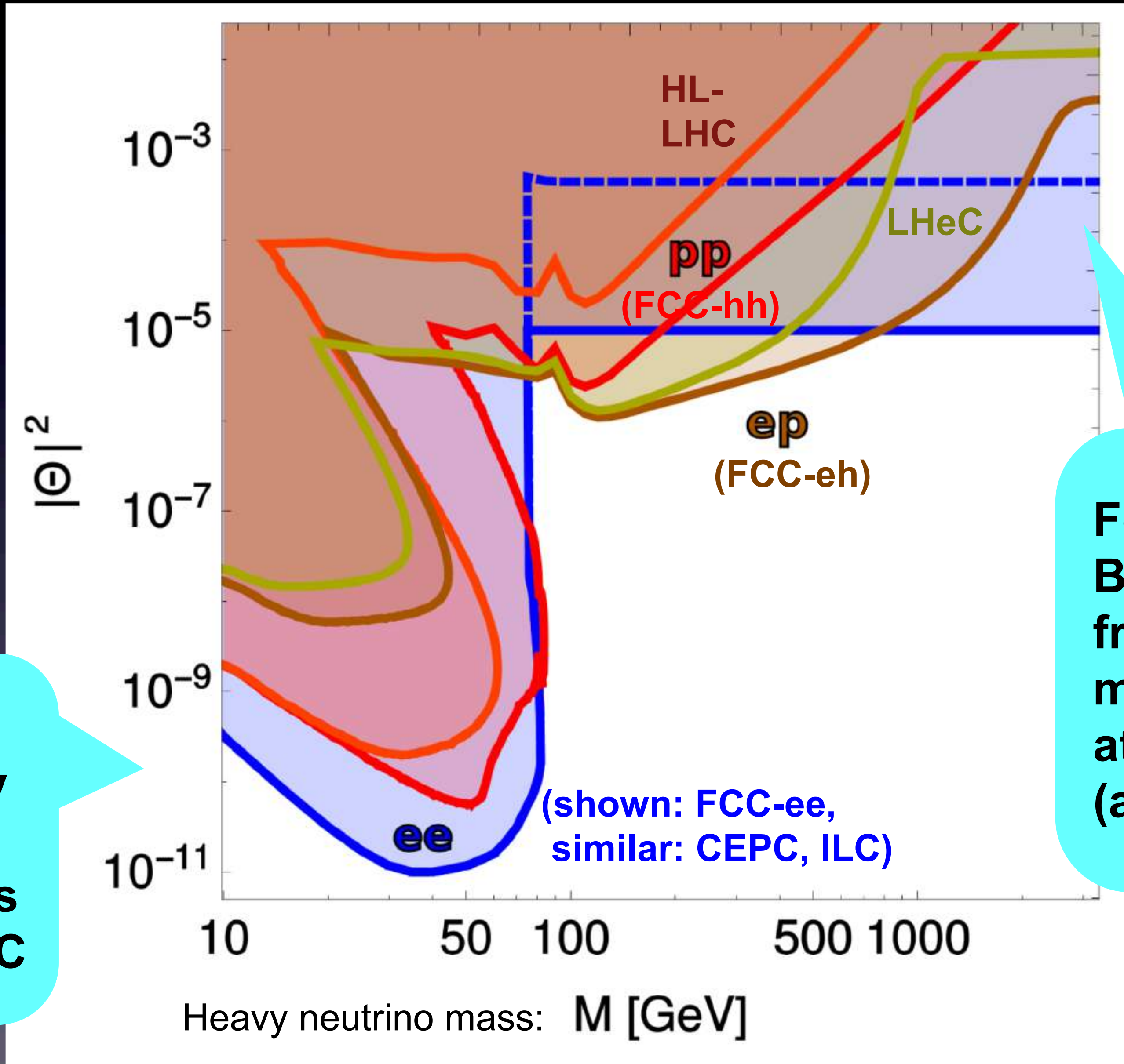
Different collider types feature different production channels:

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

<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!

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

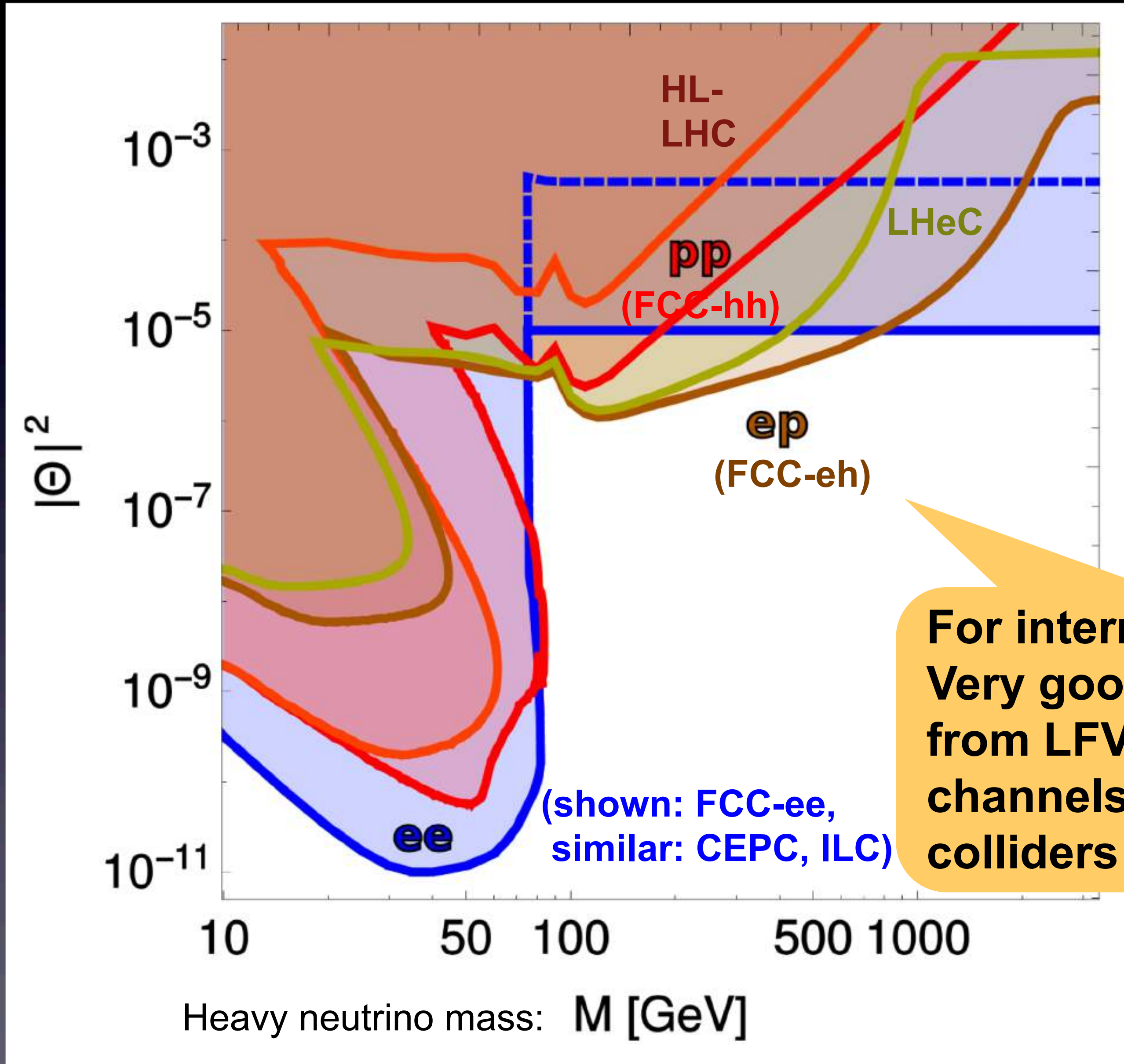


For M < m_W: Best sensitivity from displaced vertex searches at FCC-ee/CEPC

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

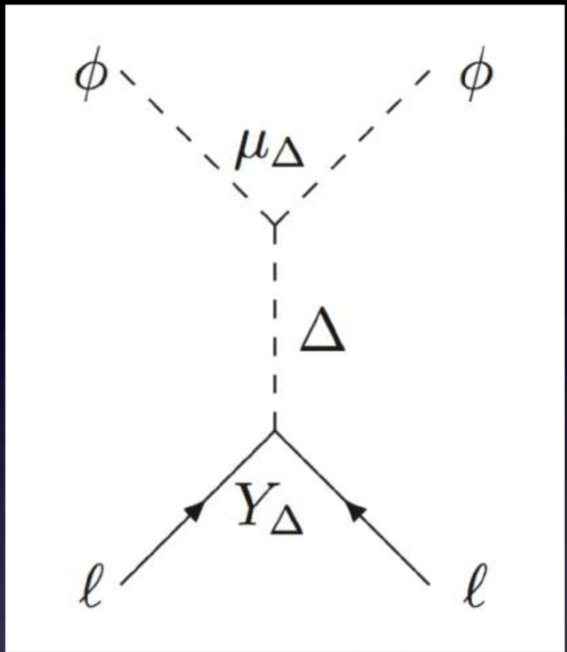
Plot from: S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

Part 2:
Collider signature of low scale type II seesaw scenarios

Recent result: Interesting parameter space with long-lived doubly charged scalar (from type II seesaw)

S. A., O. Fischer, A. Hammad, O. Fischer, C. Scherb (arXiv:1811.03476)

Doubly charged scalar from the type II seesaw mechanism



Type II Seesaw

SM + scalar triplet Δ in $(1,3)_1$ of G_{SM}

Neutrino masses from the induced vev of a new Higgs field in the rep $(1,3)_1$ of G_{SM}

$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

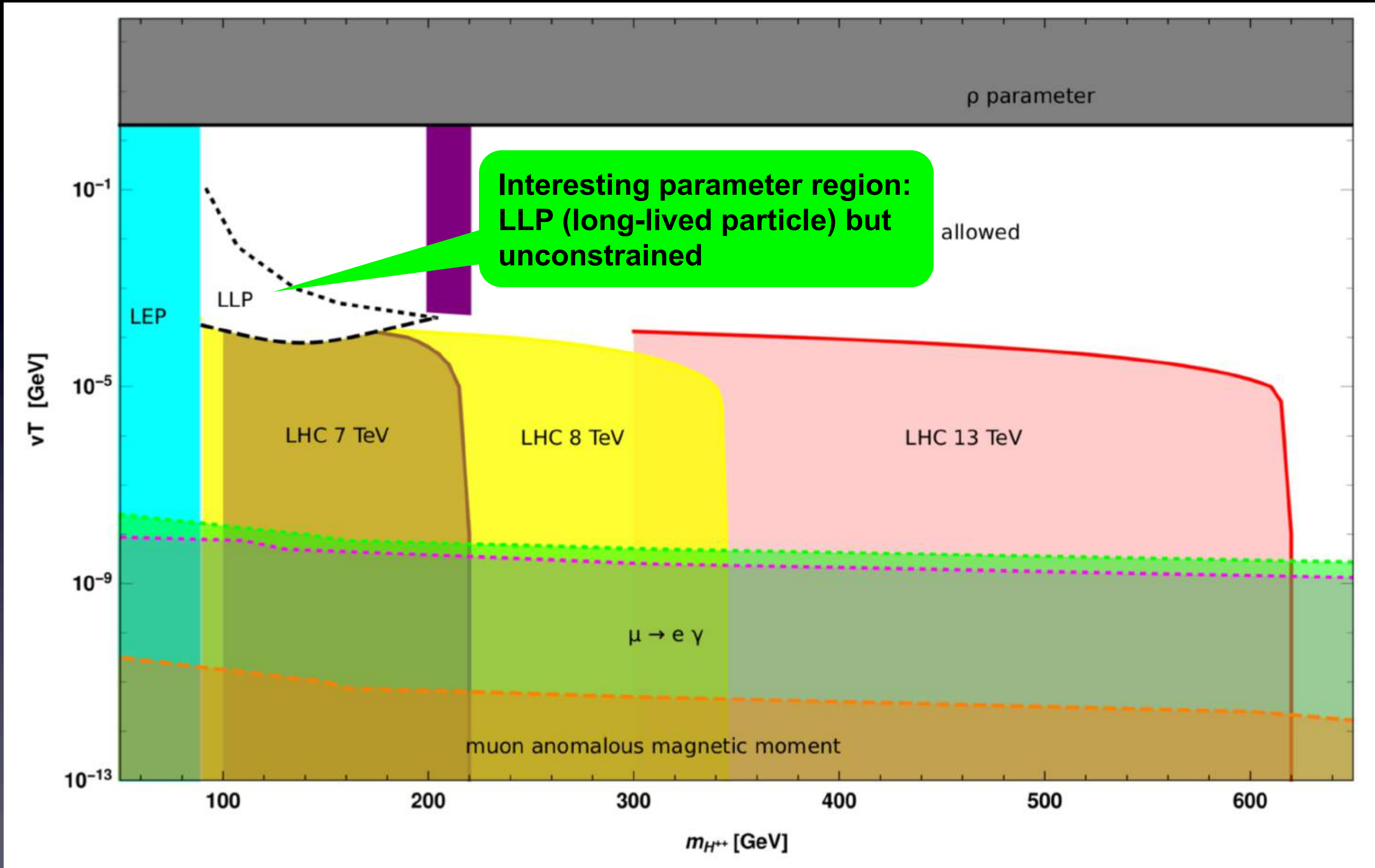
Can be searched for efficiently art colliders via decay into same-sign leptons

… however typically assumed that the decays are prompt!

$$\langle \Delta \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_T & 0. \end{pmatrix}$$

Many works by many autors on possible collider signatures, indirect test (LFV), etc …

Summary of present constraints

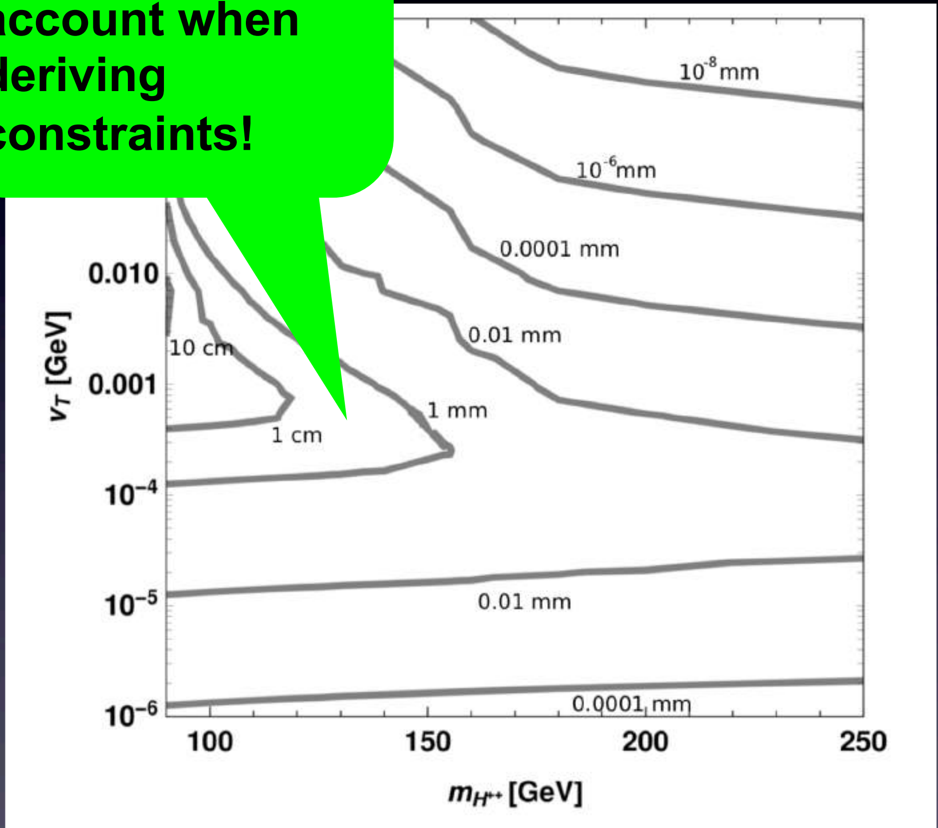


Summary of present constraints from: S. A., O. Fischer, A. Hammad, O. Fischer, C. Scherb (arXiv:1811.03476)

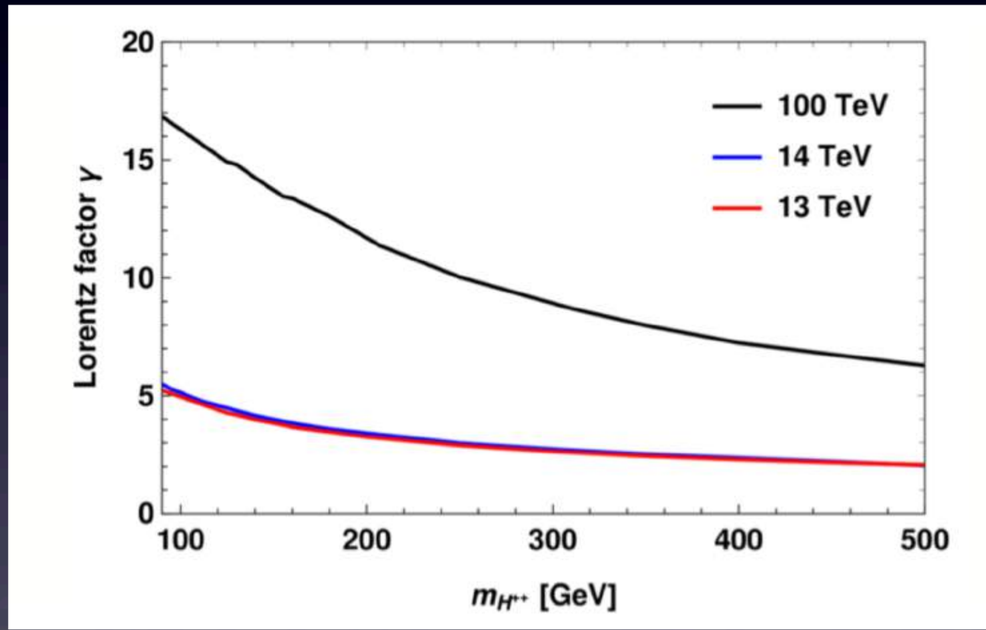
Lifetime of doubly charged scalars in the type II seesaw mechanism

Longevity has to be taken into account when deriving constraints!

Plot: $c\tau$ (with lifetime τ in the eigenframe)



Average Lorentz factor at LHC/FCC-hh:



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

S. A., O. Fischer, A. Hammad, O. Fischer, C. Scherb (arXiv:1811.03476),
See also e.g.: Dev, Zhang, arXiv:1808.00943

Revisting the LHC bounds from decays into same sign leptons

LHC bounds are NOT applicable in this region when longevity is taken into account, because the "promptness"-criteria used in the analysis are not fulfilled!

S. A., O. Fischer, A. Hammad, O. Fischer, C. Scherb (arXiv:1811.03476)

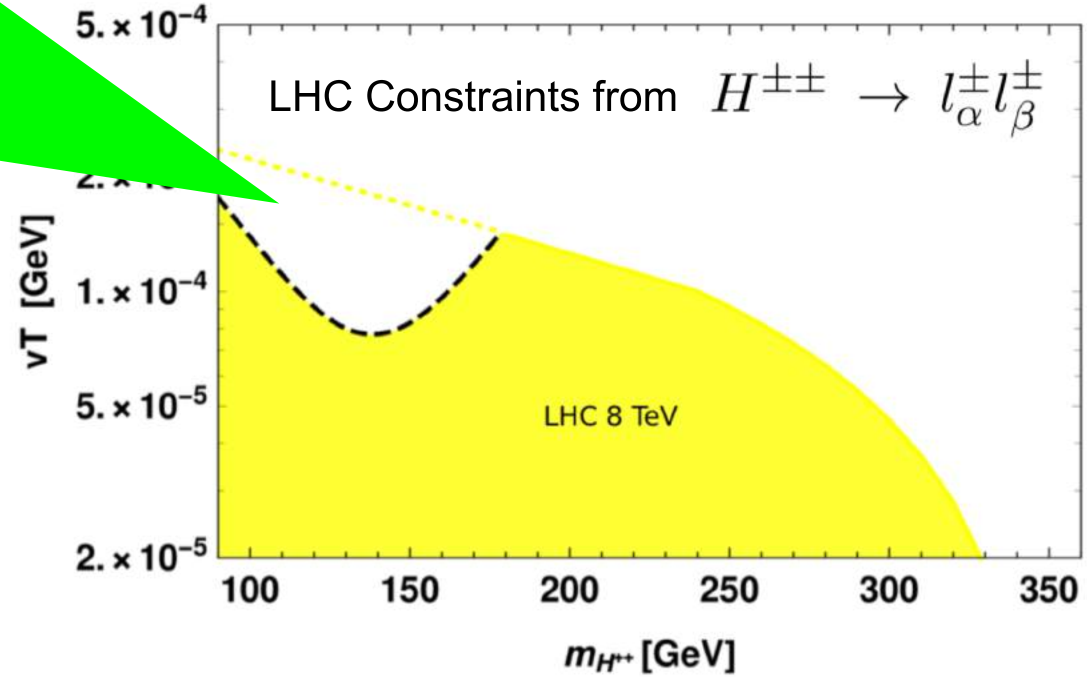


Figure 7: Parameter space constraints from prompt LHC ($\sqrt{s} = 8$ TeV) searches for same-sign dileptons at 95% confidence level [20], taking the possible displacement into account. The dashed black line indicates where the effective cross section is smaller than the observed limit. The dotted yellow line shows where the limit from the prompt search would be if all decays were prompt.

ATLAS Collaboration], arXiv:1412.0237

Also: Existing analyses for heavy stable charged particles (HSCPs) from ATLAS and CMS are not applicable (in the considered parameter space).

We did a detailed analysis of the displaced vertex signature at the reconstructed level ...

For a selected benchmark point (simulated):

Table 1: Cut flow of simulated signal samples for displaced decays of the $H^{\pm\pm}$ to same sign dimuons. For this table, the benchmark point with $v_T = 5\times10^{-4}$ GeV and $m_{H^{\pm\pm}} = 130$ GeV was considered. For the LHC, HL-LHC, and FCC-hh we use 13, 14, and 100 TeV center-of-mass energy and an integrated luminosity of 100 fb^{-1}, 3000 fb^{-1}, and 20 ab^{-1}, respectively. In our analysis we consider the production channel $pp \to \gamma^* Z^* \to H^{\pm\pm} H^{\mp\mp}$ only.

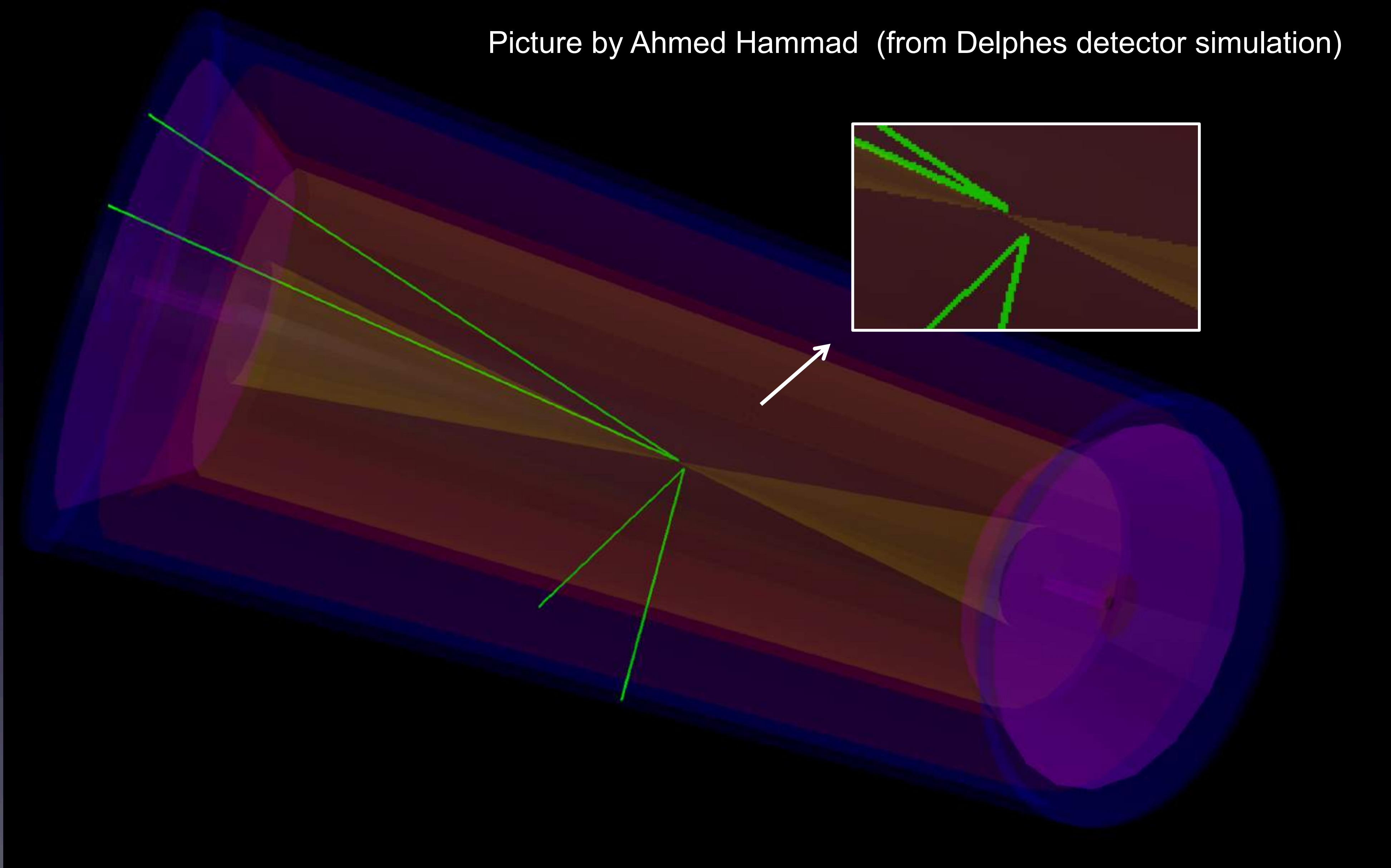
Cuts	LHC	HL-LHC	FCC-hh
Expected events (detector level)	280	10640	345323
Two same sign muons	220	8135	244050
$P_T(\mu) > 25$ GeV$\&|\eta(\mu)| < 2.5\&\Delta R(\mu,\mu) > 0.2$	180	6508	209883
110 GeV$< m_{H^{\pm\pm}} <$ 150 GeV	175	6332	203586
$L_{xy} > 8$ mm	76	2749	105864
$d0 > 4$ mm	13.6	467	31759

Benchmark point can be tested even with present LHC data!

S. A., O. Fischer, A. Hammad, O. Fischer, C. Scherb (arXiv:1811.03476)

Example of a simulated displaced vertex decay of $H^{--}H^{++}$ to tow pairs of same sign muons

Picture by Ahmed Hammad (from Delphes detector simulation)



… signal might be hidden in present LHC data!

Summary

- With a protective “lepton number”-like symmetry, neutrino mass generation can well occur at the EW/TeV scale (& be technically natural).
- Low scale type I seesaw:
  Using a benchmark scenario (SPSS) we discussed various promising signatures (e.g. displaced vertices, LNV in heavy neutrino-antineutrino oscillations, LFV, ...)
- Low scale type II seesaw:
  For long-lived doubly charged scalars, we have revisited the present LHC constraints → interesting parameter space with long-lived doubly charged scalars (untested by current analyses but discovery might be hidden already in present LHC data)!
- Fascinating possibilities for testing neutrino mass generation at future colliders (if realized around the EW scale)!

Thanks for your attention!

Extra Slides

Resolvable heavy neutrino-antineutrino oscillations at colliders

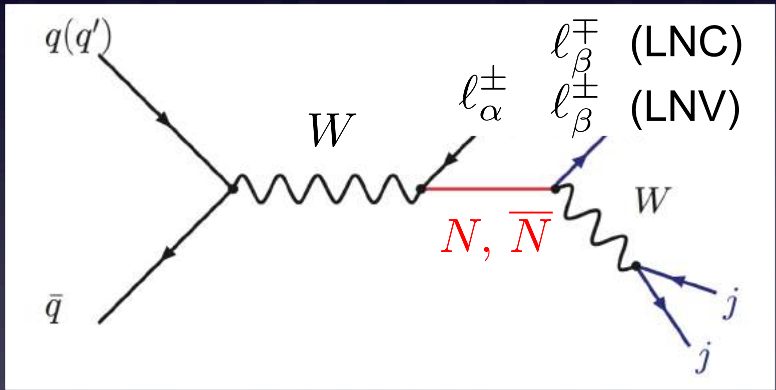
Heavy neutrino-antineutrino oscillations at colliders

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 ➔ $l_\alpha\, l_\beta$ 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!

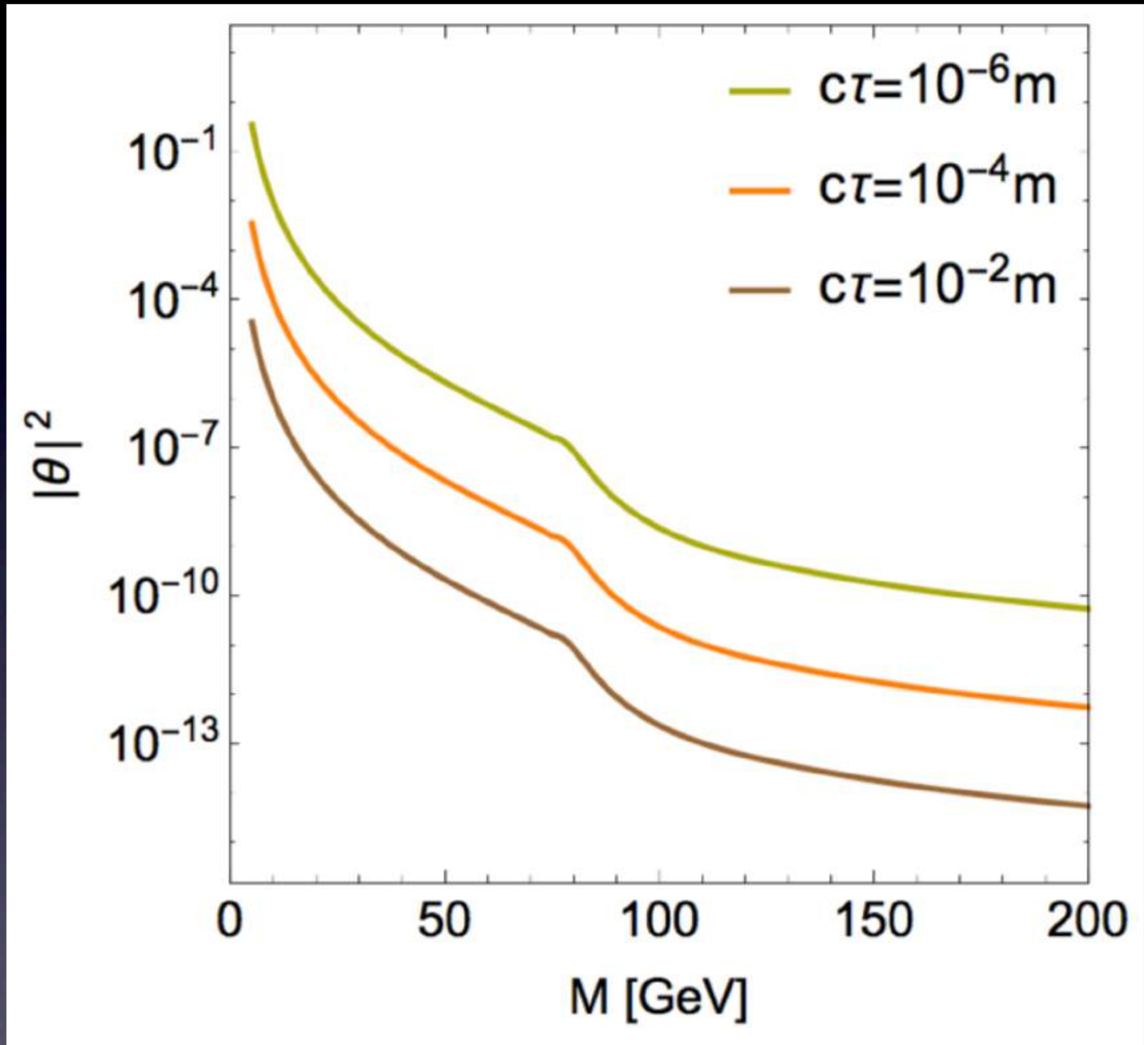
Signature: Ratio of LNV/LNC final states oscillates as function of heavy neutrino lifetime (or of vertex displacement in the laboratory system)

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

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

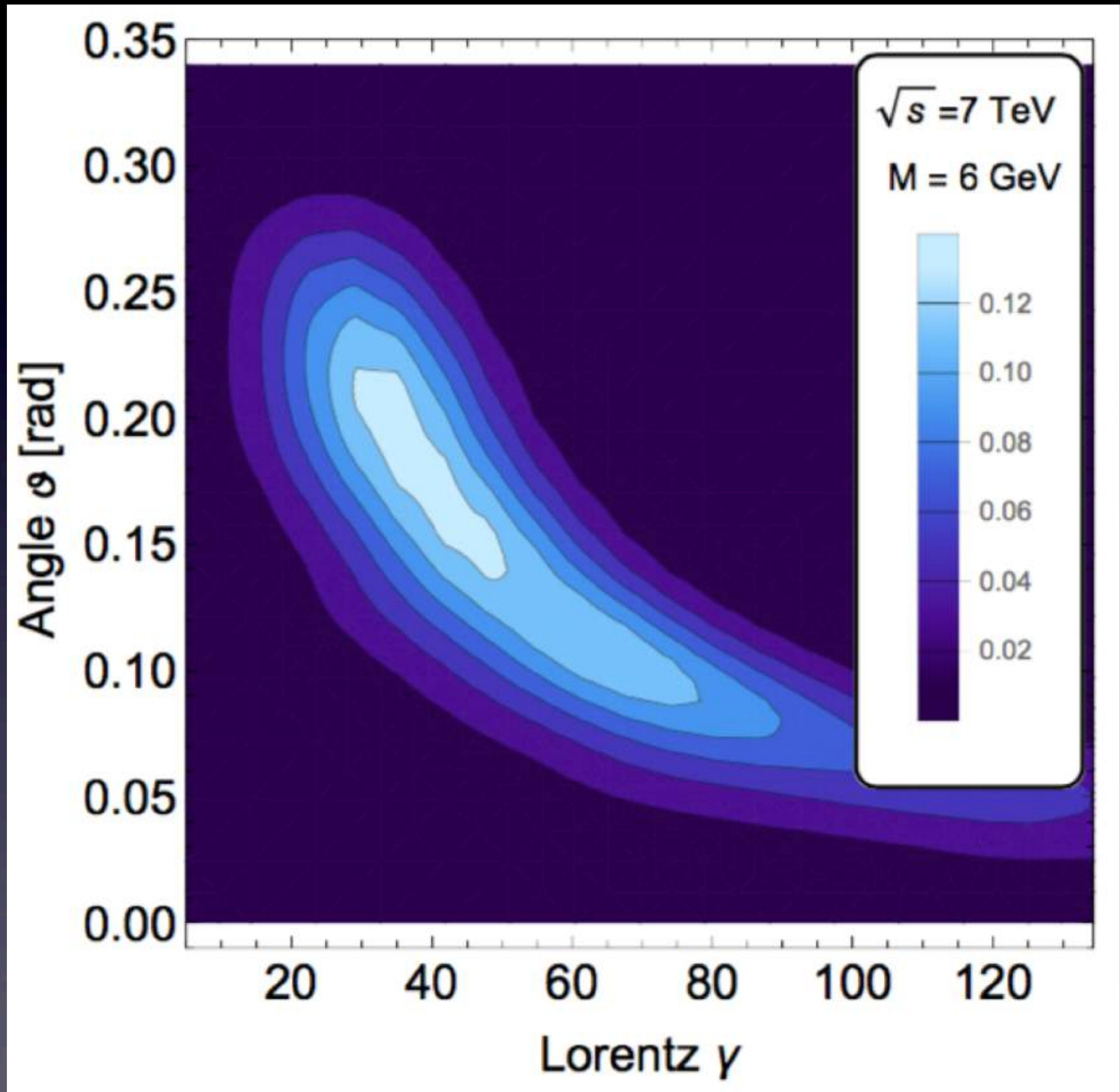
As shown earlier: Lifetime and decay length of heavy neutrinos



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

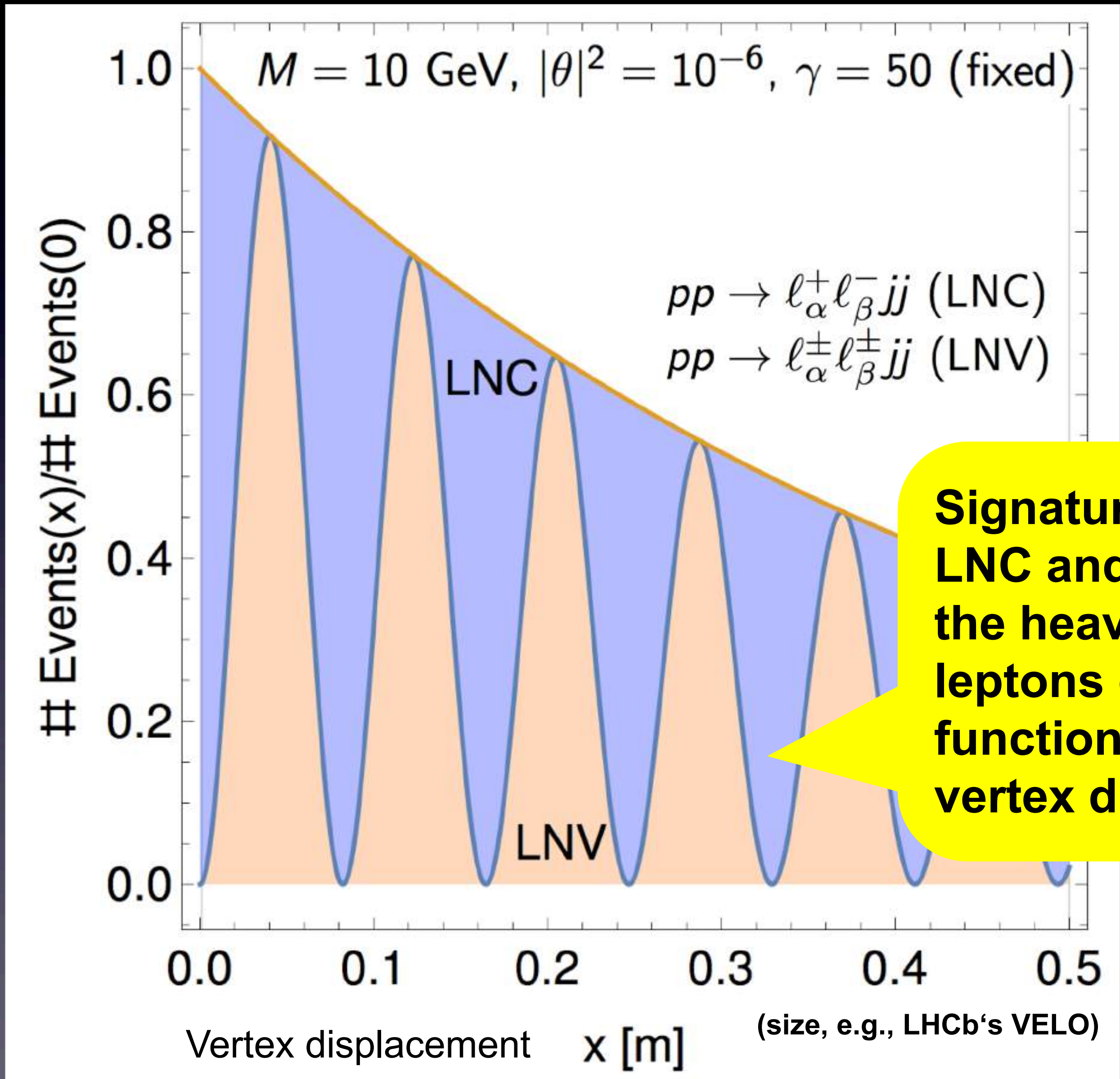


S. A., E. Cazzato, O. Fischer; arXiv:1706.05990

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)

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 B. R. N. Mohapatra (2017)

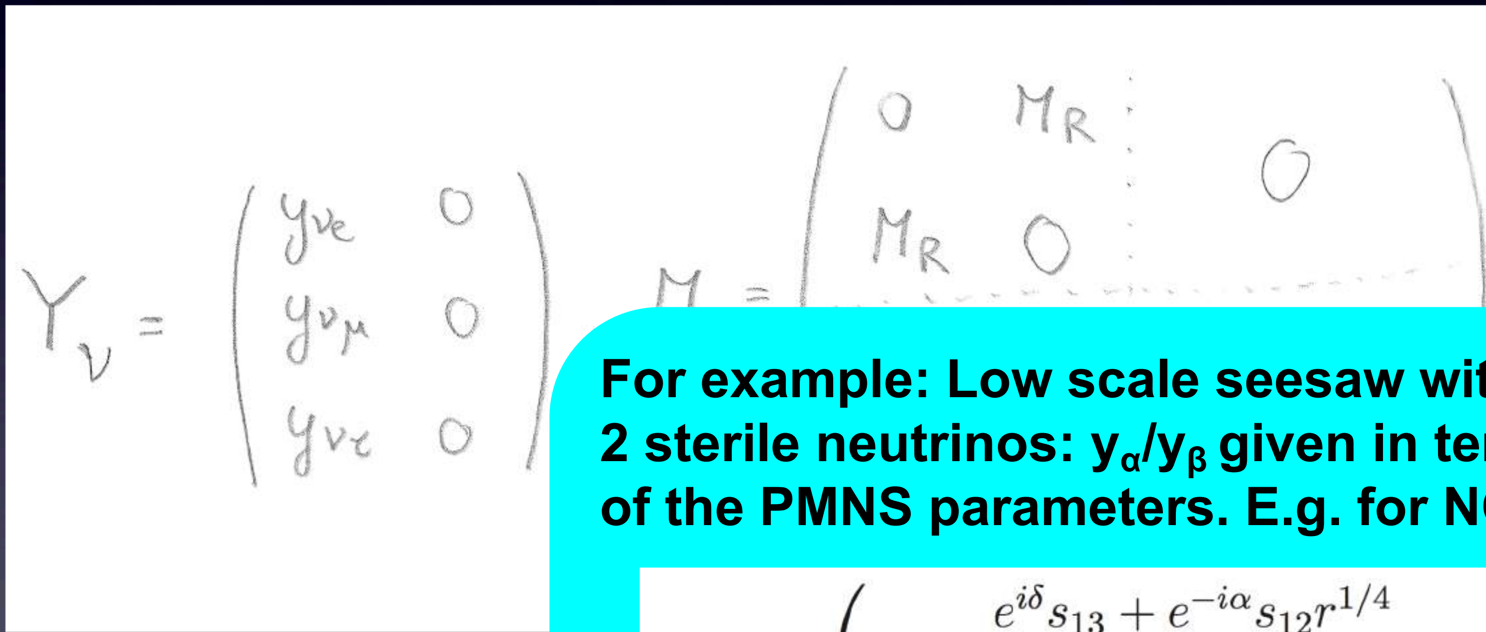
Testing specific low scale seesaw models: Examples

A benchmark model for EW scale sterile ν:

SPSS (Symmetry Prote

Note: 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 g



+ 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:* $M_\nu = \begin{pmatrix} 0 & m_D & \varepsilon_{\rm lin} \\ (m_D)^T & \tilde{\varepsilon} & M \\ \varepsilon_{\rm lin}^T & M & \varepsilon_{\rm inv} \end{pmatrix}$

$\varepsilon_{\rm lin}$ linear seesaw

$\varepsilon_{\rm inv}$ inverse seesaw

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

Perturbations $O(\varepsilon)$ 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**):

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

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

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

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

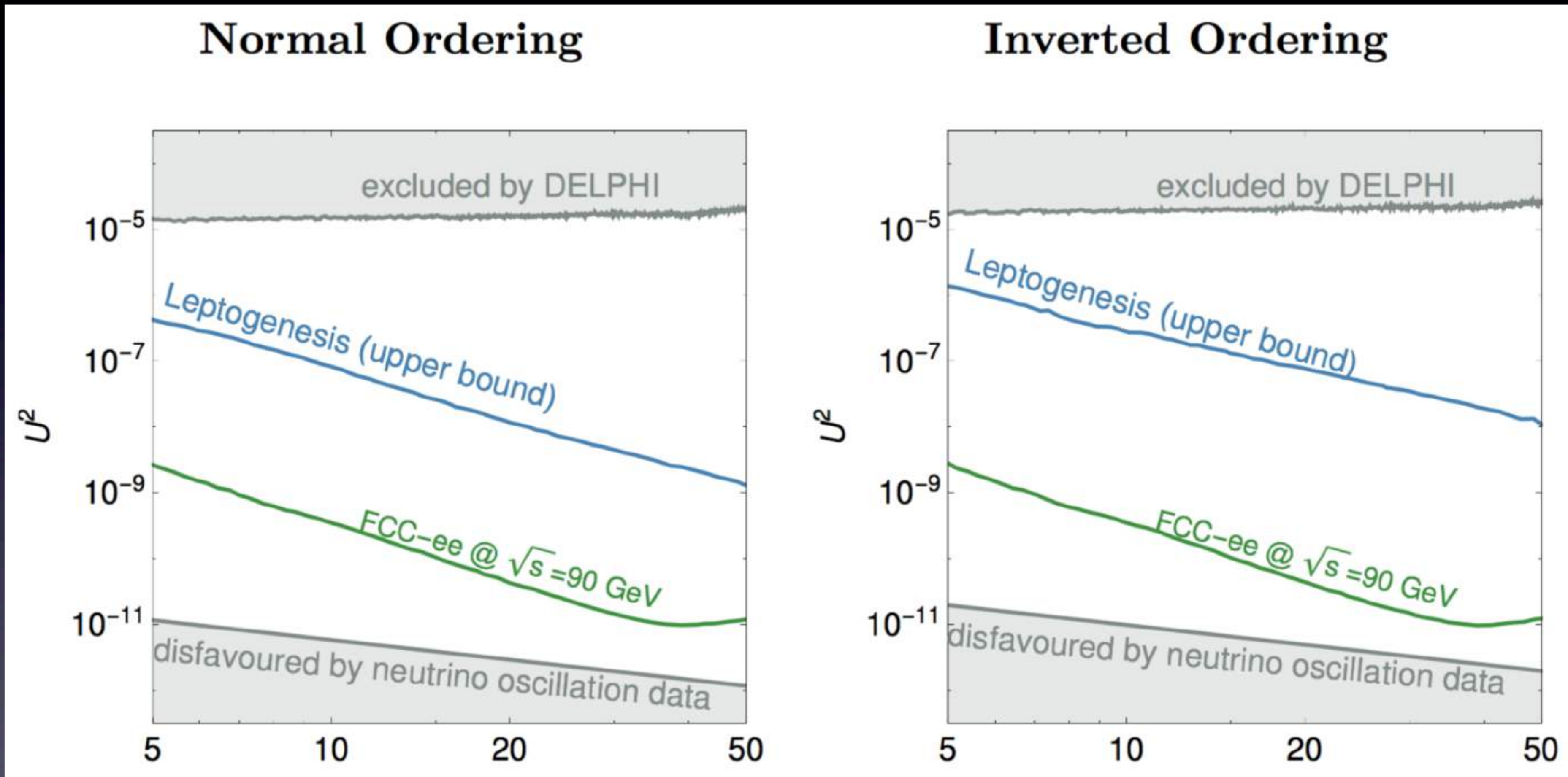
Cf.: S.A., E. Cazzato, O. Fischer (arXiv:1709.03797)

... more about this later in my talk!

Towards probing leptogenesis at Future Colliders

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

Here: only 2 RH neutrinos assumed!



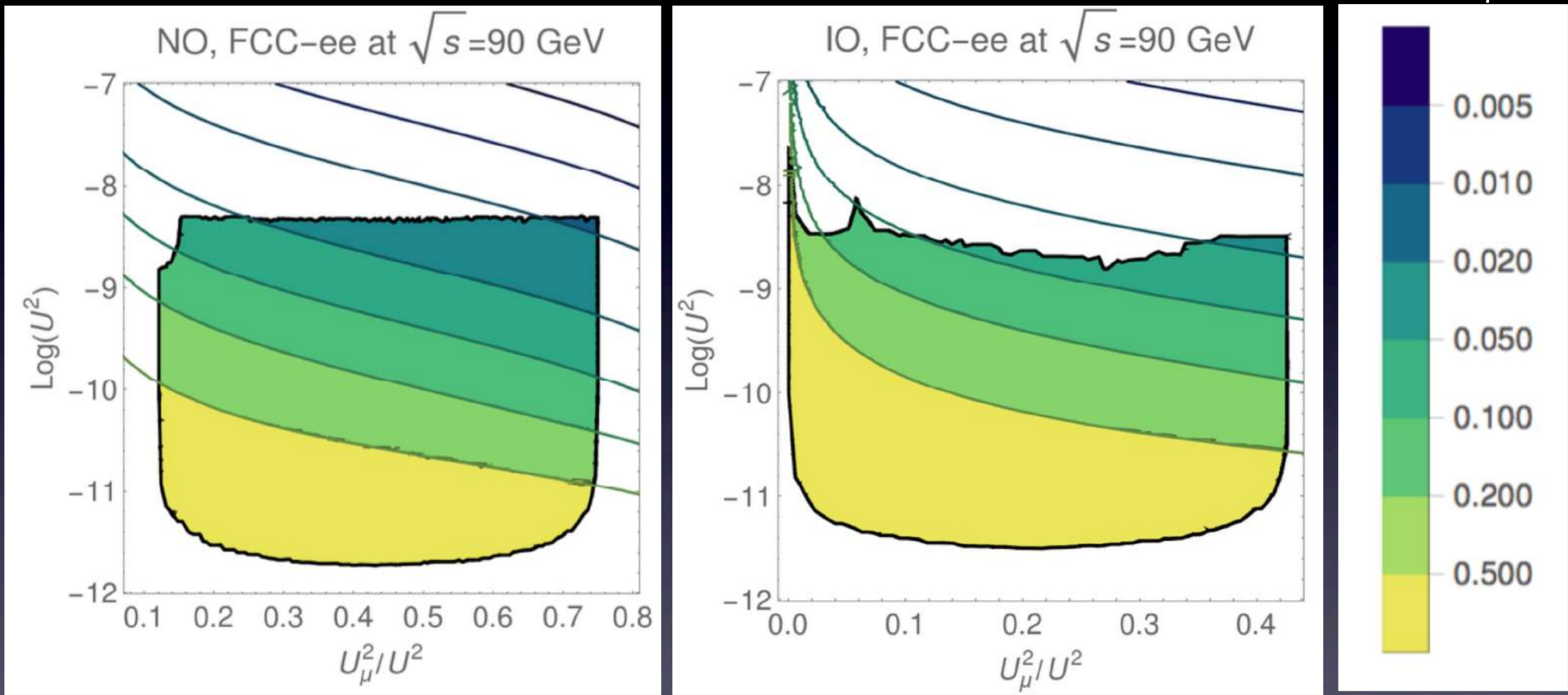
[GeV]

With: $\mathbf{U^2 = |\theta|^2}$

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

Precision for measuring the flavour-dependent active-sterile mixing angles

Precision for U_μ^2 / U^2



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)

With: **$U^2 = |\theta|^2$ and for example $U_\mu^2 = |\theta_\mu|^2$**

Sensitivity estimates for signatures of sterile neutrinos at pp and ep colliders

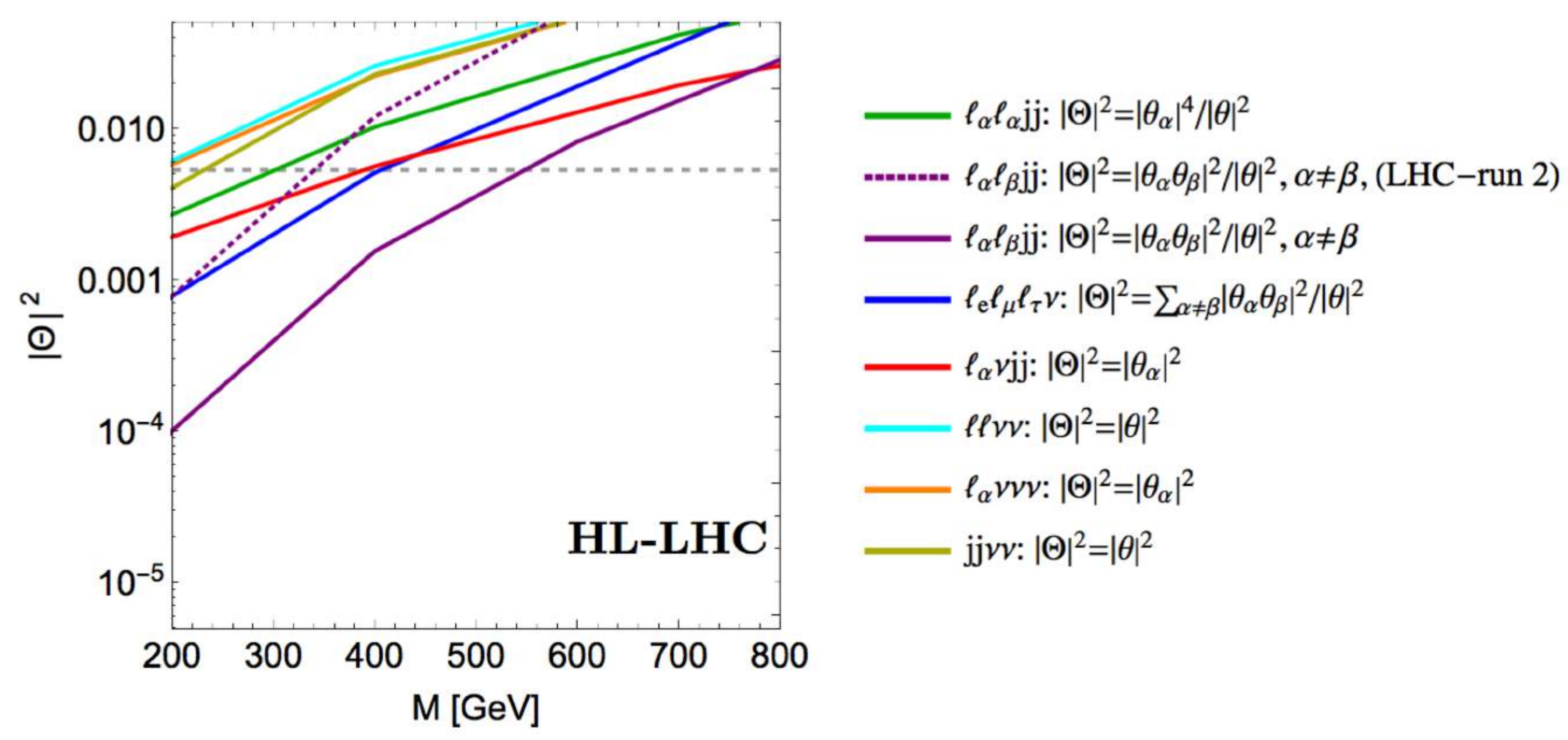
Sterile neutrino signatures at pp colliders

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.

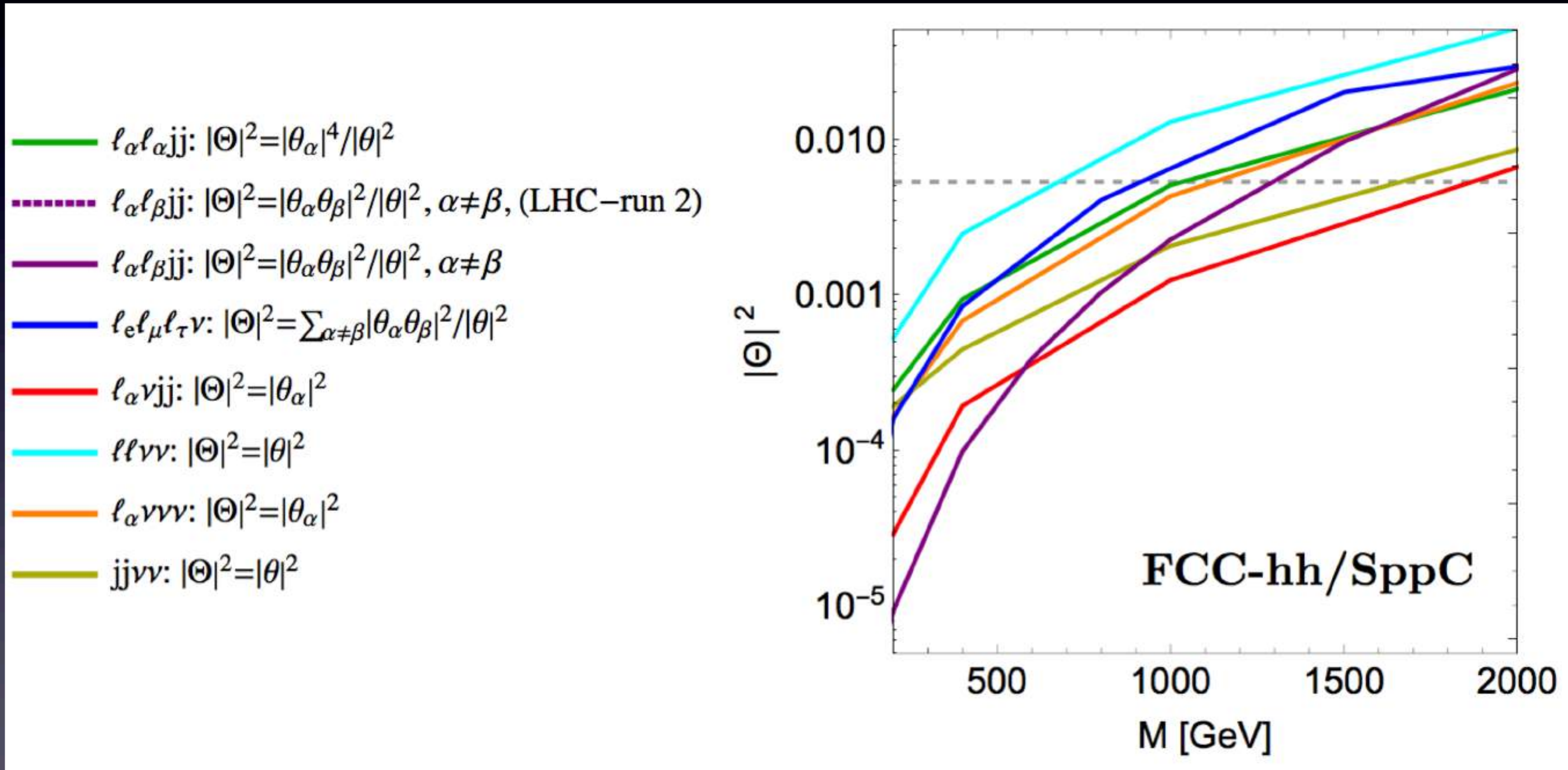
S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

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)

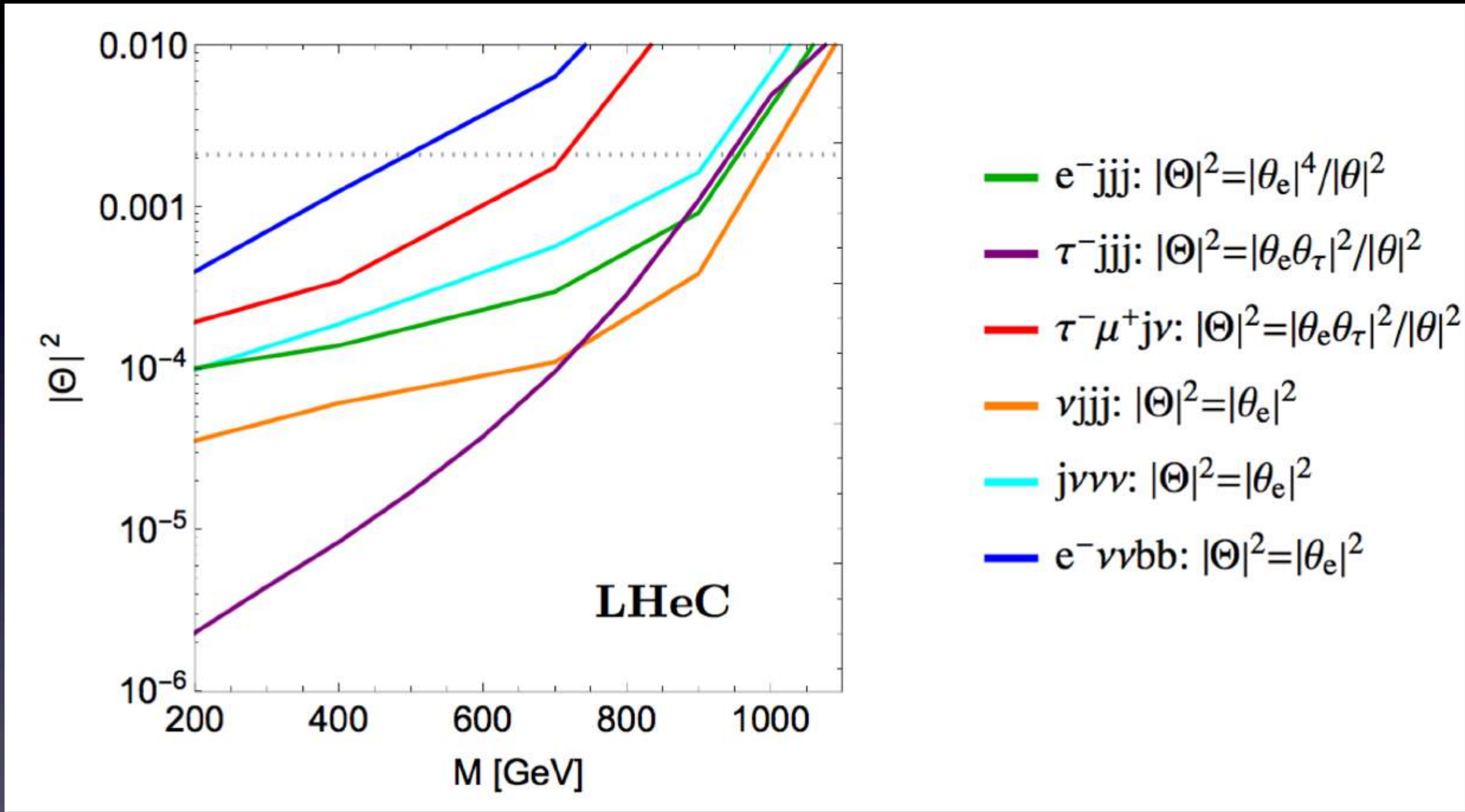
Sterile neutrino signatures at e⁻p colliders

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

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

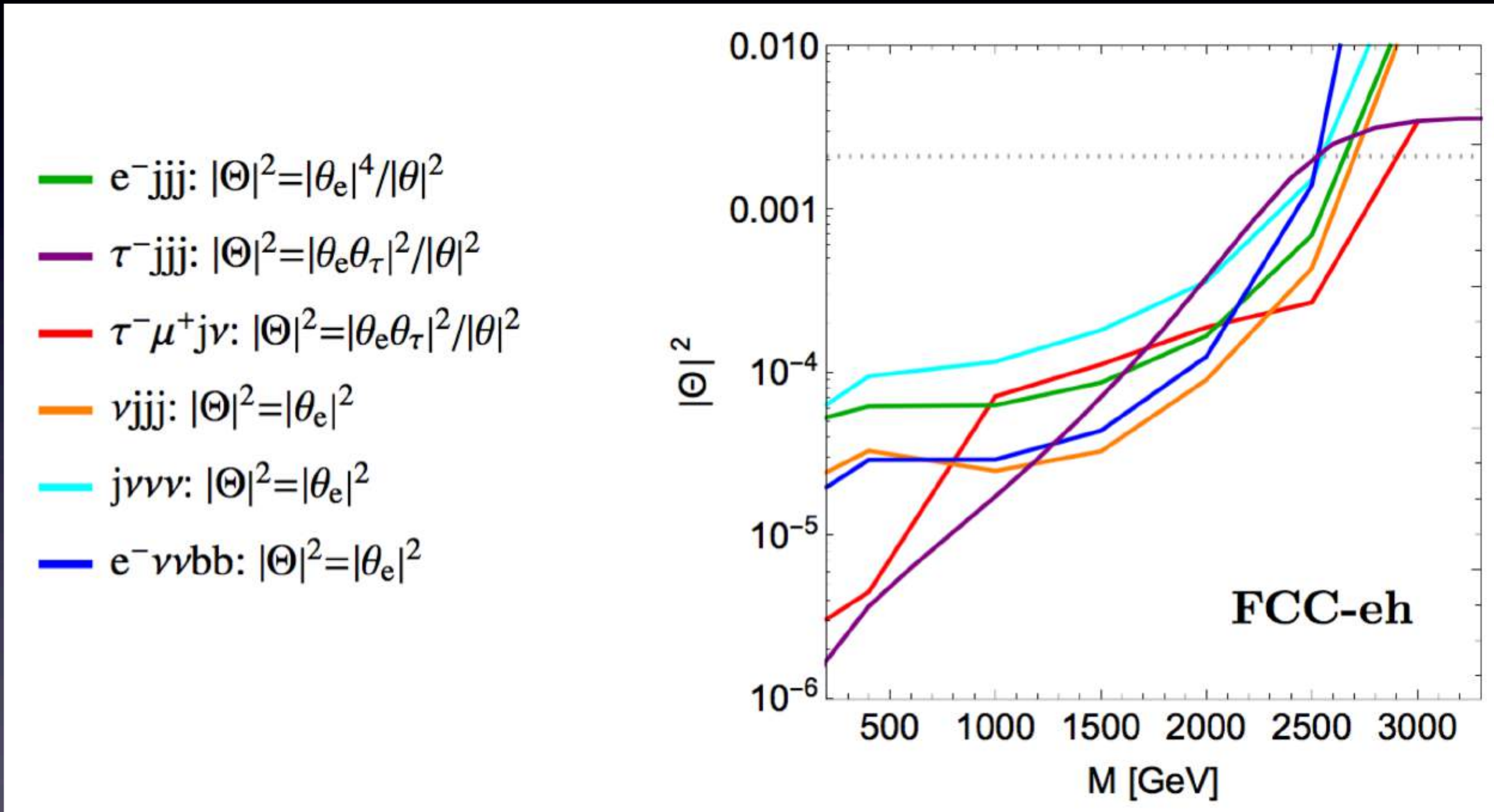
Table 5: Signatures of sterile neutrinos at leading order for e^-p colliders with their corresponding final states, production and decay channels (cf. section 2.2), and their dependency on the active-sterile mixing parameters. A checkmark in the "LNV/LFV" column indicates that an unambiguous signal for 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 for sterile neutrinos at 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.

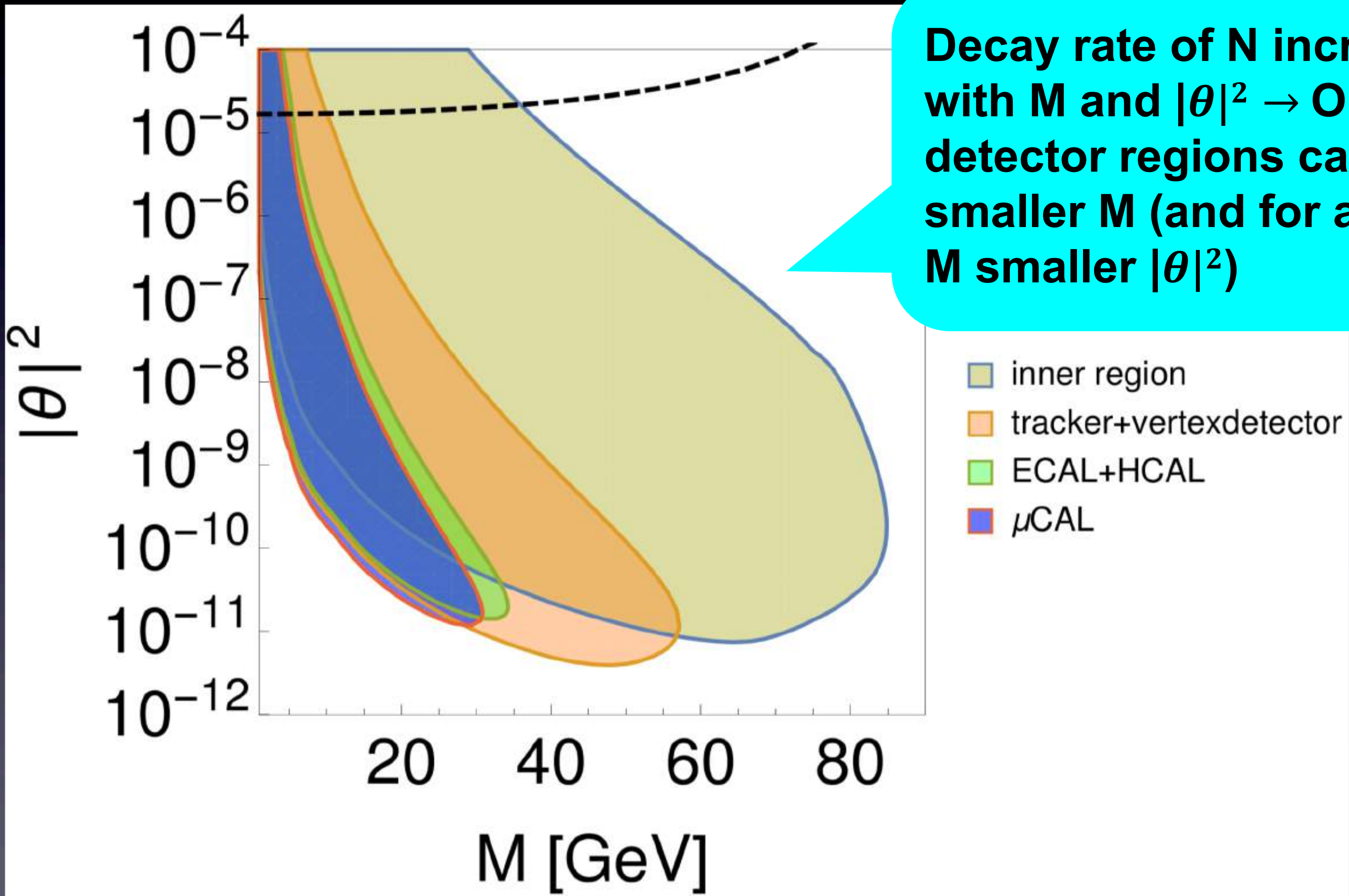
D_{xN}: Probability distribution for for the decay to occur within a certain detector part.

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

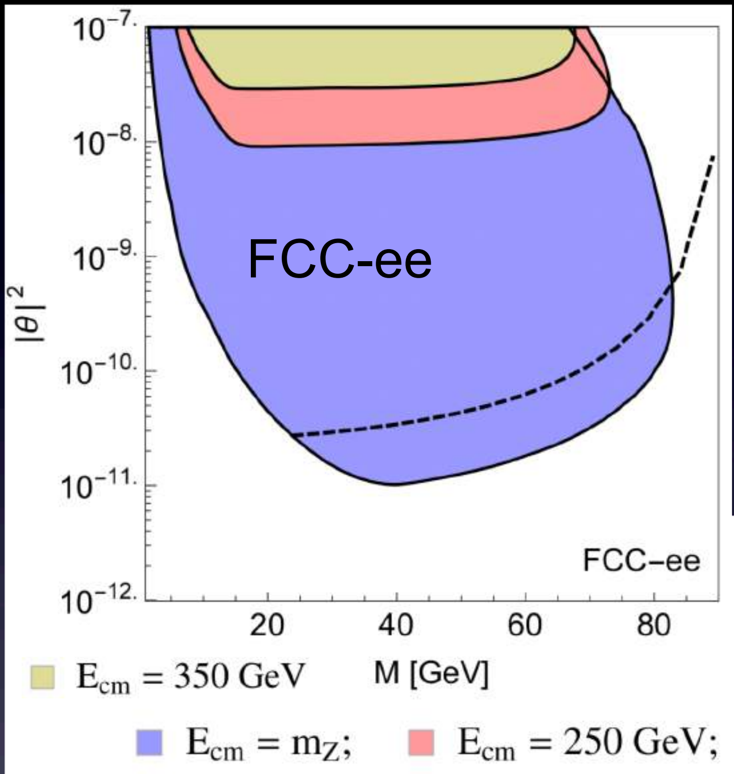
Example: FCC-ee, Z pole run, SiD-like detector



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

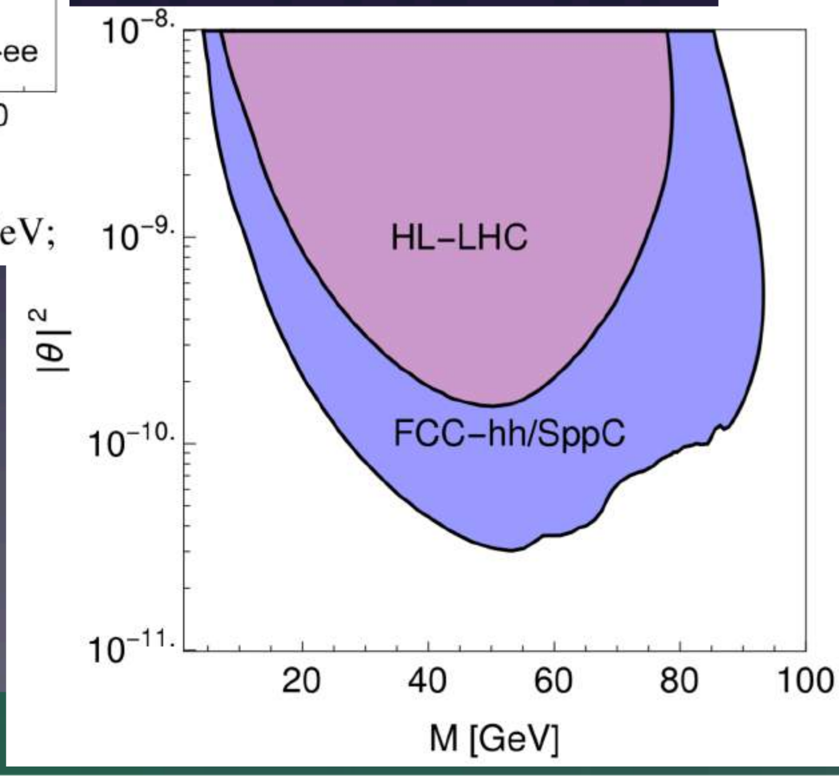
Estimated/"first look" sensitivities via displaced vertices at FCC-ee, -hh and -eh

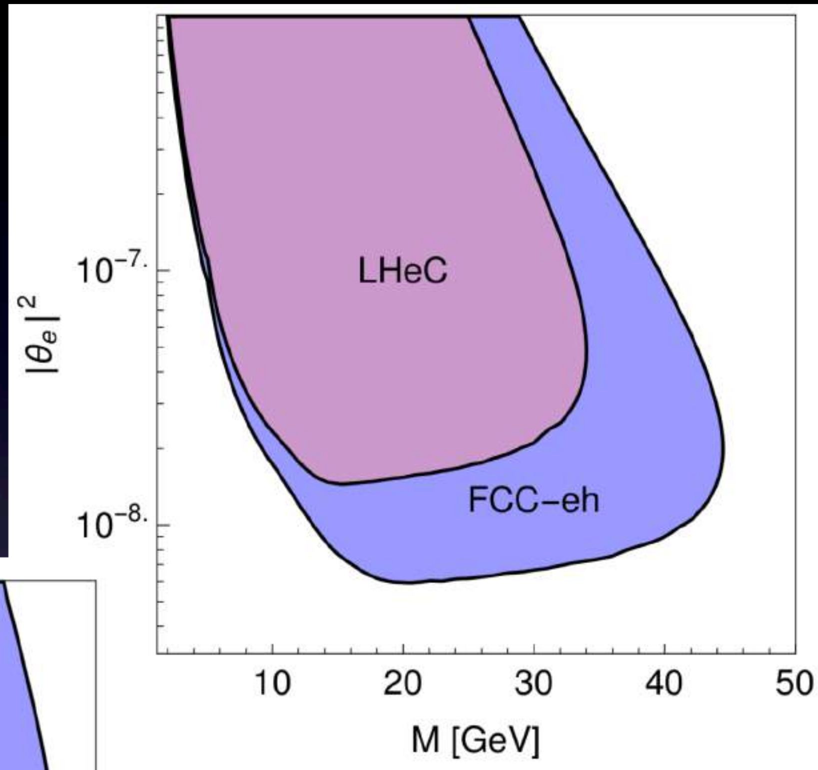


Estimate for FCC-ee [using SiD-like detector, L = 110 ab^{-1} at the Z pole]:
S.A., E. Cazzato, O. Fischer (arXiv:1604.02420)
See also:
Blondel, Graverini, Serra, Shaposhnikov (FCC study team, 2014)

"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]



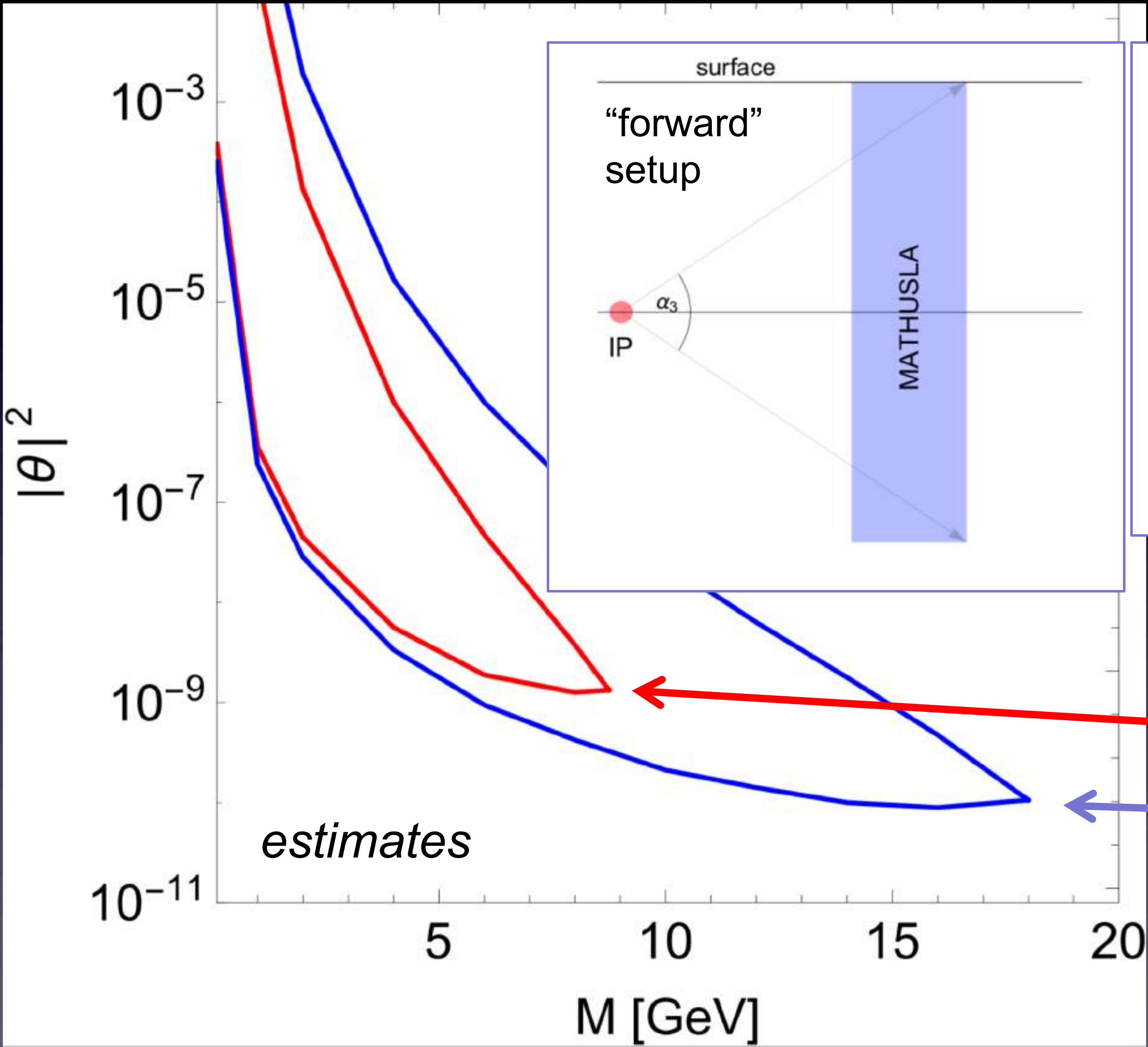


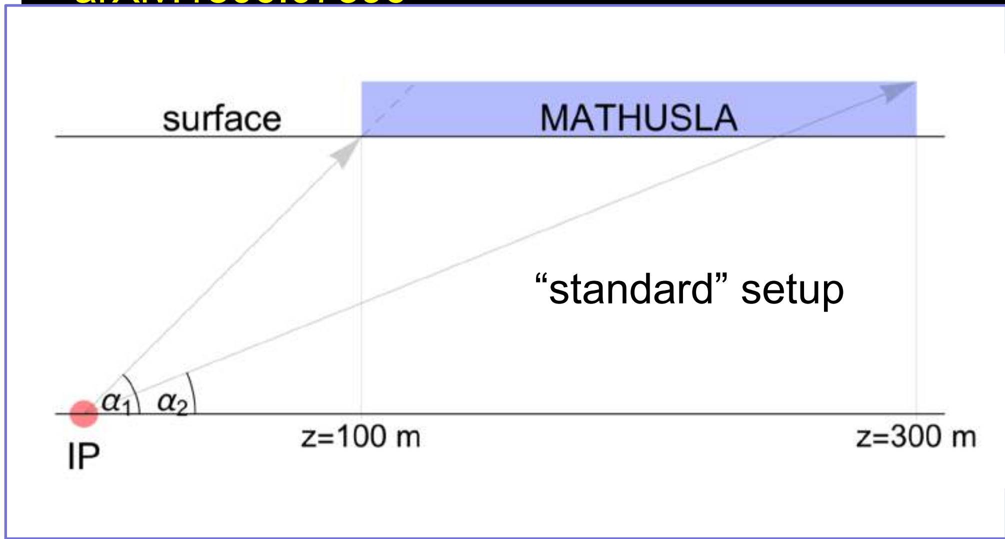
"First look" result for FCC-eh:
S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

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

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).