The search for sterile neutrinos at high-energy colliders

Oliver Fischer

UNI BASEL

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based on:
Basso, OF, van der Bij [1310.2057]
Antusch, OF [1407.6607], [1502.05915]
Antusch, Cazzato, OF [1512.06035], [1604.00208], [1604.02420], [1612.02728]

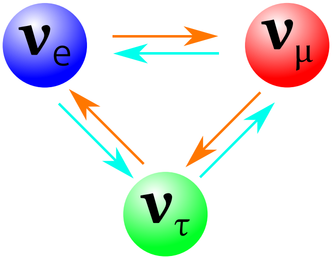
& work in progress

Outline

1) Motivating sterile neutrinos
2) Future particle colliders
3) Collider phenomenology (of sterile neutrinos)

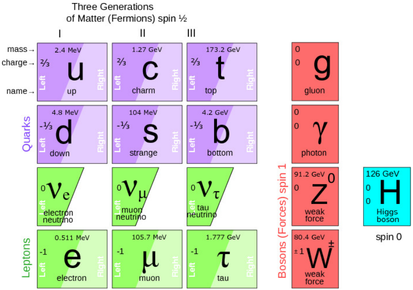
Part 1:
Motivating sterile neutrinos

Neutrino oscillations, theoretical perspective



- Mass eigenstates: linear combination of flavour eigenstates.
- Transformation between the two bases via unitary matrices.
- Oscillations allow to infer mixing angles, phases.
- In practice this is not very easy and requires dedicated experiments.

Neutrino oscillations & the Standard Model

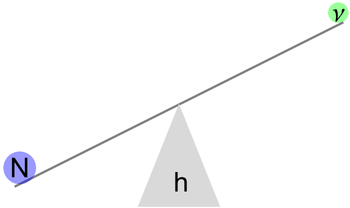


courtsy M. Shaposhnikov

- No right-handed neutrinos in the Standard Model (SM).
- No mass matrix, no mixing of the neutrino flavour states.

⇒ Neutrino oscillations are evidence of physics beyond the SM.

The Seesaw mechanism with right-handed neutrinos



- Elegant and economic: a number of Fermionic singlets, speak: "Right-handed" or "sterile" neutrinos.
- Two mass-differences ⇒ *at least* two sterile neutrinos.
- New mass scale, a priori unrelated to the known ones.
- Many constraints from experiments on all energy scales.
- May be connected to e.g. Dark Matter and Baryogenesis.

The "naïve" type I seesaw

- The simplified version: $(1\ \nu_L,\ 1\ \nu_R)$
  - ⋆ Mass matrix $\sim \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$, with $m = y_\nu v_{\rm EW} \ll M$.
  - ⋆ Light neutrino mass: $m_\nu = \frac{1}{2}\frac{v_{\rm EW}^2 |y_\nu|^2}{M_R}$.
- More realistic case: $(2\ \nu_L,\ 2\ \nu_R)$

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ 0 & \mathcal{O}(y_\nu) \end{pmatrix}, \qquad \begin{pmatrix} M_R & 0 \\ 0 & M_R(1+\varepsilon) \end{pmatrix}$$

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

$\Rightarrow$ The m_{ν_i} fix a relation between y_ν and M_R.

The effect of protective symmetries

- Specific structures of the Yukawa and mass matrices can be realised by symmetries (no fine tuning).
- A $(2\ \nu_L,\ 2\ \nu_R)$ example:

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

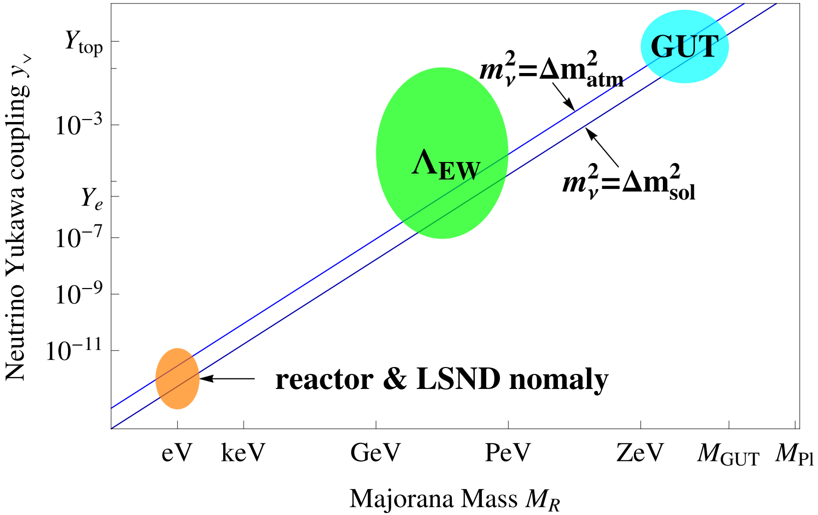
$$\Rightarrow m_{\nu_i} = 0 + \varepsilon \frac{v_{\rm EW}^2 \mathcal{O}(y_\nu^2)}{M_R^2}$$

- "Symmetry violating" parameter ε controls magnitude of m_{ν_i}.

$\Rightarrow$ No fixed relation between y_ν, M_R and m_{ν_i}.

$\Rightarrow$ Large y_ν can be compatible with neutrino oscillations if $\varepsilon \sim 0$.

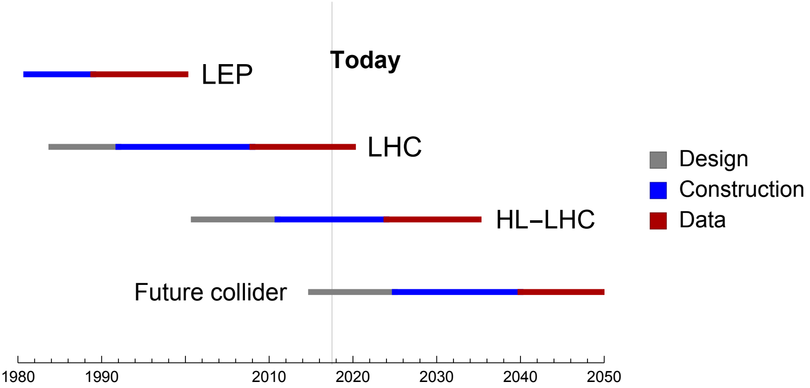
The Big Picture



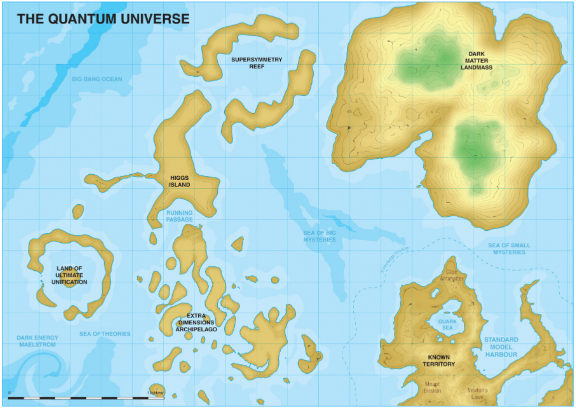
Part 2:
Future particle colliders

Why now?

The LHC just achieved the record energy of 13 TeV.



Why at all?


THE QUANTUM UNIVERSE
SUPERSYMMETRY REEF
DARK MATTER LANDMASS
BIG BANG OCEAN
HIGGS ISLAND
RUNNING PASSAGE
SEA OF BIG MYSTERIES
SEA OF SMALL MYSTERIES
LAND OF ULTIMATE UNIFICATION
EXTRA DIMENSIONS ARCHIPELAGO
DARK ENERGY MAELSTROM
SEA OF THEORIES
QUARK SEA
STANDARD MODEL HARBOUR
KNOWN TERRITORY
Mount Einstein
Newton's Lawn

* RIP F(750) - the diphoton resonance at 750 GeV.

Motivation* from the LHC?

- There is no sign of new physics at the LHC up to date.

$\Rightarrow$ Ask carefully: Why?

- Pessimistic answer not to be discussed here.
- Optimistic answer: New physics exists, but it ...
  - ... is covered in SM backgrounds.
  - ... interacts very weakly.
  - ... is too heavy to have been produced.

What can we do to improve the prospects of a discovery?
Lessons from the past:

- Lepton colliders: very precise but low energy reach.
- Hadron colliders: high energy reach but limited precision.
- LEP & LHC share the same tunnel $\Rightarrow$ **collider package**.

$\Rightarrow$ Complementarity!

Where, who, and what?

⋆ CERN: existing infrastructure and know-how.

- High-Luminosity Large Hadron Collider (HL-LHC)
- Large Hadron-electron Collider (LHeC) ⟸ Ask about this
- Future **Circular** Collider project (FCC-ee, FCC-hh, FCC-eh, includes also the HE-LHC)
- Compact **LInear** Collider (CLIC)

⋆ Japan: Strong support from Asia, America, and DESY

- International **Linear** Collider (ILC)
  Completed technical design reports (TDR)

⋆ China: expertise in civil engineering & accelerators

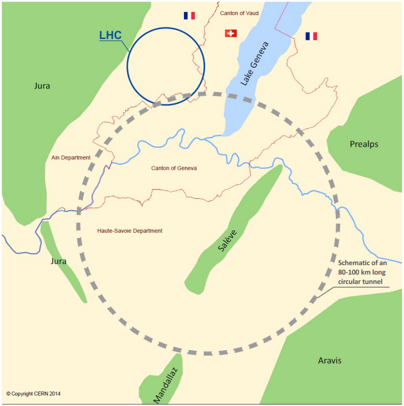
- **Circular** Electron-Positron Collider
- Super Proton-Proton Collider
- Electron-proton option

European strategy update 2013

Aimed at CERN, but also influencing China and Japan

"CERN should undertake design studies for accelerator projects in a *global* context, with emphasis on **proton-proton** and **electron-positron** high-energy frontier machines."

- No host for CLIC!
- Use of existing infrastructure (LHC→ booster).
- First step: lepton colliders
- Focus on the hadron colliders.
- Consider lepton-hadron mode.
- Geological constraints.

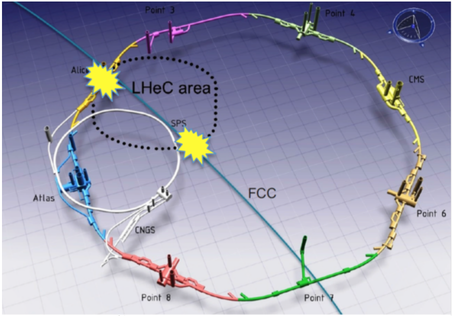


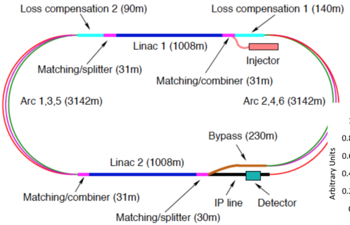
Next update planned 2018/2019.

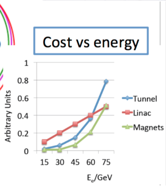
A story in pictures

The LHC upgrade with an electron beam: the LHeC

The same complex may be used for the FCC-eh.

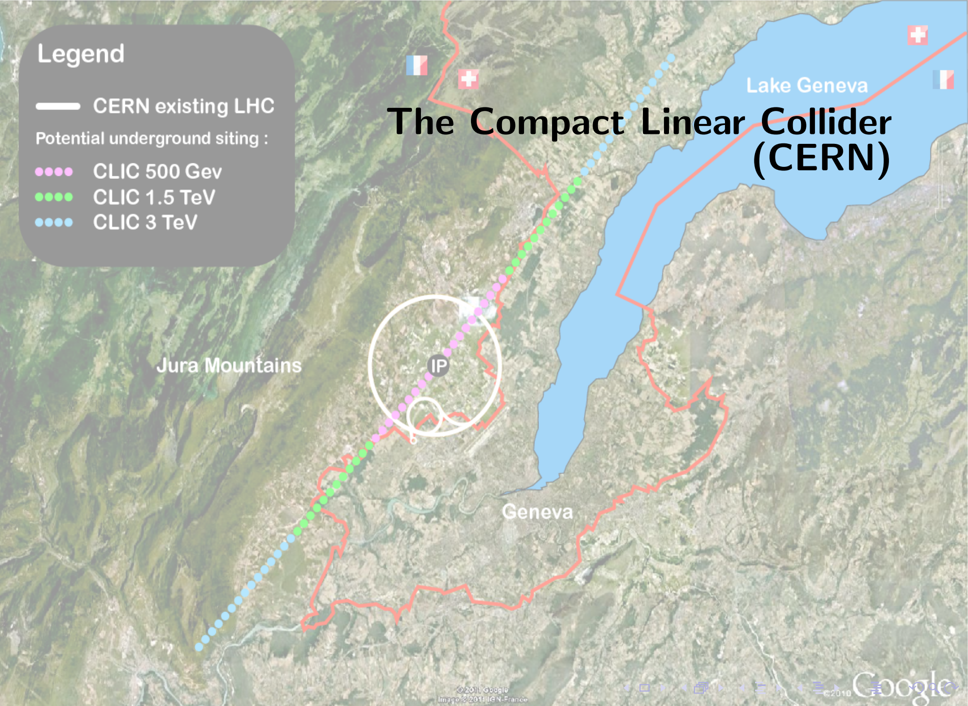




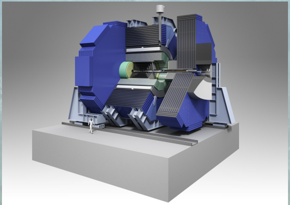


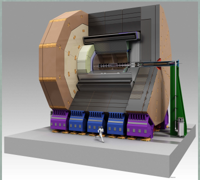
The Future Circular Collider project (CERN)

The Compact Linear Collider (CERN)



The International Linear Collider (Japan)

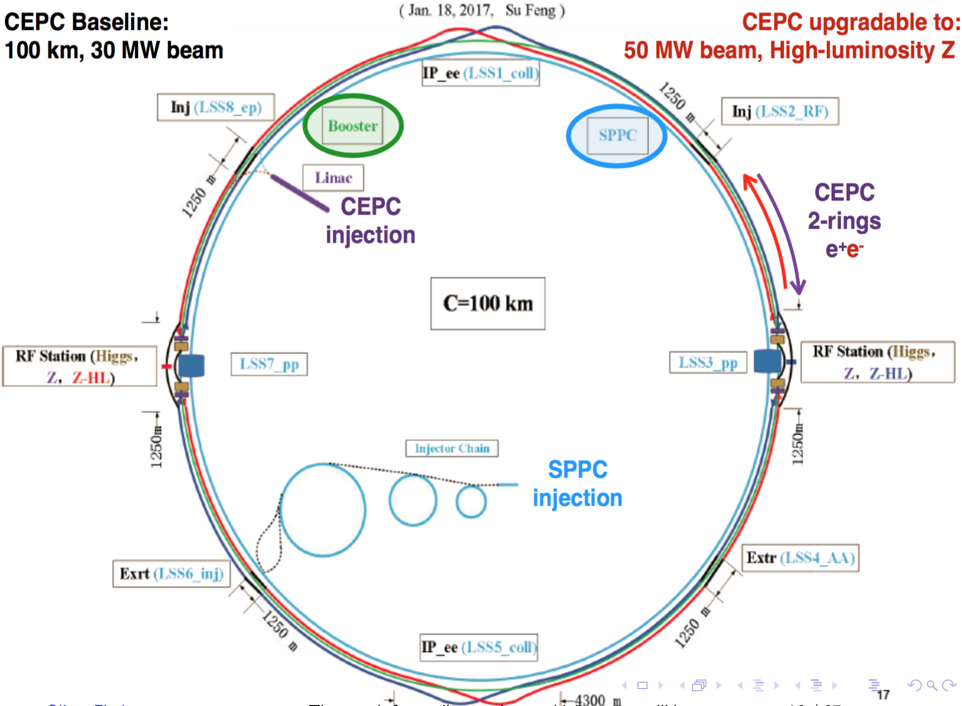




- Candidate site announced 2013.
- Planned length: 30 km.
- Higher beam energy
  ⇔ longer tunnel.
- Cost: 7.8 billion "Dollars" and
  23 million person hours.

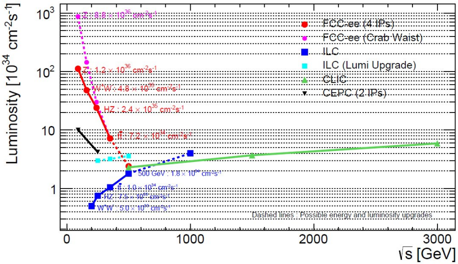
CEPC Baseline:
100 km, 30 MW beam

CEPC upgradable to:
50 MW beam, High-luminosity Z



Comparing the future colliders

- Electron-positron:
  - Center-of-mass energy limited
  - Large luminosity at $\sqrt{s} \sim m_Z$



- Hadron colliders:
  - Luminosity limited to 10^{34} cm^{-2}s^{-1} (pileup).
  - Center-of-mass energies of up to 100 TeV.
  - Large number of QCD background.
- Electron-Proton colliders:
  - Electron beams with 60 GeV, polarisation possible (baseline).
  - Center-of-mass energy $\sim$ 1 TeV (LHeC), $\sim$ 3.5 TeV (FCC-eh).
  - 100 fb^{-1} per year.

Part 3:

High-energy phenomenology (of sterile neutrinos)

Symmetry Protected Seesaw Scenario

Benchmark model, defined in Antusch, OF; JHEP **1505** (2015) 053

Similar to e.g.: Mohapatra, Valle (1986); Malinsky, Romao Valle (2005); Shaposhnikov (2007);

- Collider phenomenology dominated by two sterile neutrinos N_i with protective symmetry, such that

$$\mathscr{L}_N = -\frac{1}{2}\overline{N_R^1} M (N_R^2)^c - y_{\nu_\alpha}\overline{N_R^1}\widetilde{\phi}^\dagger L^\alpha + \mathrm{H.c.}$$

- Further "decoupled" sterile neutrinos included.
- The mass matrix:

$$\mathcal{M}_{\nu n} = -\frac{1}{2}\begin{pmatrix} 0 & \frac{y_{\nu_\alpha} v_{\mathrm{EW}}}{\sqrt{s}} & 0 \\ \frac{y_{\nu_\alpha} v_{\mathrm{EW}}}{\sqrt{s}} & 0 & M \\ 0 & M & 0 \end{pmatrix} + \text{ H.c.}$$

Neutrino mixing

- Active-sterile mixing: $\theta_\alpha = y_{\nu_\alpha} \frac{v_{\rm EW}}{\sqrt{2}M}$, $\theta^2 \equiv \sum_\alpha |\theta_\alpha|^2$
- The leptonic mixing matrix to leading order in θ_α:

$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu 1} & \mathcal{N}_{\mu 2} & \mathcal{N}_{\mu 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau 1} & \mathcal{N}_{\tau 2} & \mathcal{N}_{\tau 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{\mathrm{i}}{\sqrt{2}}\left(1 - \frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1 - \frac{\theta^2}{2}\right) \end{pmatrix}$$

- $\mathcal{N} \sim$ PMNS as submatrix in general **not** unitary ($\mathcal{N}\mathcal{N}^\dagger \neq \mathbb{1}$).
- Modification of the weak currents with light neutrinos:

$$\left(J^{\mu,\pm}\right)_{\alpha i} = \ell_\alpha \gamma^\mu \nu_i \, \mathcal{N}_{\alpha i} \,, \qquad \left(J^{\mu,0}\right)_{ij} = \nu_i \gamma^\mu \nu_j \, \left(\mathcal{N}^\dagger \mathcal{N}\right)_{ij}$$

Heavy neutrino interactions

- **Charged current** (CC):

$$j_\mu^{\pm} = \frac{g}{2}\,\theta_\alpha\,\bar{\ell}_\alpha\,\gamma_\mu\,(-\mathrm{i}N_1 + N_2)$$

- **Neutral current** (NC):

$$j_\mu^{0} = \frac{g}{2\,c_W}\left[\theta^2\,\bar{N}_2\gamma_\mu\,N_2\; + (\bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 1}\,N_1 + \bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 2}\,N_2\; + \;\text{H.c})\right]$$

- Higgs boson **Yukawa** interaction:

$$\mathscr{L}_{\text{Yukawa}} = \sum_{i=1}^{3}\xi_{\alpha 2}\frac{\sqrt{2}\,M}{v_{\text{EW}}}\nu_i\phi^0\left(\overline{N}_1 + \overline{N}_2\right)$$

- With the mixing parameters: $\xi_{\alpha 1} = (-\mathrm{i})\,\mathcal{N}^*_{\alpha\beta}\frac{\theta_\beta}{\sqrt{2}}$, $\xi_{\alpha 2} = \mathrm{i}\,\xi_{\alpha 1}$

Constraints on PMNS non-unitarity from precision data

- Analysis of non-unitarity of the PMNS matrix.
- 34 precision observables:
  Electroweak Precision Observables (EWPO), lepton universality, charged lepton flavour violation, CKM unitarity
- Highest posterior density intervals at 90% Bayesian C.L.:

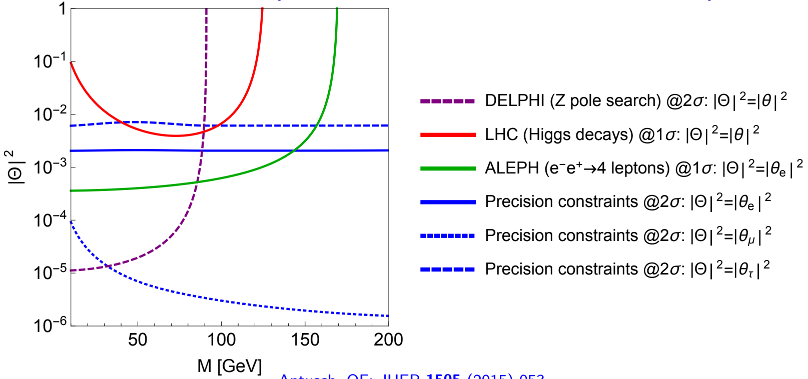
-0.0021	$\leq \varepsilon_{ee} \leq$	-0.0002		$\lvert\varepsilon_{e\mu}\rvert$	$<$	1.0×10^{-5}
-0.0004	$\leq \varepsilon_{\mu\mu} \leq$	0		$\lvert\varepsilon_{e\tau}\rvert$	$<$	2.1×10^{-3}
-0.0053	$\leq \varepsilon_{\tau\tau} \leq$	0		$\lvert\varepsilon_{\mu\tau}\rvert$	$<$	8.0×10^{-4}

Antusch, OF; JHEP 1410 (2014) 094

⋆ Non-unitarity parameters: $\varepsilon_{\alpha\alpha} = -\theta^*_\alpha \theta_\alpha$.

⋆ Weak statistical preference for non-zero mixing for ε_{ee}.

Present Constraints (dominated by LEP & MEG)



Antusch, OF; JHEP **1505** (2015) 053

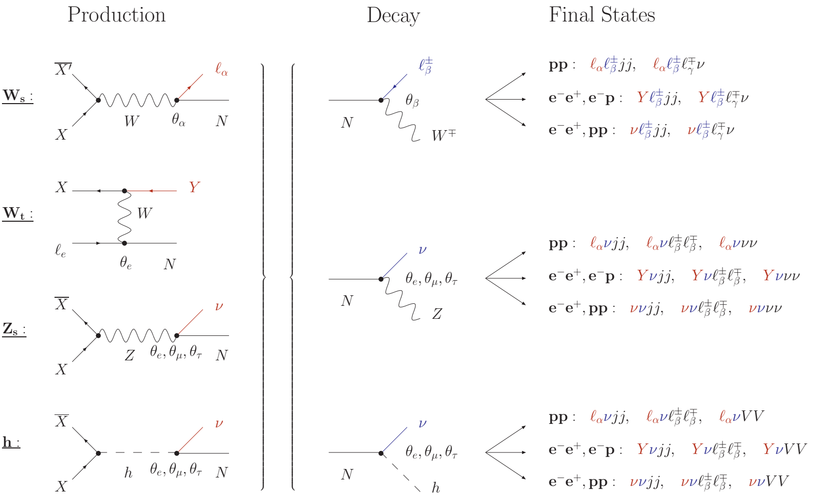
- Z pole search: limits from Z branching ratios .

  Abreu *et al.* Z.Phys. C74 (1997) 57-71

- Higgs decays: Best constraints from $h \to \gamma\gamma$.
- Direct Search: $\delta\sigma_{\rm SM}^{WW} = 0.011_{stat} + 0.007_{syst}$

  OPAL collaboration, Abbiendi **et al.** (2007)

Collider signatures of sterile neutrinos at leading order



Antusch, Cazzato, OF, (2016); [1612.02728]

Promising signatures at lepton colliders

⋆ **Comment on the violation of lepton number:**

- Large unsuppressed backgrounds at parton level.

⋆ **Displaced vertices**

- For $M < m_W$ the heavy neutrinos may be long lived.
- Secondary vertex with visible displacement.

⋆ **Indirect searches via EWPO:**

- The mixing matrix of the three active neutrinos is non-unitary.
- Modification of the theory prediction of precision observables.

⋆ **Indirect searches via Higgs boson properties:**

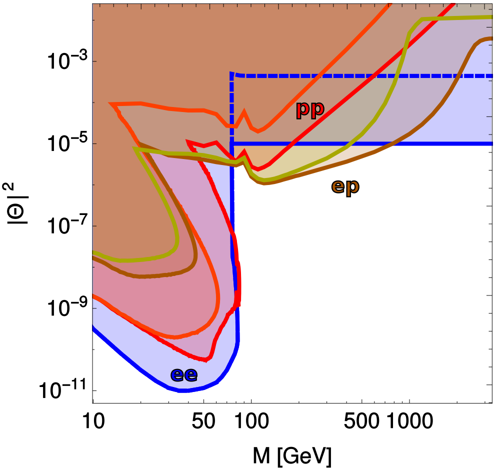
- Production at high energies (mono-Higgs).
- New decay channel $\Rightarrow$ modified branching ratios.

Promising signatures at colliders with proton beams

- Unambiguous **lepton-number-violating** signatures:
  - ⋆ Proton-proton: same-sign dileptons, e.g. $\mu^\pm\mu^\pm jj$
  - ⋆ Electron-proton: positrons, e.g. $e^+ jjj$
  - ⋆ Both: strongly suppressed by m_ν
- Unambiguous **lepton-flavour-violating** final states
  - ⋆ Proton-proton: $\ell_\alpha^\pm \ell_\beta^\mp jj$, and $\ell_\alpha^\pm \ell_\beta^\mp \ell_\gamma^\pm$.
  - ⋆ Electron-proton: $\mu^- jjj$ and $\tau^- jjj$.
- Missing P_t to separate signal from background with same final state plus additional neutrinos.

Overview of the estimated sensitivities

At one-sigma confidence level.



Antusch, Cazzato, OF, (2016); [1612.02728]

The combination of *ee* with *pp* and *ep* colliders provides complementary tests for symmetry protected sterile neutrinos.

Conclusions

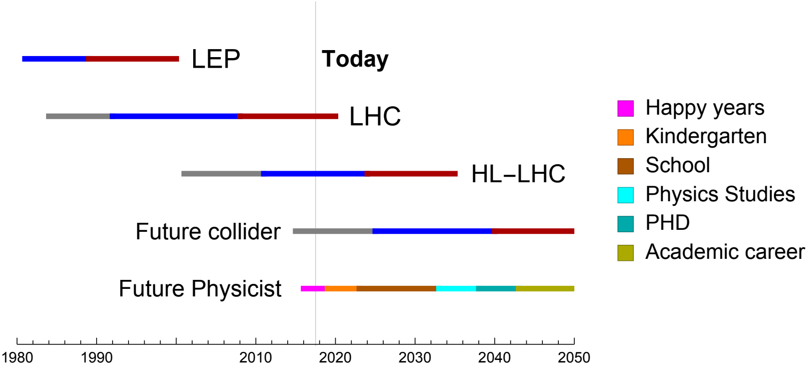
Conclusions

- Sterile neutrinos are well motivated extensions of the SM.
- Symmetry protected seesaw scenarios allow for electroweak scale sterile neutrino masses and $\mathcal{O}(1)$ active-sterile mixings.
- Present constraints: active-sterile mixing $|\theta|^2 \leq 10^{-3}$.
- Lepton-flavour-violation entails **great prospects** at *pp* and *ep* colliders.
- Electron-positron colliders powerful via precision observables.
- Displaced vertex searches promising at all colliders.
- If HL-LHC finds no hints of sterile neutrinos:
  - ⋆ Active-sterile mixing too small (lepton collider),
  - ⋆ Masses above $\sim$ 500 GeV (ep collider).
  - ⋆ Of course, small mixing and large masses is a possibility.

Are we **convinced** we need more HEP colliders?

Thank you for your attention.

The Future of High-Energy Physics



Backup I - EWPO

Experimental results and SM predictions for the EWPO, and the modification*, to first order in the "non-unitarity" parameters $\varepsilon_{\alpha\alpha} = \theta^*_\alpha \theta_\beta$. (formulae for $M \gg m_Z$)

Prediction in MUV	SM Prediction	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)
$\left[\sigma^0_{had}\right]_{\rm SM}\,(1 - 0.25(\varepsilon_{ee} + \varepsilon_{\mu\mu}) - 0.27\varepsilon_\tau)/\text{nb}$	41.470(15)	41.541(37)
$[R_{inv}]_{\rm SM}\,(1 + 0.75(\varepsilon_{ee} + \varepsilon_{\mu\mu}) + 0.67\varepsilon_\tau)$	5.9723(10)	5.942(16)
$[M_W]_{\rm SM}(1 - 0.11(\varepsilon_{ee} + \varepsilon_{\mu\mu}))/\text{GeV}$	80.359(11)	80.385(15)
$[\Gamma_{\rm lept}]_{\rm SM}(1 - 0.59(\varepsilon_{ee} + \varepsilon_{\mu\mu}))/\text{MeV}$	83.966(12)	83.984(86)
$[(s^{\ell,\rm lep}_{W,\rm eff})^2]_{\rm SM}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	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)

* Minimal Unitarity Violation scheme: Antusch *et al.*; JHEP **0610** (2006) 084.

Backup II - lepton universality

Modification due to sterile neutrinos (formulae for $M \gg m_Z$):

$$R_{\alpha\beta} = \sqrt{\frac{(NN^\dagger)_{\alpha\alpha}}{(NN^\dagger)_{\beta\beta}}} \simeq 1 + \frac{1}{2}\left(\varepsilon_{\alpha\alpha} - \varepsilon_{\beta\beta}\right) .$$

	Process	Bound		Process	Bound
$R^\ell_{\mu e}$	$\frac{\Gamma(\tau \to \nu_\tau \mu \bar{\nu}_\mu)}{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}$	1.0018(14)	$R^\pi_{\mu e}$	$\frac{\Gamma(\pi \to \mu \bar{\nu}_\mu)}{\Gamma(\pi \to e \bar{\nu}_e)}$	1.0021(16)
$R^\ell_{\tau\mu}$	$\frac{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}{\Gamma(\mu \to \nu_\mu e \bar{\nu}_e)}$	1.0006(21)	$R^\pi_{\tau\mu}$	$\frac{\Gamma(\tau \to \nu_\tau \pi)}{\Gamma(\pi \to \mu \bar{\nu}_\mu)}$	0.9956(31)
$R^W_{e\mu}$	$\frac{\Gamma(W \to e \bar{\nu}_e)}{\Gamma(W \to \mu \bar{\nu}_\mu)}$	1.0085(93)	$R^K_{\tau\mu}$	$\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to \mu \bar{\nu}_\mu)}$	0.9852(72)
$R^W_{\tau\mu}$	$\frac{\Gamma(W \to \tau \bar{\nu}_\tau)}{\Gamma(W \to \mu \bar{\nu}_e)}$	1.032(11)	$R^K_{\tau e}$	$\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to e \bar{\nu}_e)}$	1.018(42)

Backup III - CKM unitarity constraint

Current world averages: $V_{ud} = 0.97427(15)$, $V_{ub} = 0.00351(15)$

$$|V_{ij}^{th}|^2 = |V_{ij}^{exp}|^2(1 + f^{\rm process}(\varepsilon_{\alpha\alpha}))\ ,$$
$$|V_{ud}^{th}|^2 = |V_{ud}^{exp,\beta}|^2(NN^\dagger)_{\mu\mu}\ .$$

For the kaon decay processes we have:

$$|V_{us}^{th}|^2 = |V_{us}^{exp,K\to e}|^2(NN^\dagger)_{\mu\mu}\ ,$$
$$|V_{us}^{th}|^2 = |V_{us}^{exp,K\to \mu}|^2(NN^\dagger)_{ee}\ .$$

Process	$V_{us}f_+(0)$
$K_L \to \pi e \nu$	0.2163(6)
$K_L \to \pi \mu \nu$	0.2166(6)
$K_S \to \pi e \nu$	0.2155(13)
$K^\pm \to \pi e \nu$	0.2160(11)
$K^\pm \to \pi \mu \nu$	0.2158(14)
Average	0.2163(5)

Processes involving tau leptons:

Process	$f^{\rm process}(\varepsilon)$	$\lvert V_{us}\rvert$
$\frac{B(\tau\to K\nu)}{B(\tau\to\pi\nu)}$	$\varepsilon_{\mu\mu}$	0.2262(13)
$\tau \to K\nu$	$\varepsilon_{ee} + \varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}$	0.2214(22)
$\tau \to \ell,\ \tau \to s$	$0.2\varepsilon_{ee} - 0.9\varepsilon_{\mu\mu} - 0.2\varepsilon_{\tau\tau}$	0.2173(22)

Backup IV - lepton flavour violation

- Present experimental limits at 90% C.L.:

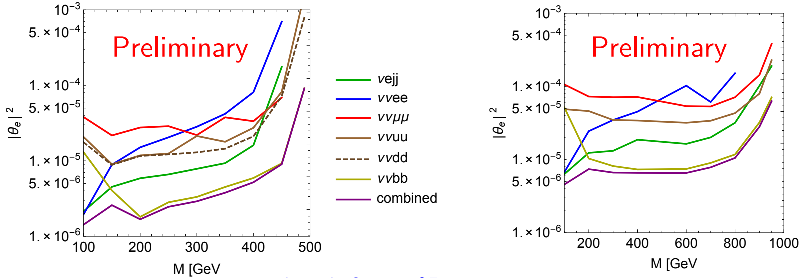
Process	MUV Prediction	Bound	Constraint on $\lvert\varepsilon_{\alpha\beta}\rvert$
$\mu \to e\gamma$	$2.4 \times 10^{-3} \lvert\varepsilon_{\mu e}\rvert^2$	5.7×10^{-13}	$\varepsilon_{\mu e} < 1.5 \times 10^{-5}$
$\tau \to e\gamma$	$4.3 \times 10^{-4} \lvert\varepsilon_{\tau e}\rvert^2$	1.5×10^{-8}	$\varepsilon_{\tau e} < 5.9 \times 10^{-3}$
$\tau \to \mu\gamma$	$4.1 \times 10^{-4} \lvert\varepsilon_{\tau \mu}\rvert^2$	1.8×10^{-8}	$\varepsilon_{\tau \mu} < 6.6 \times 10^{-3}$

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

Process	MUV Prediction	Bound	Sensitivity
$Br_{\tau e}$	$4.3 \times 10^{-4} \lvert\varepsilon_{\tau e}\rvert^2$	10^{-9}	$\varepsilon_{\tau e} \geq 1.5 \times 10^{-3}$
$Br_{\tau \mu}$	$4.1 \times 10^{-4} \lvert\varepsilon_{\tau \mu}\rvert^2$	10^{-9}	$\varepsilon_{\tau \mu} \geq 1.6 \times 10^{-3}$
$Br_{\mu eee}$	$1.8 \times 10^{-5} \lvert\varepsilon_{\mu e}\rvert^2$	10^{-16}	$\varepsilon_{\mu e} \geq 2.4 \times 10^{-6}$
$R_{\mu e}^{Ti}$	$1.5 \times 10^{-5} \lvert\varepsilon_{\mu e}\rvert^2$	2×10^{-18}	$\varepsilon_{\mu e} \geq 3.6 \times 10^{-7}$

$\Rightarrow R_{\mu e}^{Ti}$ yields a sensitivity to m_{ν_R} up to 0.3 PeV.

Backup V: ILC direct searches



Antusch, Cazzato, OF; *in preparation*

- Operation scenario G-20, with 4 ab^{-1} at $\sqrt{s} = 500$ GeV.
- Using 1 ab^{-1} at $\sqrt{s} = 1.0$ TeV.
- Displaced vertex searches possible for $M < m_W$.