Testing the origin of neutrino masses at future high-energy colliders

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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]

& work in progress

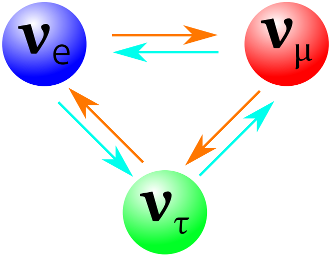
Outline

1) Neutrino masses
2) Future particle colliders
3) High-energy phenomenology (of sterile neutrinos)

Part 1:

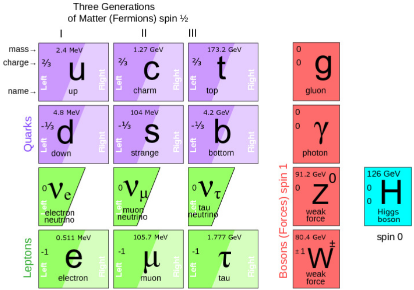
Neutrino masses

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

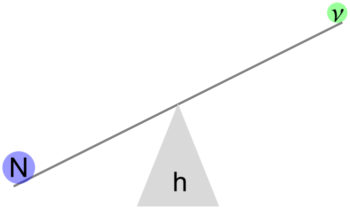


courtsy M. Shaposhnikov

- 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.

The “naïve” type I seesaw

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

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

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

$\Rightarrow$ 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:

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

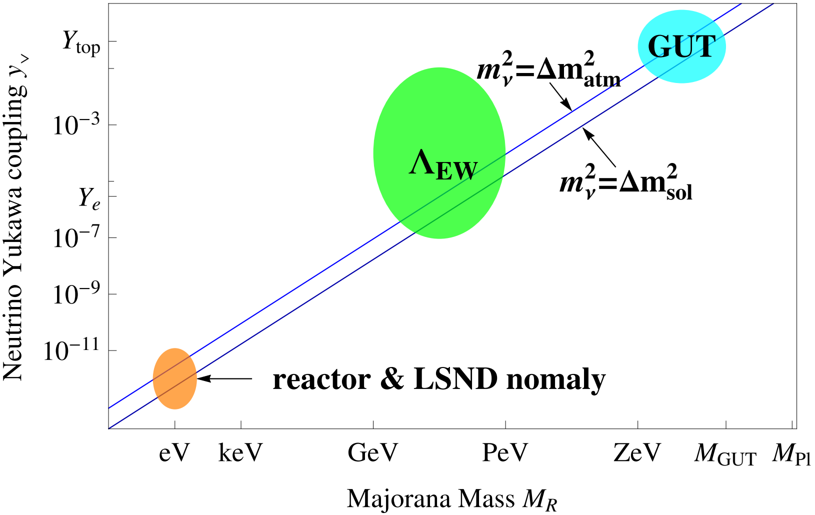
$$\Rightarrow m_{\nu_i} = 0 + \varepsilon \frac{v_{\mathrm{EW}}^2 \mathcal{O}(y_\nu^2)}{M_R^2}$$

- "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



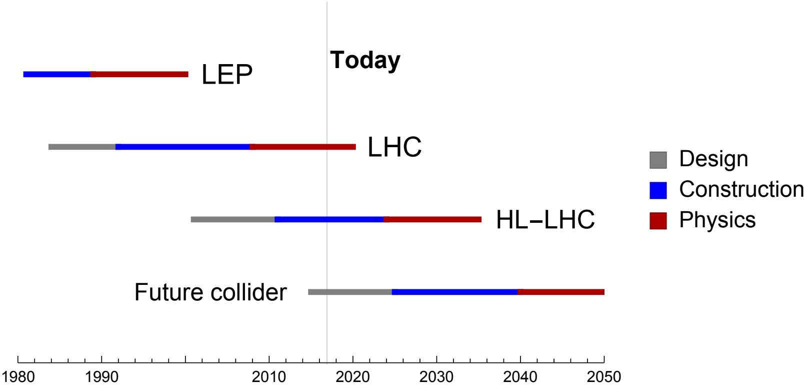
Keep in mind:

Neutrino oscillations are
evidence
for
physics **beyond the SM**
from the **laboratory**.

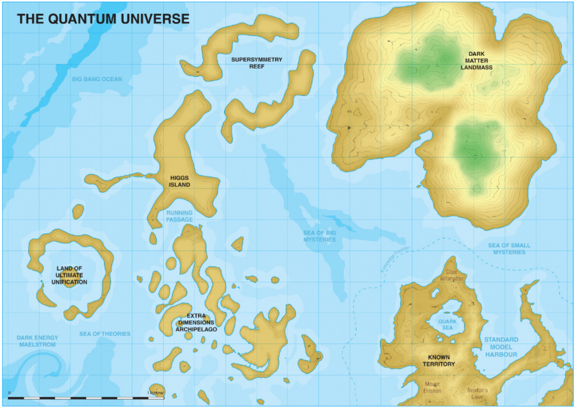
Part 2:
Future particle colliders

Why now?

We just got the LHC running smoothly.



Why at all?


THE QUANTUM UNIVERSE
BIG BANG OCEAN
SUPERSYMMETRY REEF
DARK MATTER LANDMASS
HIGGS ISLAND
RUNNING PASSAGE
SEA OF BIG MYSTERIES
SEA OF SMALL MYSTERIES
Knowledge Frontier
LAND OF ULTIMATE UNIFICATION
Cape Antimatter
QUARK SEA
EXTRA DIMENSIONS ARCHIPELAGO
STANDARD MODEL HARBOUR
DARK ENERGY MAELSTROM
SEA OF THEORIES
KNOWN TERRITORY
Mount Einstein
Newton's Lawn
0
1 lightyear

Motivation* from the LHC?

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

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

⇒ Ask carefully: Why?

- 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 ⇒ **collider package**.

⇒ Complementarity!

Where, who, and what?

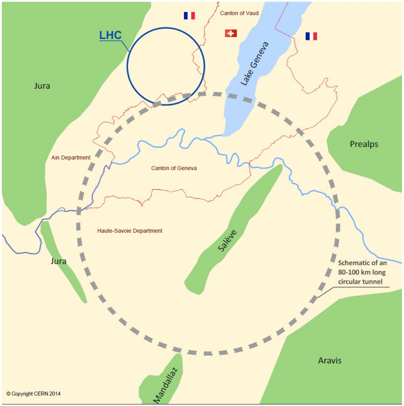
- CERN: existing infrastructure and know-how.
  - High-Luminosity Large Hadron Collider (HL-LHC).
  - Large Hadron-electron Collider (LHeC).
  - Future **Circular** Collider project (FCC-ee, FCC-hh, FCC-eh)
  - Compact **LInear** Collider (CLIC).
- Japan: Strong support from Asia, America, and DESY
  - International **Linear** Collider (ILC)
Completed technical design reports (TDR).
- China: expertise in civil engineering & accelerators
  - **Circular** Electron-Positron Collider
  - Super Proton-Proton Collider

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.

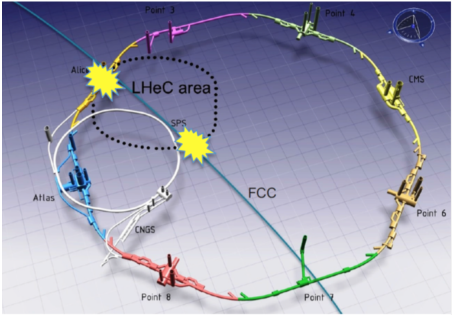


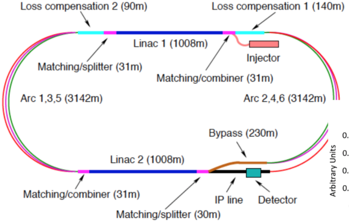
Next update planned 2018/2019.

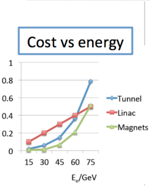
A story in pictures

The LHC upgrade with an electron beam: the LHeC

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

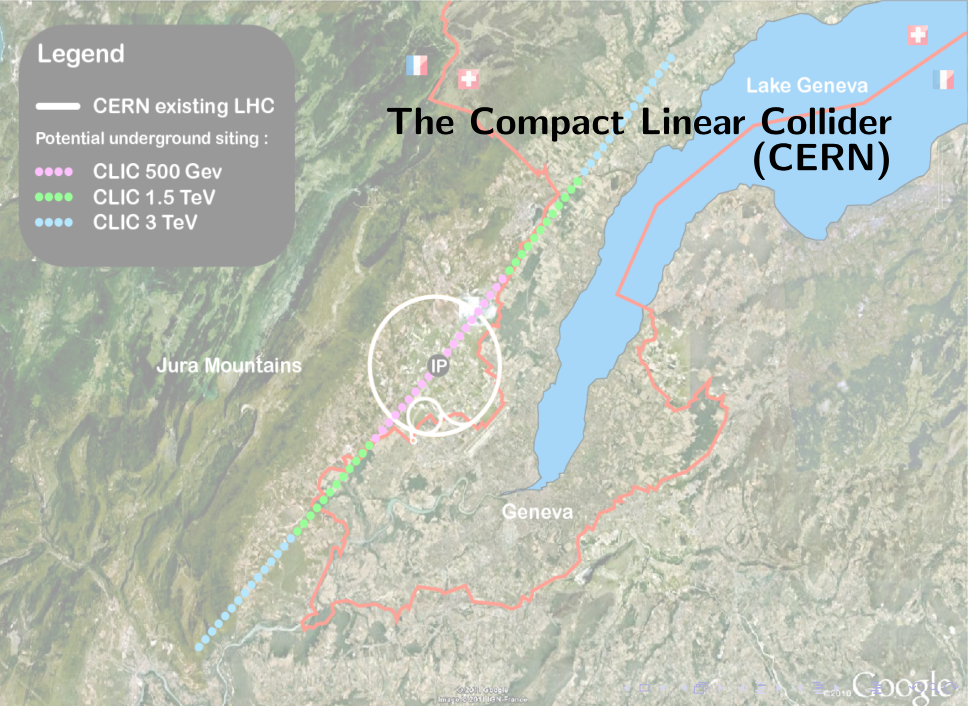




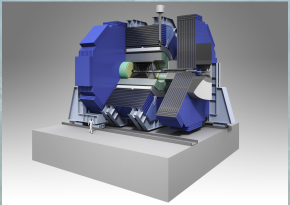


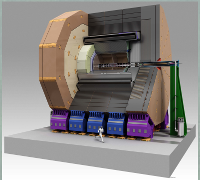
The Future Circular Collider project (CERN)

The Compact Linear Collider (CERN)



The International Linear Collider (Japan)

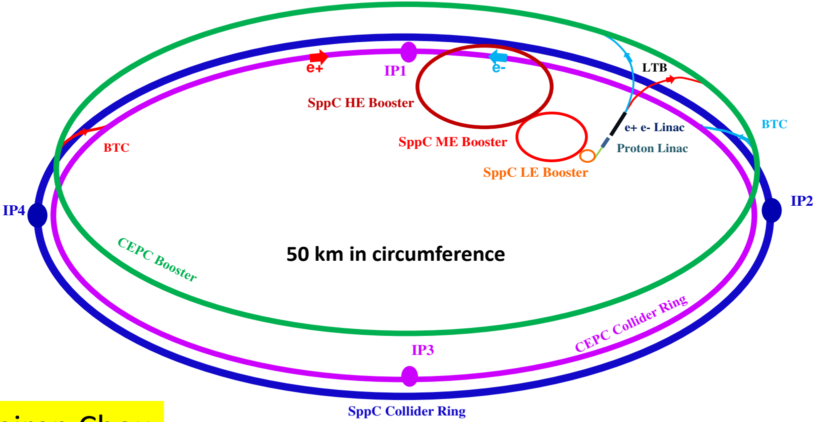




- Candidate site announced 2013.
- Over 30 km long.
- Higher beam energy
  ⇔ longer tunnel.
- Cost: 7.8 billion “Dollars” and 23 million person hours.

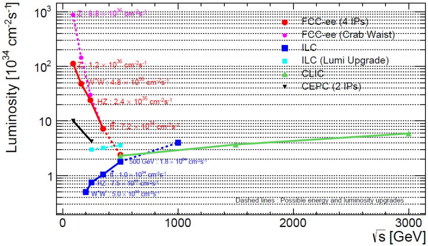
CEPC-SppC

CEPC is an 240 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70 TeV or higher pp collider SppC, to study the new physics beyond the Standard Model.



Weiren Chou

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

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

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

- $\mathcal{N} \sim$ 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):

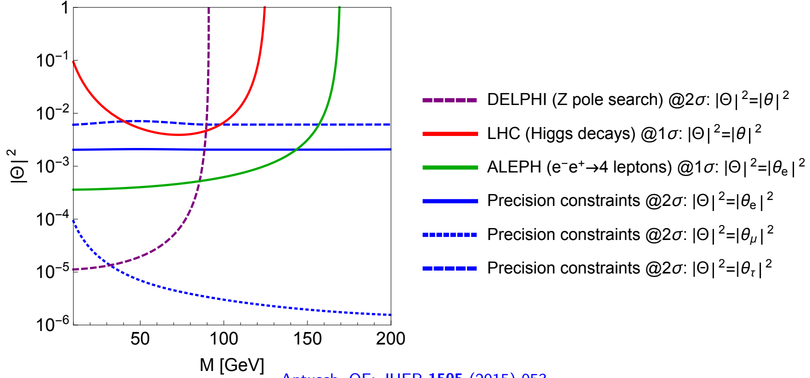
$$j_\mu^0 = \frac{g}{2\,c_W}\left[\theta^2\,\bar{N}_2\gamma_\mu\,N_2\; + (\bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 1}\,N_1 + \bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 2}\,N_2\; + \;\mathrm{H.c})\right]$$

- Higgs boson **Yukawa** interaction:

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

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

Present Constraints (dominated by LEP)



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)

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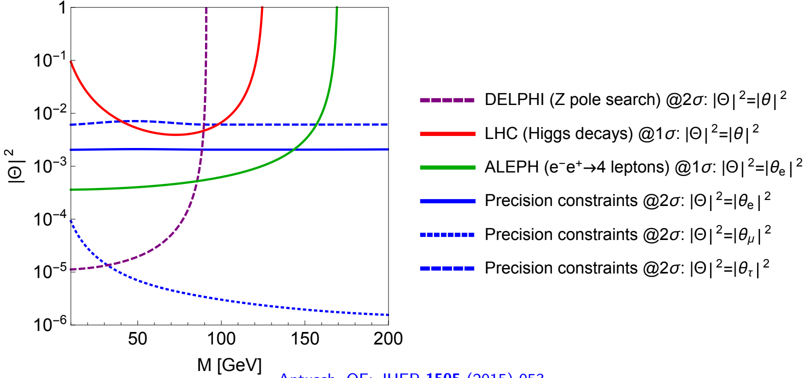
Present Constraints (dominated by LEP & MEG)



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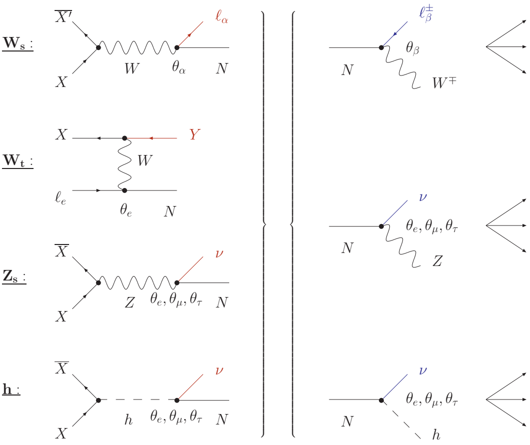
Collider signatures of sterile neutrinos at leading order

Production Decay Final States



pp : $\ell_\alpha \ell^\pm_\beta jj$, $\ell_\alpha \ell^\pm_\beta \ell^\mp_\gamma \nu$
$\mathbf{e^-e^+, e^-p}$: $Y \ell^\pm_\beta jj$, $Y \ell^\pm_\beta \ell^\mp_\gamma \nu$
$\mathbf{e^-e^+}$, **pp** : $\nu \ell^\pm_\beta jj$, $\nu \ell^\pm_\beta \ell^\mp_\gamma \nu$

pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu\nu\nu$
$\mathbf{e^-e^+, e^-p}$: $Y \nu jj$, $Y \nu \ell^\pm_\beta \ell^\mp_\beta$, $Y \nu\nu\nu$
$\mathbf{e^-e^+}$, **pp** : $\nu\nu jj$, $\nu\nu \ell^\pm_\beta \ell^\mp_\beta$, $\nu\nu\nu\nu$

pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu VV$
$\mathbf{e^-e^+, e^-p}$: $Y \nu jj$, $Y \nu \ell^\pm_\beta \ell^\mp_\beta$, $Y \nu VV$
$\mathbf{e^-e^+}$, **pp** : $\nu\nu jj$, $\nu\nu \ell^\pm_\beta \ell^\mp_\beta$, $\nu\nu VV$

Antusch, Cazzato, OF, (2016); *in preparation*

Promising signatures at lepton colliders

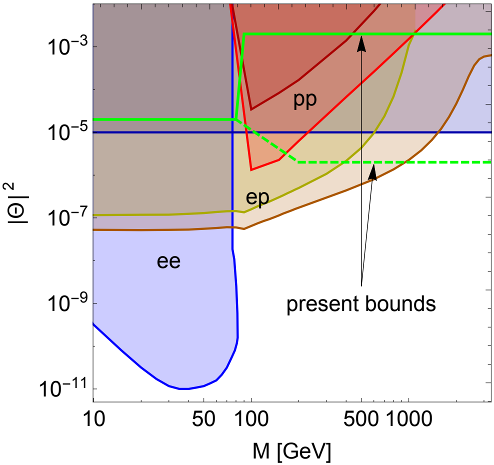
- **Comment on the violation of lepton number:**
  - Large unsuppressed backgrounds at parton level.
- **Displaced vertices**
  - For $M < m_W$ the heavy neutrinos may be long lived.
  - Secondary vertex with visible displacement.
- **Indirect searches via EWPO:**
  - The mixing matrix of the three active 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 ⇒ modified branching ratios.

Promising signatures at colliders with proton beams

- Unambiguous **lepton-number-violating** signatures:
  - ⋆ Proton-proton: same-sign dileptons, e.g. $\mu\mu jj$
  - ⋆ Electron-proton: positrons, e.g. $e^+ jjj$
  - ⋆ Both: strongly suppressed by m_ν
- Unambiguous **lepton-flavour-violating** final states
  - ⋆ Proton-proton: $\ell_\alpha \ell_\beta jj$, and $\ell_\alpha \ell_\beta \ell^\gamma$.
  - ⋆ 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); *in preparation*

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

Conclusions

Conclusions

- Neutrino oscillations: evidence for **physics beyond the SM**.
- Neutrino mass mechanism from **sterile neutrinos**.
- Experimental constraints at **various energy scales**.
- **Symmetry protected** scenarios can be tested at **colliders**.
- Predict lepton-flavour-violating (LFV) effects in general.
- **LFV** entails **great prospects** at *pp* and *ep* colliders.
  Has LHC run 2 excluded LVF dilepton-dijet?
- Electron-positron colliders sensitive via precision observables.

- 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.

The real question: are we **convinced** we need more HEP collider?

Thank you for your attention.