Testing the origin of neutrino masses at future colliders

Oliver Fischer

Karlsruher Institut für Technologie

Seminar

May 2, 2019

Outline

1) Future particle colliders – update from the European Strategy discussion
2) Motivating sterile neutrinos
3) Collider phenomenology (of sterile neutrinos)

Part 1 – Future particle colliders

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)
- In March Japan "expressed interest" but did not commit.

⋆ China: expertise in civil engineering & accelerators

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

I focus on the Future Circular Collider project (CERN)

Motivation* from the LHC?

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

$\Rightarrow$ Ask carefully: Why?

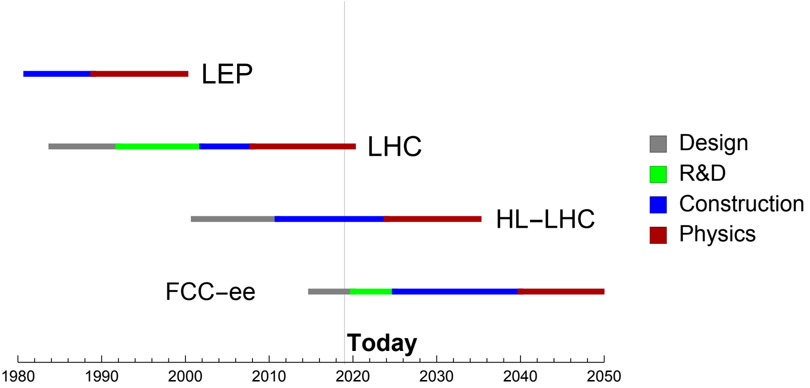
- Pessimistic answer not to be discussed here.
- Optimistic answer: New physics exists, but it ...
  - ... is covered in SM backgrounds.
  - ... interacts very weakly.
  - ... is too heavy to have been produced.

What can we do to improve the prospects of a discovery?

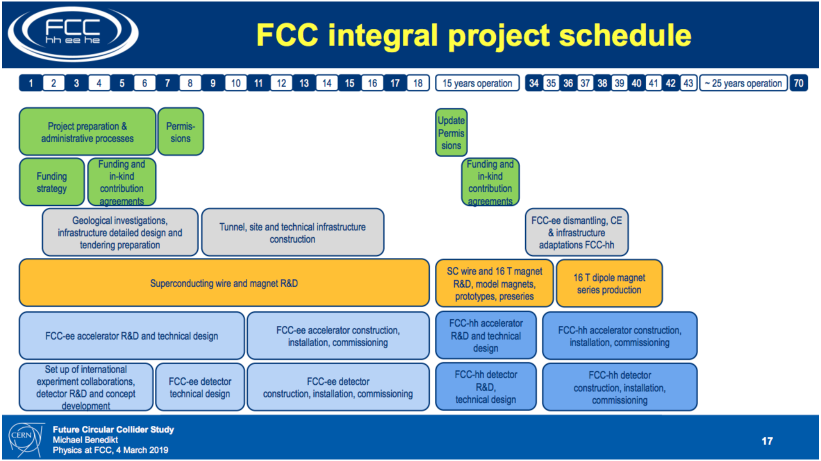
- Lepton colliders: very precise but low energy reach.
- Hadron colliders: high energy reach but limited precision.
- Electron-proton colliders: a little bit of both.

$\Rightarrow$ Complementarity!

A timely question: why now?



In fact...

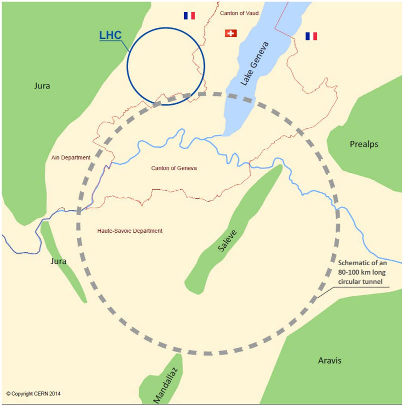


from M. Benedikt, FCC Symposium, March 19 @ CERN

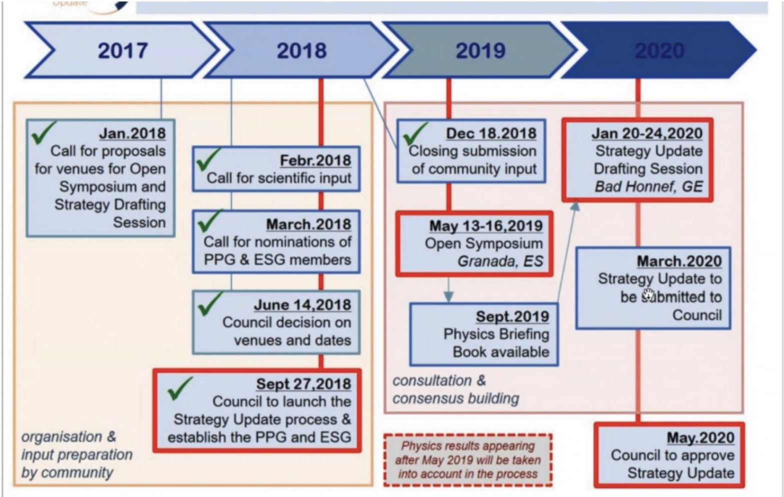
European strategy update 2013

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

- Use of existing infrastructure (LHC$\rightarrow$ booster).
- First step: lepton colliders
- Focus on the hadron colliders.
- Consider lepton-hadron mode.
- Geological constraints.



The 2nd Strategy Update is on



Timeline of the present European Strategy Update process with the green checkmarks symbolising the completed stages.

Recent FCC Symposium at CERN

Physics at FCC: overview of the Conceptual Design Report

4 Mar 2019, 13:30 → 5 Mar 2019, 18:30 Europe/Zurich

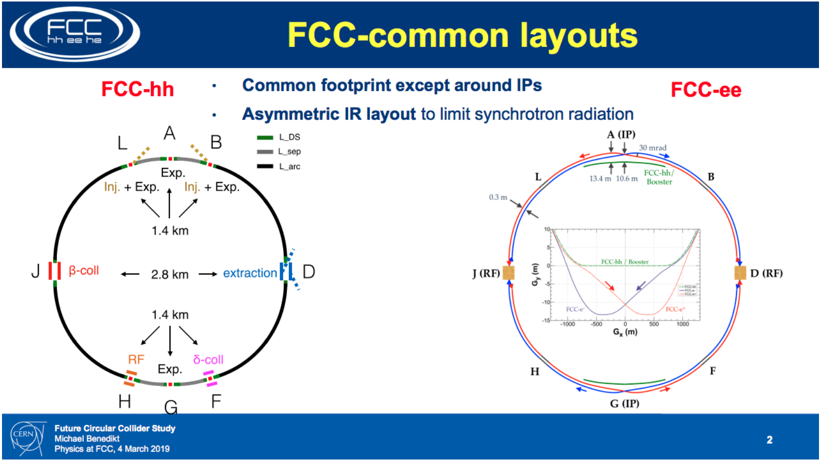
500-1-001 - Main Auditorium (CERN)

Description In preparation for the discussions at the European Strategy meeting in Granada, this Conference will review the main findings of the physics studies carried out in the context of the FCC CDR. The physics discussion will be accompanied by a status report of the overall project, reviewing the technological challenges for both accelerator and detectors, the ongoing actions to address them, the project implementation strategy, and the cost estimates.

This Conference is meant to help all colleagues, interested in the future of high energy physics in Europe, become familiar with the extraordinary progress made in the past 5 years in defining a realistic plan to meet the ambitious physics targets of the FCC.

https://indico.cern.ch/event/789349 (link online)

- Presentation of the latest machine parameters.
- Presentation of the physics case.
- I am using some of the slides.



from M. Benedikt, FCC Symposium, March 19 @ CERN

FCC-hh

FCC-ee physics operation model

working point	nominal luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ yr; half luminosity assumed in 1st two years (Z) and 1st year ($t\bar{t}$)	physics goal	run time [yr]
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	48 ab^{-1}/year		
W	25	6 ab^{-1}/year	10 ab^{-1}	2
H	7.0	1.7 ab^{-1}/year	5 ab^{-1}	3
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	0.2 ab^{-1}	1
top later (365 GeV)	1.4	0.34 ab^{-1}/year	1.5 ab^{-1}	4

total program duration: 15 years - *including machine modifications*

phase 1 (*Z*, *W*, *H*): 9 years, phase 2 (top): 6 years

from F. Zimmermann, FCC Symposium, March 19 @ CERN

FCC-hh

Hadron Collider Parameters

	LHC / HL-LHC	HE-LHC (tentative)	FCC-hh Initial	FCC-hh Ultimate
Cms energy [TeV]	14	27	100	100
Luminosity [$10^{34} cm^{-2}s^{-1}$]	1 / 5	28	5	20-30
Machine circumference	27	27	97.75	97.75
Arc dipole field [T]	8	16	16	16
Bunch charge	1.15 / 2.2	2.2	1	1
Bunch distance [ns]	25	25	25	25
Background events/bx	27 / 135	800	170	<1020
Bunch length [cm]	7.5	7.5	8	8

D. Schulte FCC-hh, CERN, March 2019 2

from D. Schulte, FCC Symposium, March 19 @ CERN

FCC-eh ERL Configuration:

Consistent Performance Projections for ep:

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

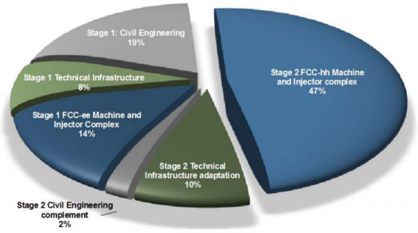
EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, "A Baseline for the FCC-he"

Oliver Brüning, John Jowett, Max Klein, Dario Pellegrini, Daniel Schulte, Frank Zimmermann

from O. Brüning, FCC Symposium, March 19 @ CERN

FCC-integrated cost estimate

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**



Future Circular Collider Study
Michael Benedikt
Physics at FCC, 4 March 2019

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from D. Schulte, FCC Symposium, March 19 @ CERN

Part 2 – Motivating sterile neutrinos

An incomplete history of neutrino experiments

1931 Pauli presents hypothetical neutral particle.

1934 Fermi Theory of weak interactions, coins the term "neutrino".

1956 Experimental discovery via a reactor and a water tank.

1962 Detection of muon neutrinos at AGS.

1968 Detection of solar neutrinos.

1987 Supernova neutrinos at Kamiokande.

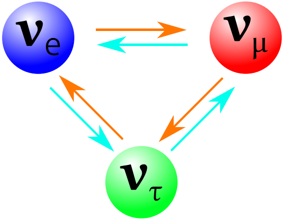
1990 Atmospheric neutrino anomaly, Kamiokande and IMB.

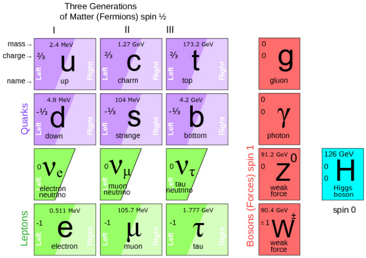
1991 2.9840 ± 0.0082 lepton generations from LEP.

Credit: https://icecube.wisc.edu/outreach/neutrinos

21^{st} FCC, SBNP, DUNE, HyperK, IceCube, ...

Neutrino masses & the Standard Model





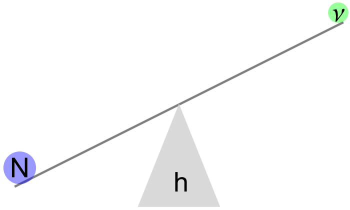
courtsy M. Shaposhnikov

We measure neutrino parameters, but:

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

$\Rightarrow$ Neutrino oscillations are evidence for physics beyond the SM.

The Seesaw mechanism with right-handed neutrinos



- Economic extension: 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

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

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

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

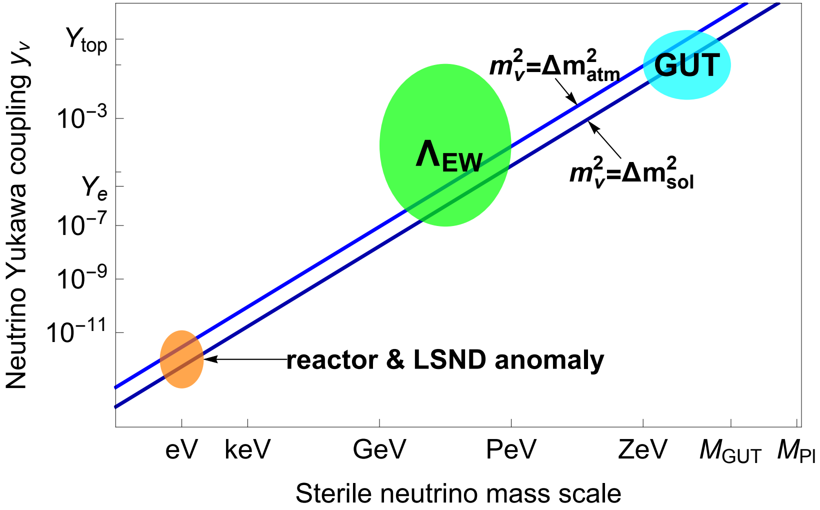
$$\Rightarrow m_{\nu_i} = 0 + \varepsilon \frac{v_{\mathrm{EW}}^2 \mathcal{O}(y_\nu^2)}{M_R^2}$$

- "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



Part 3 – Collider phenomenology (of sterile neutrinos)

Lowscale seesaw

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

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

- Lowscale seesaw Lagrangian, two sterile neutrinos N_i with protective symmetry:

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

- The mass matrix after electroweak symmetry breaking:

$$M_\nu = \begin{pmatrix} 0 & m_D & m_D' \\ (m_D)^T & 0 & M \\ (m_D')^T & M & \mu \end{pmatrix},$$

- Perturbations $\Rightarrow m_\nu$ and HNL mass splitting (ΔM)
- m_D': Linear seesaw, $\Delta M^{\mathrm{NO}} = 0.0416\,\mathrm{eV}$, $\Delta M^{\mathrm{IO}} = 0.000753\,\mathrm{eV}$
- μ: inverse seesaw, $\Delta M \sim \frac{m_{\nu_i}}{|\theta|^2}$.

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:

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

- $\mathcal{N} \sim$ PMNS as submatrix in general **not** unitary ($\mathcal{N}\mathcal{N}^\dagger \neq \mathbb{1}$).
  $\Rightarrow$ Model independent constraints Antusch, OF; JHEP 1410 (2014) 094
- 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

Diagonalisation of the mass matrix yields heavy (mostly sterile) neutrinos N and light (mostly active) neutrinos ν.

- **Charged current** (CC):

$$j_\mu^{\pm} = \frac{g}{2}\,\theta_\alpha\,\bar{\ell}_\alpha\,\gamma_\mu N$$

- **Neutral current** (NC):

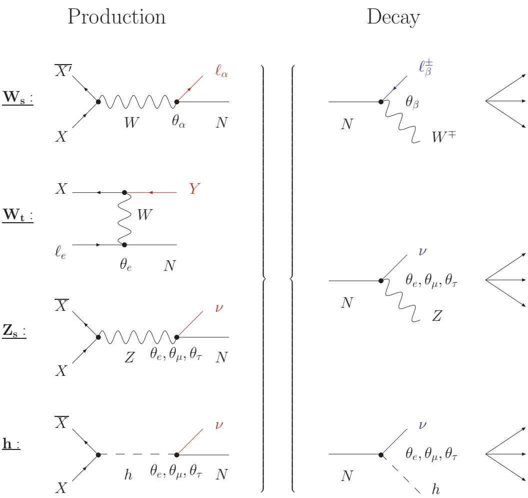
$$j_\mu^{0} = \bar{\nu}_\alpha\,\gamma_\mu\,\theta_\alpha\,N$$

- Higgs boson **Yukawa** interaction:

$$\mathscr{L}_{\mathrm{Yukawa}} = \sum_{\alpha=e,\mu,\tau} \theta_\alpha \frac{\sqrt{2}\,M}{v_{\mathrm{EW}}} \nu_\alpha \phi^0 \overline{N}$$

- Simplification: light neutrino mass eigenstates $\equiv \nu_e, \nu_\mu, \nu_\tau$

Collider signatures of sterile neutrinos at leading order



Final States

pp : $\ell_\alpha \ell_\beta^\pm jj$, $\ell_\alpha \ell_\beta^\pm \ell_\gamma^\mp \nu$
e⁻e⁺, e⁻p : $Y \ell_\beta^\pm jj$, $Y \ell_\beta^\pm \ell_\gamma^\mp \nu$
e⁻e⁺, pp : $\nu \ell_\beta^\pm jj$, $\nu \ell_\beta^\pm \ell_\gamma^\mp \nu$

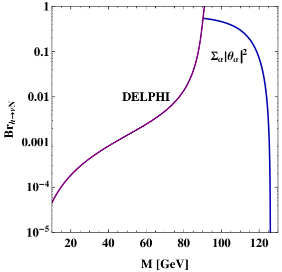
pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell_\beta^\pm \ell_\beta^\mp$, $\ell_\alpha \nu\nu\nu$
e⁻e⁺, e⁻p : $Y \nu jj$, $Y \nu \ell_\beta^\pm \ell_\beta^\mp$, $Y \nu\nu\nu$
e⁻e⁺, pp : $\nu\nu jj$, $\nu\nu \ell_\beta^\pm \ell_\beta^\mp$, $\nu\nu\nu\nu$

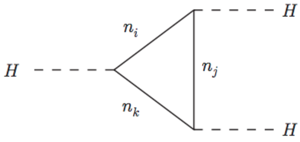
pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell_\beta^\pm \ell_\beta^\mp$, $\ell_\alpha \nu VV$
e⁻e⁺, e⁻p : $Y \nu jj$, $Y \nu \ell_\beta^\pm \ell_\beta^\mp$, $Y \nu VV$
e⁻e⁺, pp : $\nu\nu jj$, $\nu\nu \ell_\beta^\pm \ell_\beta^\mp$, $\nu\nu VV$

Antusch, Cazzato, OF; Int.J.Mod.Phys. A32 (2017) no.14, 1750078

A few selected processes only
(a few more in the backup)

Higgs boson decay properties



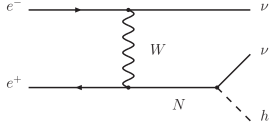


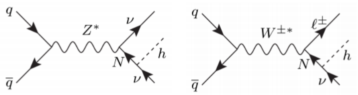
- New Higgs decay channels, w/ large branching e.g. $h \to \nu N$; $\Rightarrow h \to \ell^+_\alpha \ell^-_\beta$ via loops Herrero-Garcia, Rius, Santamaria; JHEP **1611** (2016) 084
- The Higgs self coupling can receive measurable contributions at the loop level Baglio *et al.*; JHEP **1704** (2017) 038
- In models with left-right or $B - L$ symmetry, the Higgs can decay into two LLP with displaced vertices and LNV

Accomando *et al.*; JHEP **1704** (2017) 081 Maiezza *et al.*; Phys. Rev. Lett. **115** (2015) 081802

Additional Higgs boson production processes...

Production of heavy neutrino $\oplus$ $N \to \nu h$:





- "Mono-Higgs" signature at electron-positron colliders.
  - Neutrino Yukawa couplings ~ 0.01 observable
  - More sensitivity at higher center-of-mass energy
  - SM measurement can be contaminated and increase by a few percent.

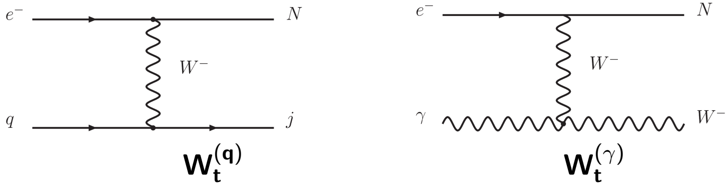
Antusch, OF; JHEP **1604** (2016) 189

- Pseudo "mono-Higgs" signature at proton-proton colliders.
  - No sensitivity to open parameter space at LHC.
  - Problem: towering background rates, especially di-top.

Basso; JHEP **1604** (2016) 087

… continued

$W\gamma$ fusion $\oplus$ $N \to \nu h$:

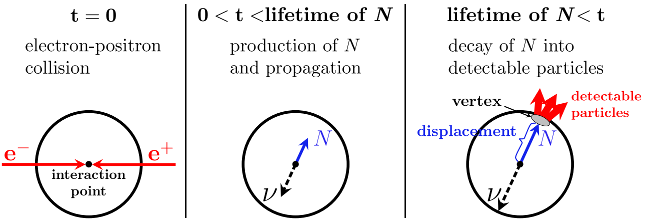


- Production only via $|\theta_e|^2$
- Intermediate state: $W^- h\nu$
- We checked $(e^-\nu_e)(b\bar{b})\nu$; very good sensitivity at FCC-he.
- May involve a hard jet with very small P_t.

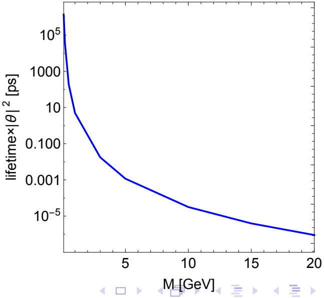
For $m_N < m_W$ heavy neutrinos are long lived
Exotic signature via displaced secondary vertex.

Displaced vertices at the Z pole ...

Antusch, Cazzato, OF; JHEP **1612**, 007 (2016)   Blondel *et al.*; Nucl. Part. Phys. Proc. **273-275** (2016) 1883



- Lifetime $\sim \mathcal{O}(1 - 100)$ ps.
- Assumption: no SM background for displacements > 0.1 mm.
- Considered ILC detector SiD as benchmark.



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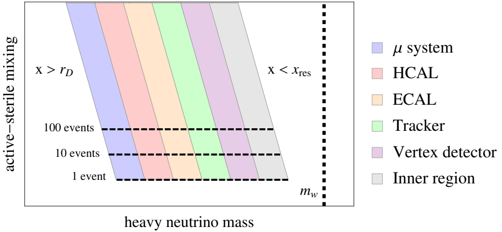
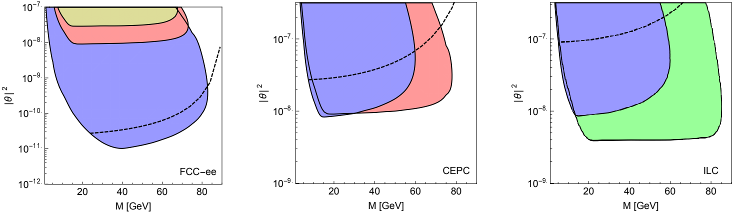
Schematic of the detector components’ sensitivities:



Sensitivities:



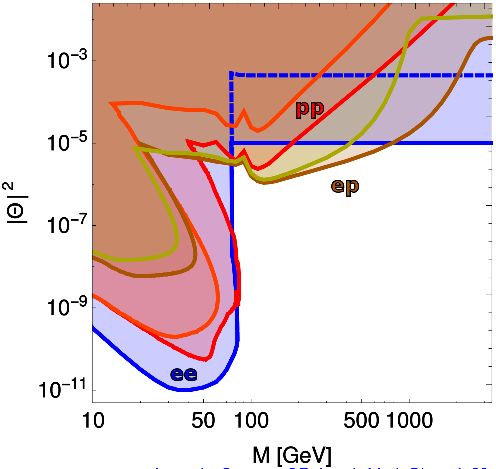
$E_{cm} = m_Z$; E_{cm} = 250 GeV; E_{cm} = 350 GeV; E_{cm} = 500 GeV; Conventional search (95% C.L.)

Many more processes in the backup.

Overview of the estimated sensitivities

At one-sigma confidence level.

ep and pp at parton level



Antusch, Cazzato, OF; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078

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

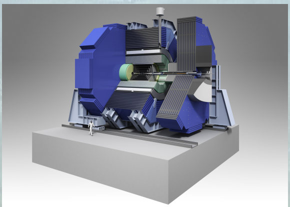
That's it.

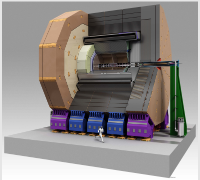
Conclusions

- The discussion on future colliders is important.
- So far motivation is thin; discovery @ LHC desirable.
- Neutrino oscillations are proof for BSM physics.
- It is possible that this new physics is a type I seesaw with symmetry protection.
- This can be tested in various ways at future colliders.

Backup

The International Linear Collider (Japan)

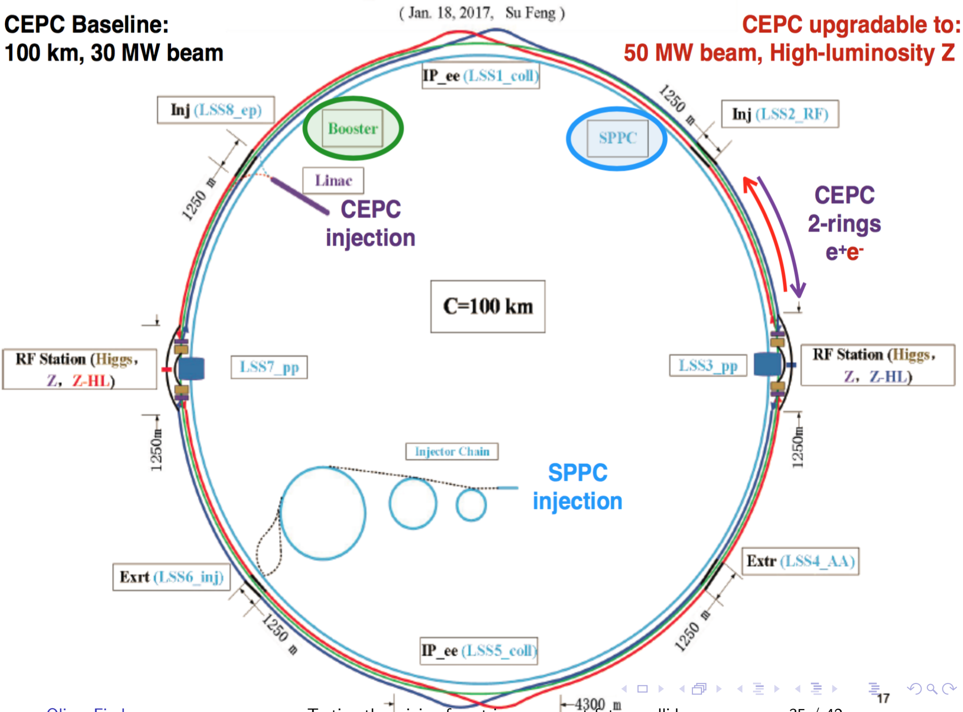




- Candidate site announced 2013.
- Planned length: 30 km.
- Cost: $\sim$ 8 billion “Dollars”.
- Recent proposal of 250 GeV did not get support from Japan

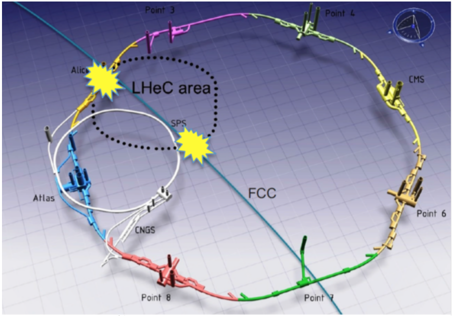
CEPC Baseline:
100 km, 30 MW beam

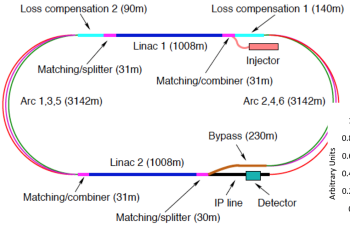
CEPC upgradable to:
50 MW beam, High-luminosity Z

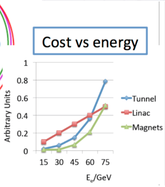


The LHC upgrade with an electron beam: the LHeC

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



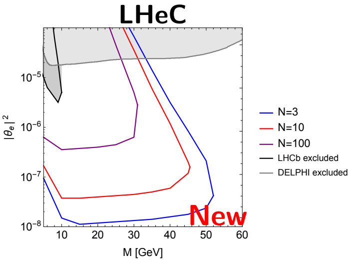




Promising signatures at colliders with proton beams

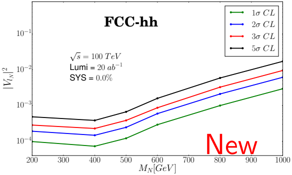
⋆ **Displaced vertices:**

- Possible at all FCC's.
- Easier at FCC-he compared to -hh.
- Best prospects for $M < m_W$.



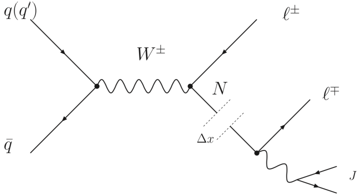
⋆ **Unambiguous LFV:**

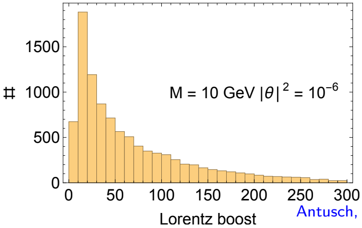
- Proton-proton: $\ell^\pm_\alpha \ell^\mp_\beta jj$, and $\ell^\pm_\alpha \ell^\mp_\beta \ell^\pm_\gamma$.
- Electron-proton: $\mu^- jjj$ and $\tau^- jjj$.
- Best prospects for $M \gg m_W$.

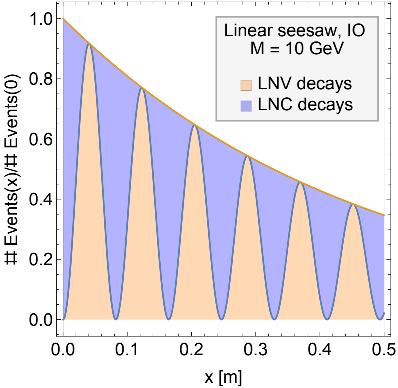


Antusch et al.; JHEP **1810** (2018) 067

Heavy neutrino-antineutrino oscillations @ FCC-hh & -he



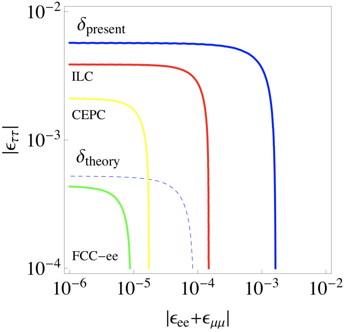




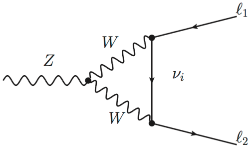
Antusch, Cazzato, OF; Mod. Phys. Lett. A **34** (2019) no.07n08, 1950061

- Oscillation from Δm_ν^2, can be $\sim$ mm.
- $M = \mathcal{O}(10)$ GeV and $|\theta|^2 \sim 10^{-6}$ yields displaced decays.
- Prompt lepton and displaced lepton are SS/OS as function of proper flight time

Indirect searches in electroweak precision data



Antusch, OF; JHEP 1410 (2014) 094



Exotic lepton flavor violating Z boson decays

A. Abada *et al.*; JHEP04 (2015) 051

- The mixing matrix of the three active neutrinos is non-unitary.
- Modification of the theory prediction of precision observables.
- Present constraints include:
  EWPO, lepton universality, charged LFV, CKM unitarity
- Constraints dominated by LEP and MEG, $\theta^*_\alpha \theta_\beta = \mathcal{O}(10^{-3})$.

Neutrino anomalies

1986 Anomalous Electron Production at PS191 (CERN)
$\Rightarrow$ oscillation with $(\Delta m^2, \sin^2 2\theta) = (\sim 7.5\ \text{eV}^2, 0.02)$

G. Bernardi *et al.*, Phys. Lett. B **181** (1986) 173.

1989 Search for neutrino oscillations (at E816, BNL)
$\Rightarrow$ Results compatible with PS191 P. Astier *et al.*; Nucl. Phys. B **335** (1990) 517.

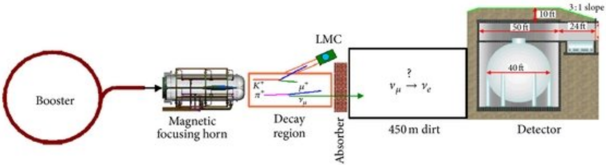
2001 LSND anomaly, excess of electron-like events.
$\Rightarrow$ oscillation with $(\Delta m^2, \sin^2 2\theta) = (0.003, 1.2\ \text{eV}^2)$

A. Aguilar-Arevalo *et al.* [LSND Collaboration], Phys. Rev. D **64** (2001) 112007

2018 MiniBooNE anomaly, excess of electron-like events

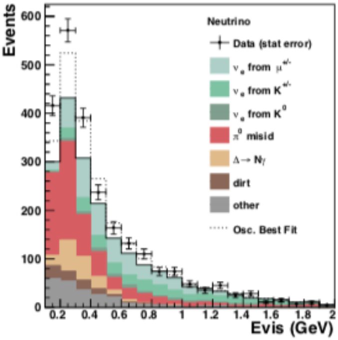
A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **121** (2018) no.22, 221801

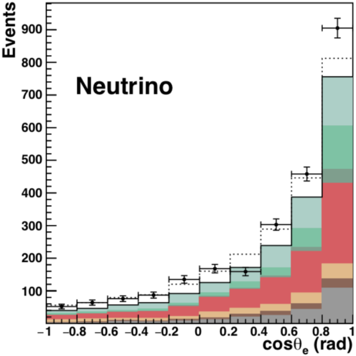
The MiniBooNE experiment



- Was designed to test LSND findings.
- Began data collection in August 2002.
- Sourced with ∼8 GeV Boosted Neutrino Beam (BNB).
- Magnetic horn for focusing of π^+ and π^-
  $\Rightarrow$ Neutrino vs. antineutrino mode.
- Baseline of about 450 Meter.
- Target for neutrino interactions: 8 m tank of mineral oil.

MiniBooNE observation: the excess





[MiniBooNE Collaboration], Phys. Rev. Lett. **121** (2018) no.22, 221801

- POT: 12.84×10^{20} (ν mode), 11.27×10^{20} ($\bar{\nu}$ mode)
- Excess of about 430 electron-like events in ν mode.
- Active-sterile oscillation: $(\Delta m^2, \sin^2 2\theta) = (0.039 eV^2, 0.84)$