Right-Handed neutrino searches at FCC-(ee)

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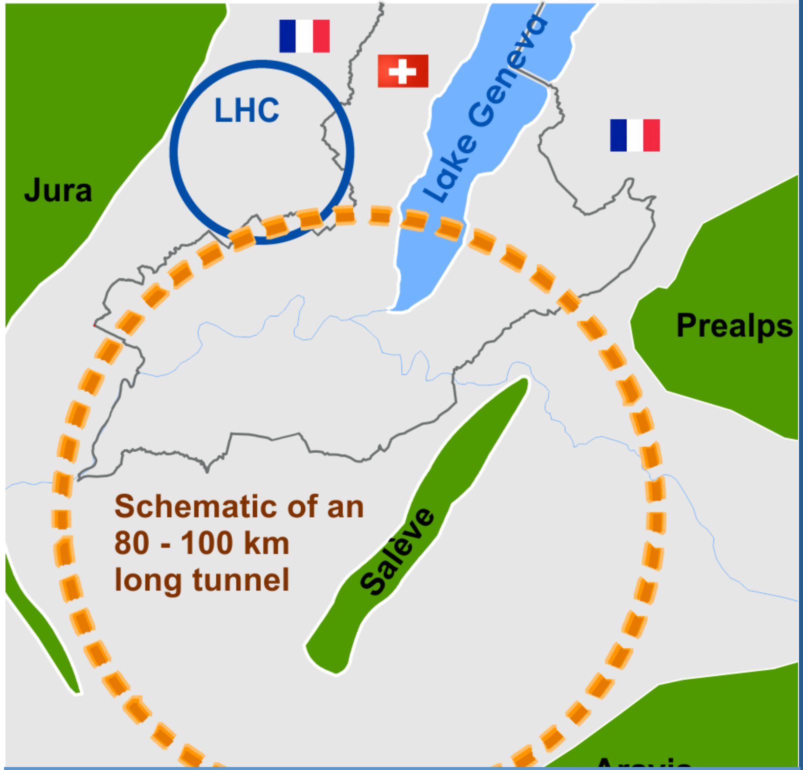
On behalf of the FCC-ee physics group

Thanks to Alain Blondel and Oliver Fisher for the input material

The FCC

- International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the Geneva area
- Ultimate goal:
  ≥100 TeV pp-collider (FCC-hh)
  - → defining infrastructure requirements
  - → Few possible first steps:
- e^+e^- collider (FCC-ee)
  High Lumi, E_{CM} =90-500 GeV
- HE-LHC 16T ⇒ 27 TeV
  in LEP/LHC tunnel
- Low energy FCC <50TeV (after ESPPU)
- Possible addition:
  - p-e (FCC-he) option
- This is the center of discussions for the European Strategy Update



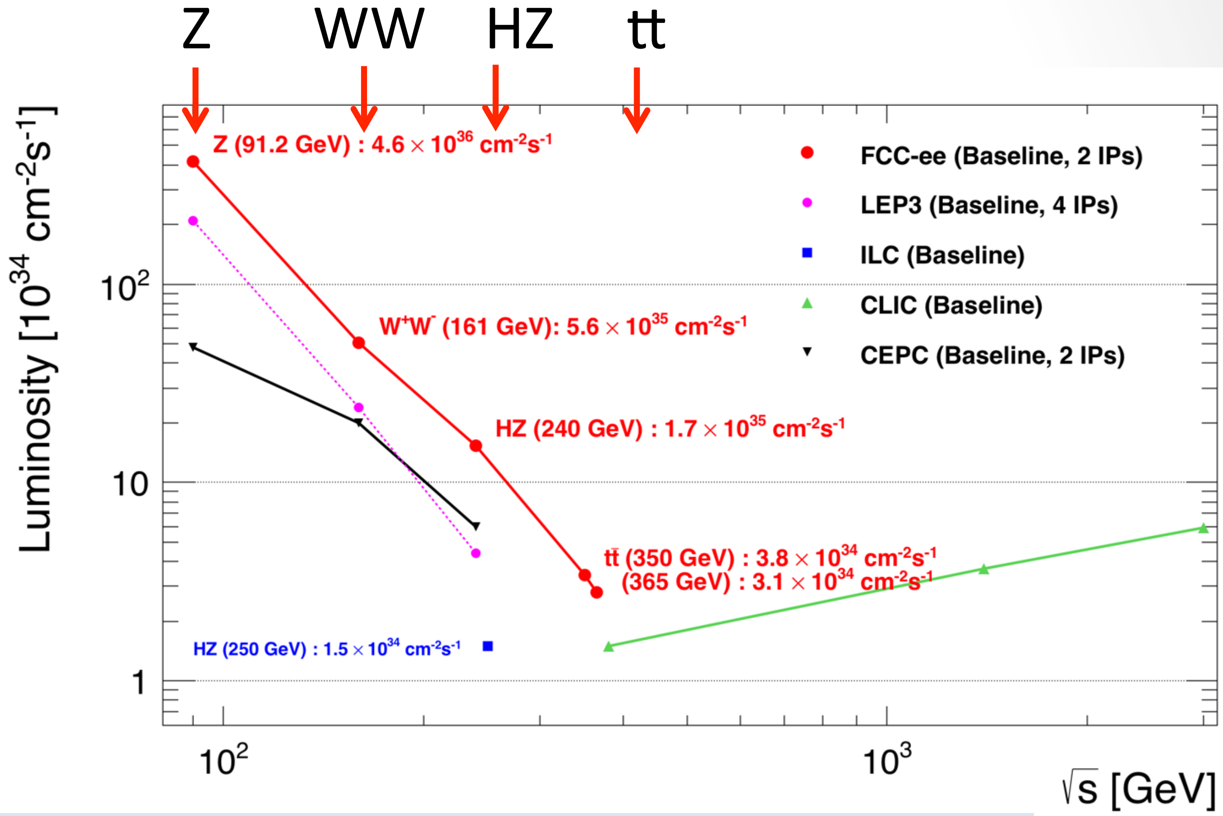
The way by FCC-ee is the fastest and cheapest way to 100 TeV, also produces the most physics. Prefered scenario presented in the CDR. https://cerncourier.com/cern-thinks-bigger/

It's also a good start for a μμC!

FCC-ee

FCC-ee CDR Vol2
Eur.Phys.J.ST 228 (2019)

FCC-ee FAQ
arXiv:1906.02693



Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$	e+e- → Z	LEP x 10^5
WW threshold	E_{cm} : 161 GeV	10^8	e+e- → WW	LEP x 2.10^3
ZH threshold	E_{cm} : 240 GeV	10^6	e+e- → ZH	Never done
tt threshold	E_{cm} : 350 GeV	10^6	e+e- → tt	Never done

FCC-ee running scenario

From FCC CDR Volume 2

Table 2.1: Run plan for FCC-ee in its baseline configuration with two experiments. The number of WW events is given for the entirety of the FCC-ee running at and above the WW threshold.

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could do

- Explore
  - ~20-50 (stat 400…) fold improved precision on many EW quantities
    - x 5-7 in mass $m_{Z,}$ m_W, m_{top} , $\sin^2\theta_W^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\, m_W\, m_\tau)$, top quark couplings
  - Model-independent Higgs width and couplings measurements at percent-permil level
  - 10-100 TeV energy scale (and beyond) with Precision Measurements (through EFT)
  - ~3σ of effect of Higgs self-coupling from Vertex corrections (also maybe directly with FCC-ee 500GeV)
  - Only machine with possible investigation of Hee coupling at $\sqrt{s} = m_H$

- Discover
  - Violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
  - FCNC ($Z \rightarrow \mu\tau$, $e\tau$) in 5 10^{12} Z decays and τ BR in 2 10^{11} $Z \rightarrow \tau\tau$ (also FCNC in top decays with 10^6 tops)
  - Flavour physics with 10^{12} bb events ($B \rightarrow s\,\tau\,\tau$ etc..)
  - Dark matter as «invisible decay» of H or Z (or in LHC loopholes)

- Direct Discovery
  - Very weakly coupled particle in 5-100 GeV energy scale such as: Right-Handed neutrinos, Dark Photons etc…

- Not only a «Higgs Factory», «Z factory» and «top» are important for 'discovery potential' (also QCD)

Electroweak eigenstates

I=1/2	I=0	
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0

- We measure neutrino parameters, but:
  - No right-handed neutrinos in the SM
  - No mass matrix, no mixing of the neutrino flavour states

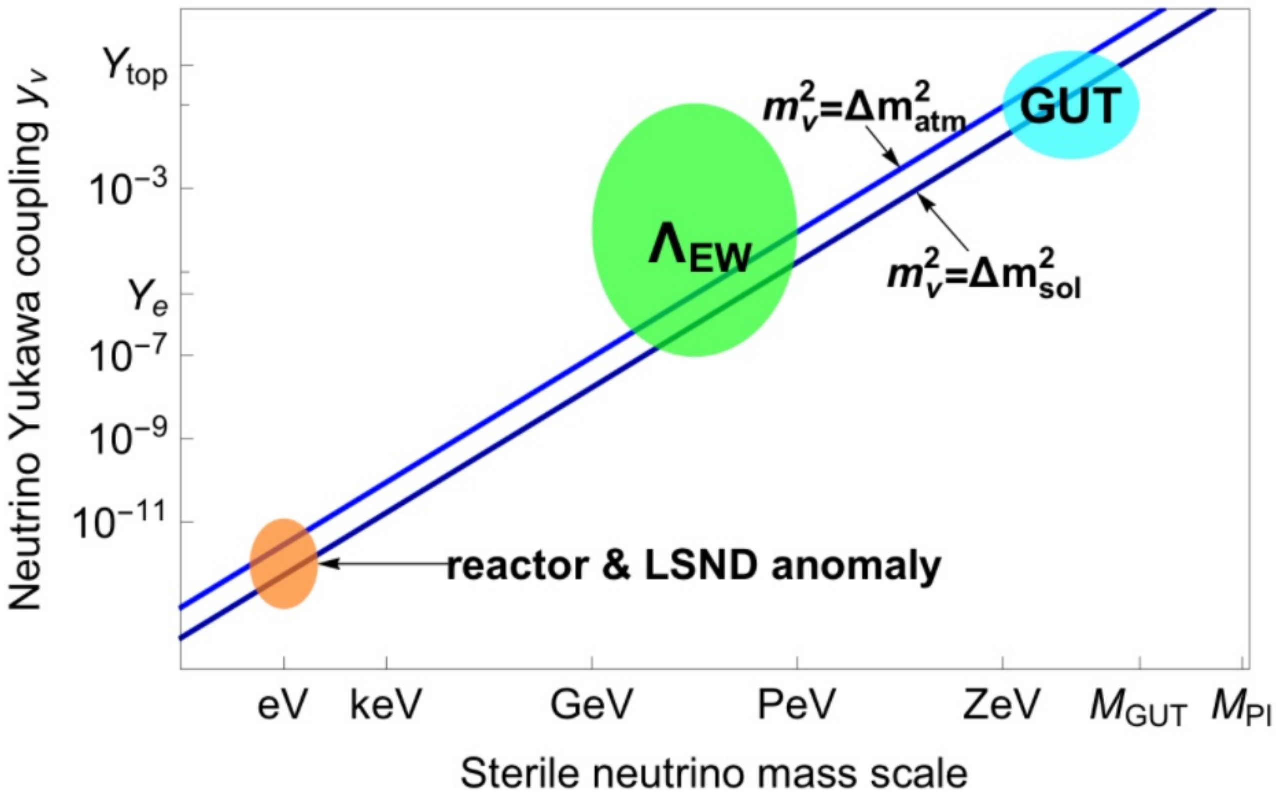
⇒ Neutrino oscillations are evidence for physics beyond the SM.

- Right handed neutrinos are singlets,
  - No weak interaction
  - No EM interaction
  - No strong interaction
- Can't produce them, Can't detect them
  - So why bother? (also called Sterile)

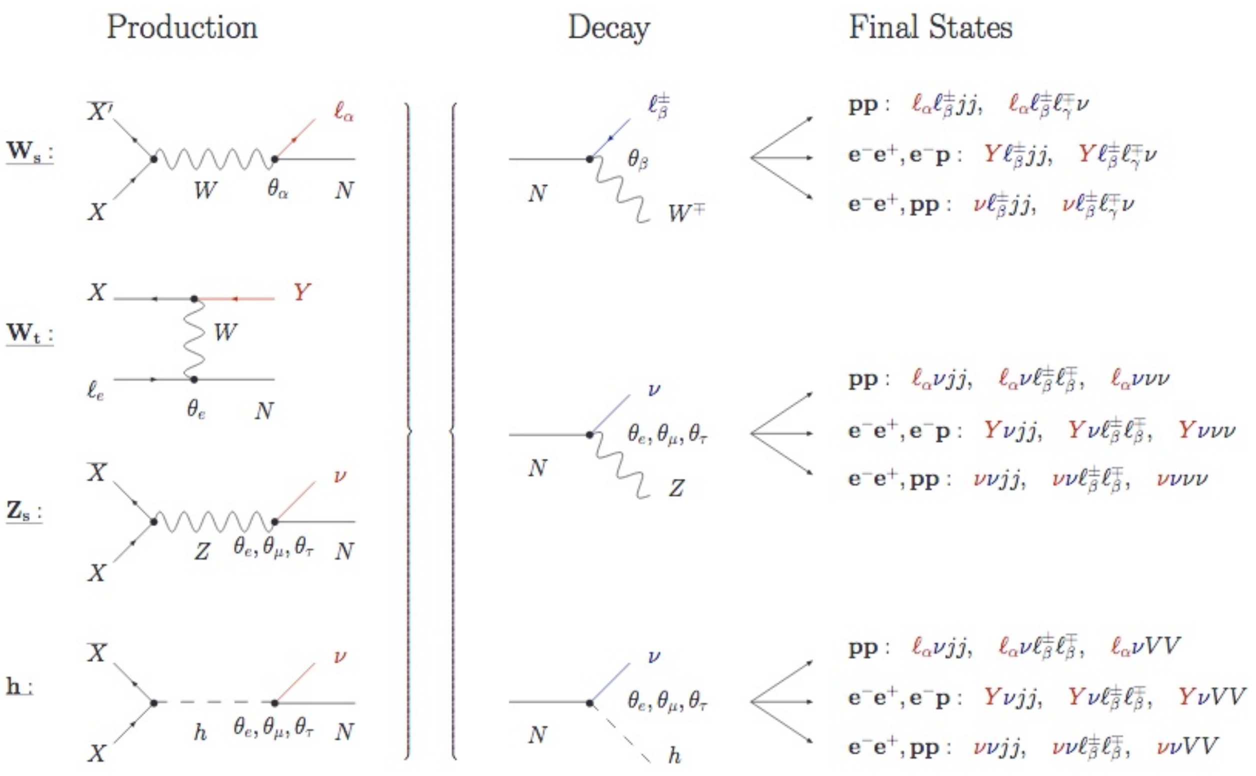
The Seesaw mechanism with RH neutrinos

- Economic extension by adding a number of Fermionic singlets
  - "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 Big Picture



Searches at FCC

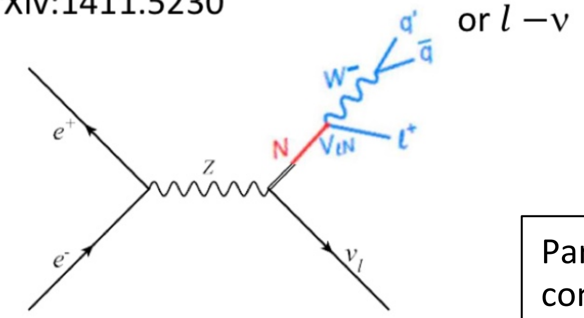


S. Antusch *et al.*; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078

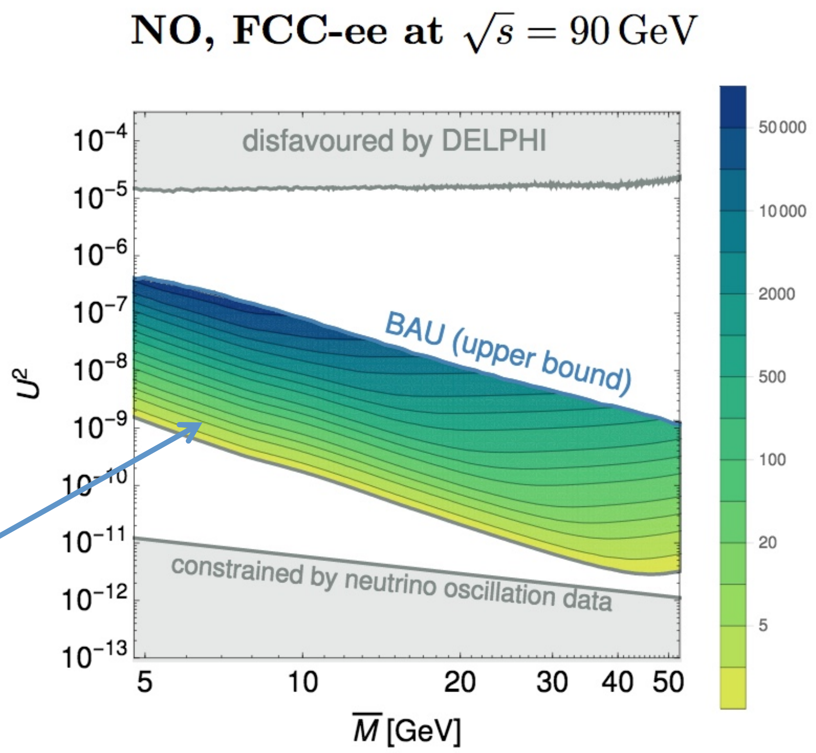
Displaced vertex searches at FCC-ee

- Test minimal type I seesaw hypothesis
- Together with ΔM also tests the compatibility with leptogenesis
- Long life time→detached vertex for ~<M_Z
- Backgrounds: four fermions
  - e^+e^-->W*W*, e^+e^-->Z*(nunu)(Z/gamma)*

arXiv:1411.5230

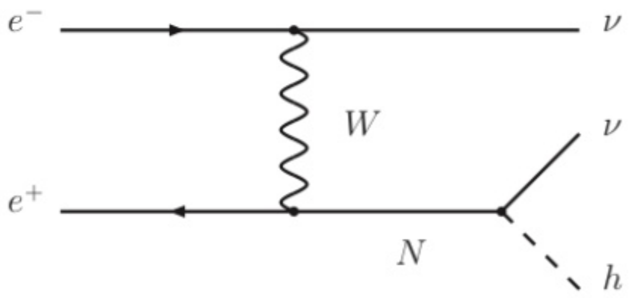


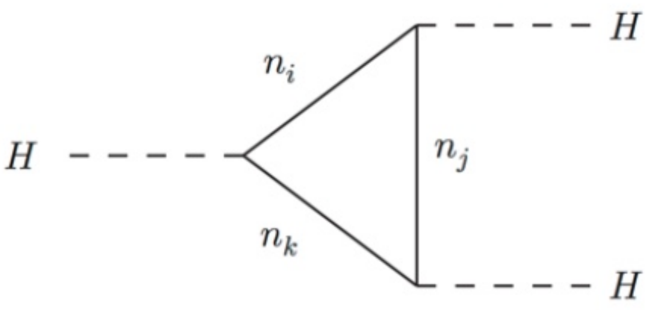
Antusch et al. JHEP 1809 (2018) 124



Parameter points consistent with baryogenesis

Indirect searches in Higgs properties





- Additional mono-Higgs production mechanism
- New Higgs decay channels:
  - Modification of Higgs branching ratios
  - New exotic decay channels: h → νN, N → SM
  - New invisible decay channels
- N contribution to the triple Higgs coupling

Outlook for FCC-hh

- Z factory like FCC-ee offers a clean method for detection of Heavy Right-Handed neutrinos

- W bosons are less abundant at the lepton colliders
  - At the 100 TeV FCC-hh W is the dominant particle: Expect 10^{13} real W's
  - There is a lot of pile-up/backgrounds/lifetime/trigger issues which need to be investigated

- But.... in the regime of long lived HNLs the simultaneous presence of
  - the initial lepton from W decays
  - the detached vertex with kinematically constrained decay
  - -> Would allow for a significant background reduction

- Could also served as a characterization both in flavour and charge of the produced neutrino
  - information of the flavour sensitive mixing angles
  - test of the fermion violating nature of the intermediate (Majorana) particle

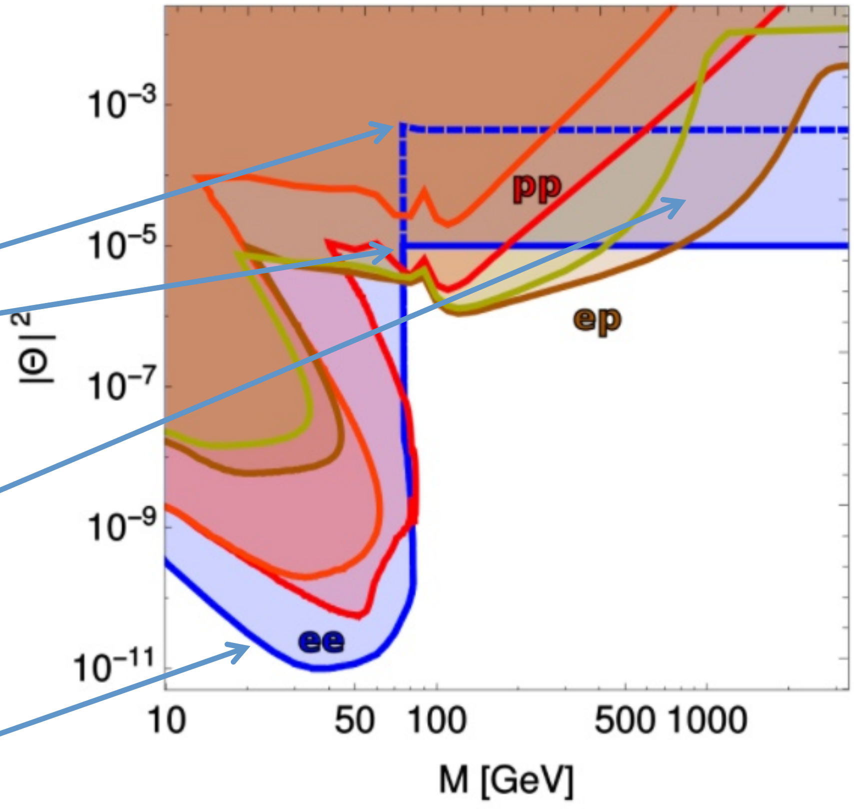
Overview of sensitivities

- At one-sigma confidence level
- ep and pp at parton level

EWPO sensitivity up to very high mass scales

Good sensitivity reach from FCC-hh and FCC-eh

Best sensitivity from displaced vertex searches at FCC-ee



S. Antusch *et al.*; Int. J. Mod. Phys. A **32** (2017)

Synergy and complementarity

- FCC-ee
  - Highest sensitivity in the low mass regime ($M<m_W$)
    - test model predictions: seesaw, leptogenesis
  - SM precision tests have high sensitivity; mass independent
    - Test heavy neutrinos up to ~60TeV
    - Not sensitive to the model details

- FCC-hh and he
  - Direct test of lepton-flavor and number violation
    - Number of heavy neutrino generations and their masses
  - Indirect test via measurement of Higgs potential
  - Sensitive to high mass regime

Conclusion

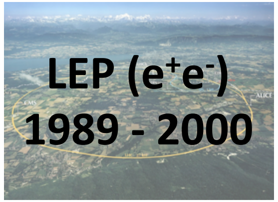
- The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology.
- Both FCC-ee and FCC-hh have outstanding physics cases
  - each in their own right
  - the sequential implementation of FCC-ee, FCC-hh, would maximise the physics reach
- FCC has unique prospects of testing model predictions.
- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities
- Neutrino mass physics should be a benchmark for future collider studies!

A 100km circular collider as next the step

Tevatron 2TeV → x 7 → **LHC 14TeV** → x 7 → **FCC-hh 100TeV**

27km tunnel

The next step: 100km tunnel



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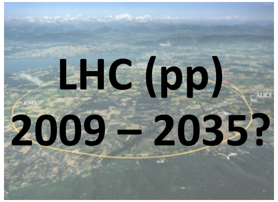

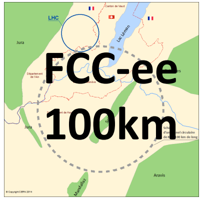

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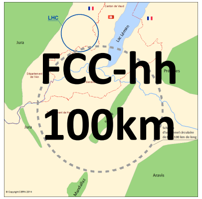

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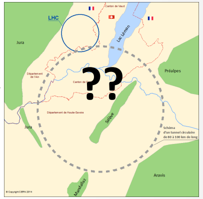
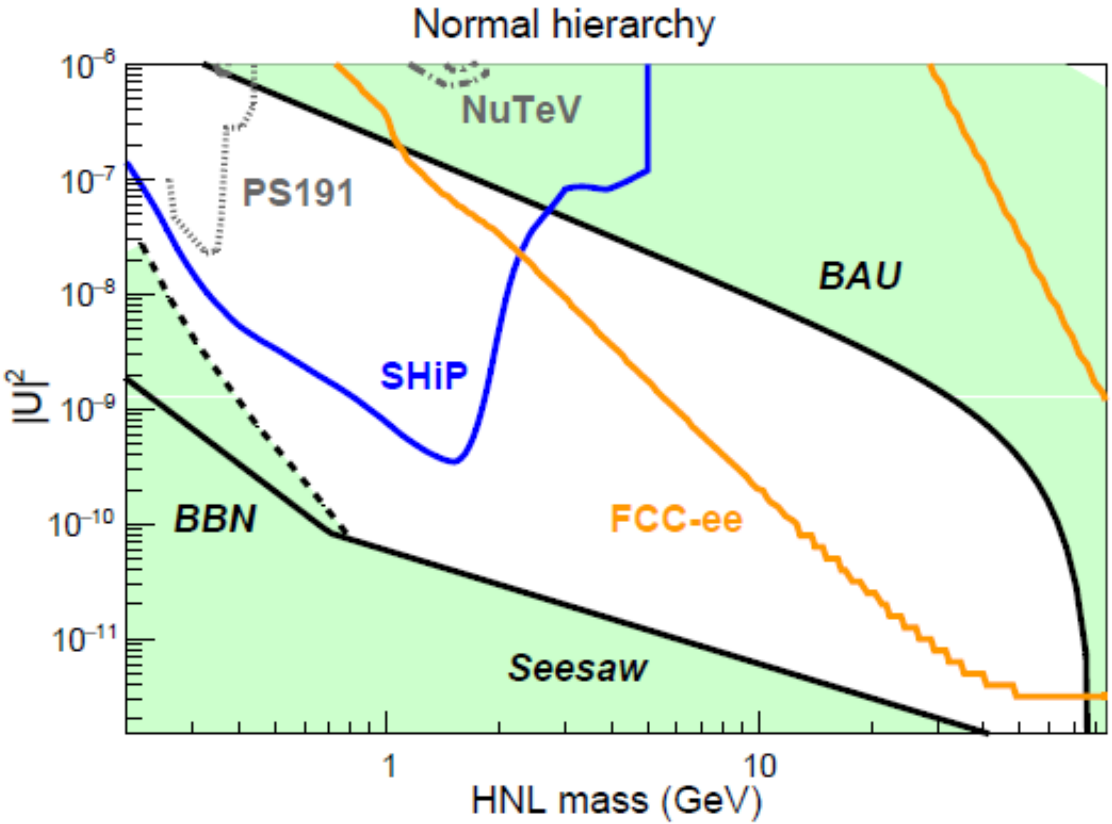


The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology

Both FCC-ee and FCC-hh have outstanding physics cases

We are preparing to move to the next step, as soon as possible (EPPSU)

Bonus



(a) Decay length 500 μm to 2 m

With 5 10^{12} Z

Manifestation of Right-Handed neutrinos

One see saw family

$\theta \approx (m_D / M)$

$m_\nu \approx m_D^2 / M$

$m_N \approx M$

$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$$\nu = \nu L \cos\theta - N^c{}_R \sin\theta$$

$$N = N_R \cos\theta + \nu_L{}^c \sin\theta$$

What is produced is W,Z decays is:

$\nu_L = \nu \cos\theta + N \sin\theta$

ν = light mass eigenstate

N=heavy mass eigentstate

≠ ν_L active neutrino which couples to weak inter

≠ N_R which does not

- mixing with active neutrinos leads to various observable consequences
  - if very light (eV) , possible effect on neutrino oscillations
  - if in keV region (dark matter), monochromatic photons from galaxies with E=mN/2
- possibly measurable effects at High Energy
  - If N is heavy it will decay in the detector (not invisible)
    - PMNS matrix unitarity violation and deficit in Z «invisible» width
    - Higgs, Z, W visible exotic decays H→ νiNi and Z→ νiNi , W-> li Ni
    - also in K, charm and b decays via W*-> li ±N , N→lj ± with any of six sign and lepton flavour combination
    - violation of unitarity and lepton universality in Z, W or τ decays
- Couplings are very small (m_ν / m_N) (but *who knows?)* and generally seem out of reach at high energy colliders.

(indirect) Effect of RH ν on EW precision obs.

- The relationship $|U|^2 \propto \theta^2 \approx \boldsymbol{m_\nu} / m_N$ is valid for one family see-saw
- For two or three families the mixing can be larger
- *Shaposhnikov, Antush and Fisher*, have shown that a slight # in Majorana mass can generate larger mixing between the left- and right-handed neutrinos
- «$\boldsymbol{\nu L} = \boldsymbol{\nu} \cos\theta + \boldsymbol{N} \sin\theta$» →$(\cos\theta)^2$ becomes parametrized as 1+ $\varepsilon_{\alpha\beta}$ ($\varepsilon_{\alpha\alpha}$ is negative) the coupling to light 'normal' neutrinos is typically reduced.
- In the G_F , M_Z α_{QED} scheme, G_F (extracted from $\mu \to e \nu_e \nu_\mu$) and *g* should be increased.
- This leads to correlated variations of all predictions upon e or μ neutrino mixing.
- Only the 'number of neutrinos' (R_{inv} and σ_{had}^{peak}) and the tau specific CC observables (tau decays) are sensitive to the tau-neutrino mixing.

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

Table 1: Experimental results and SM predictions for the EWPO, and the modification in the MUV scheme, to first order in the parameters $\varepsilon_{\alpha\beta}$. The theoretical predictions and experimental values are taken from Ref. [16]. The values of $(s^{\ell,{\rm lep}}_{W,{\rm eff}})^2$ and $(s^{\ell,{\rm had}}_{W,{\rm eff}})^2$ are taken from Ref. [17].

From arXiv:1407.6607