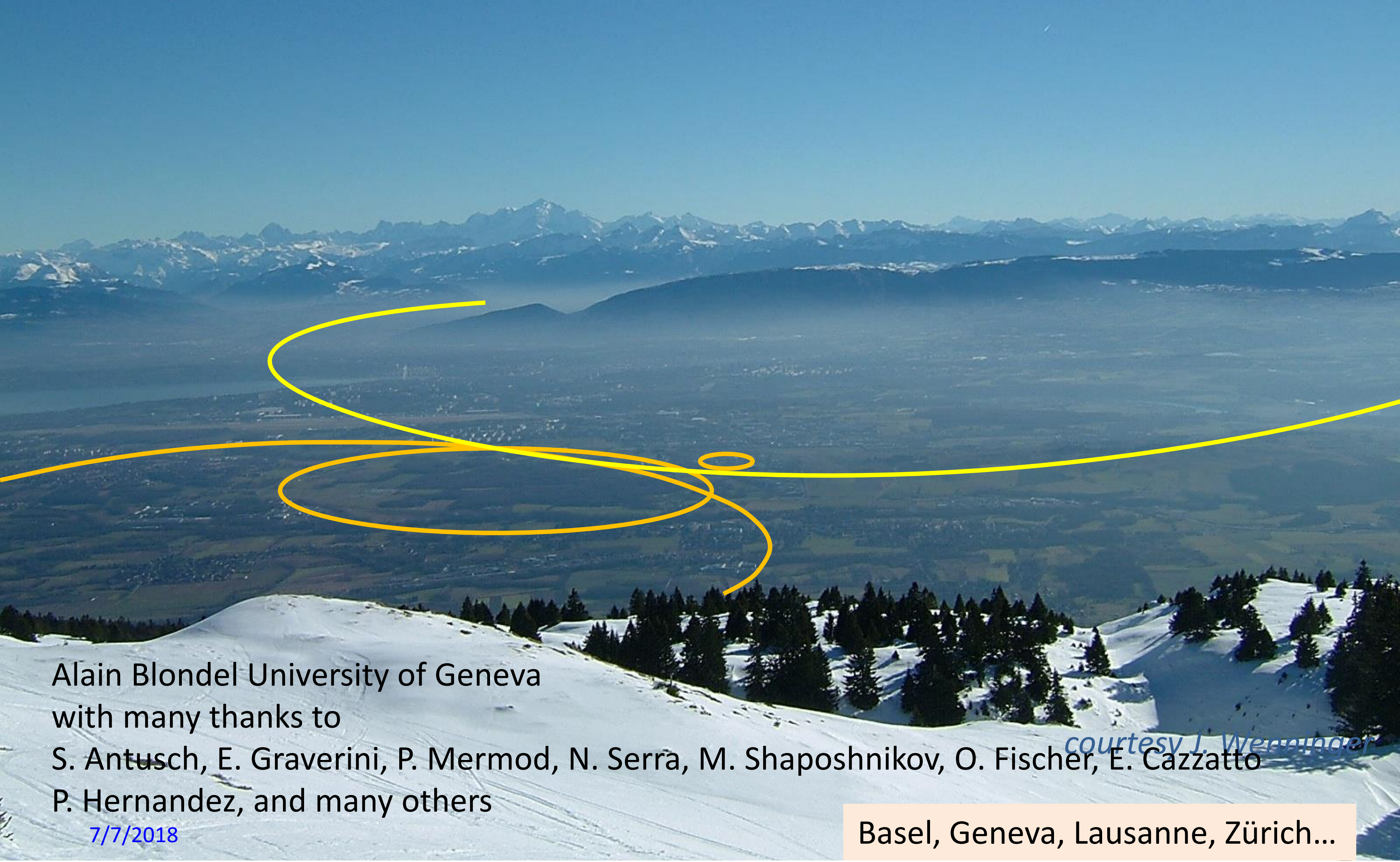
The Hunt for right-Handed Neutrinos



courtesy J. Wenninger

Alain Blondel University of Geneva
with many thanks to
S. Antusch, E. Graverini, P. Mermod, N. Serra, M. Shaposhnikov, O. Fischer, E. Cazzatto
P. Hernandez, and many others

7/7/2018

Basel, Geneva, Lausanne, Zürich…

The Future Circular Colliders
CDR and cost review to appear Q4 2018 for ESU

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- ***Ultimate goal:*** **~16 T magnets**
  100 TeV pp**-collider (*****FCC-hh*****)**

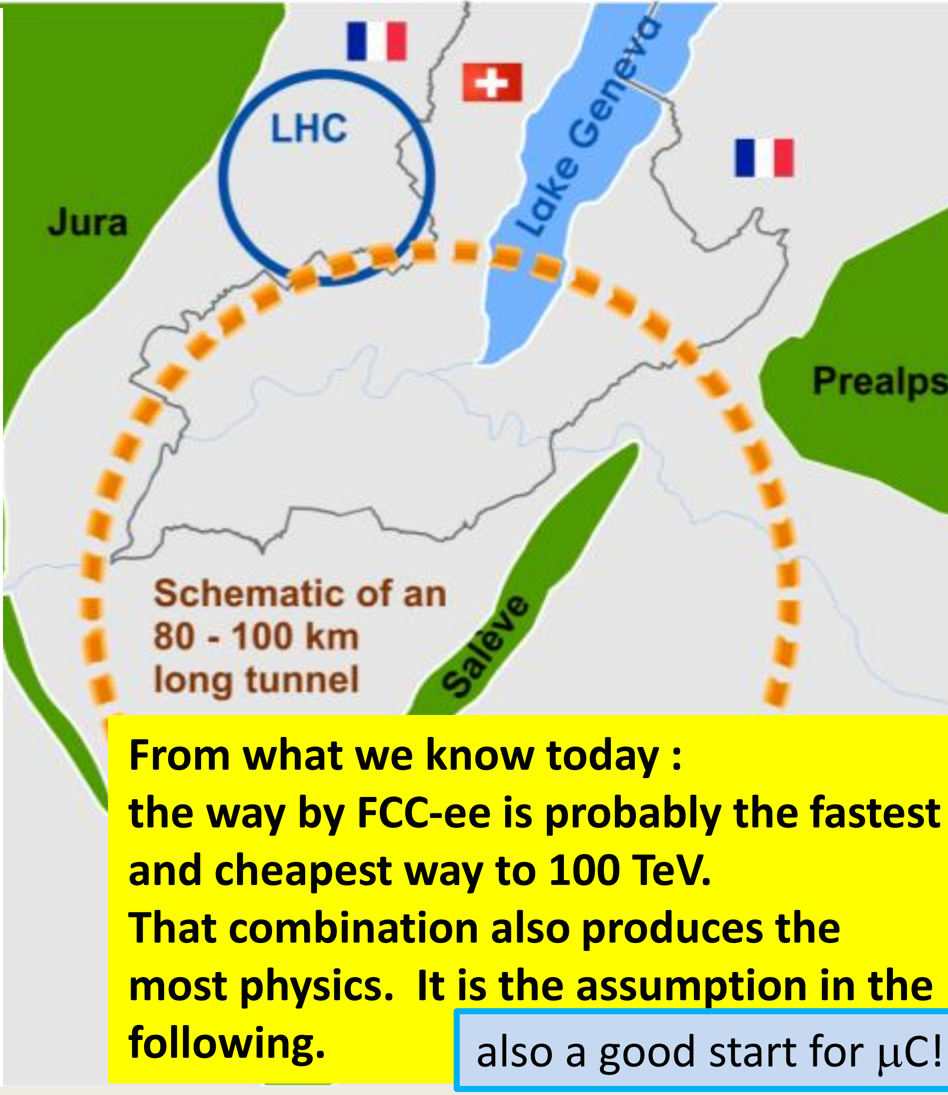
→ defining infrastructure requirements

Two possible first steps:

- **e^+e^- collider (*FCC-ee*)**
  High Lumi, E_{CM} =90-400 GeV
- ***HE-LHC*** **16T ⇒ 28 TeV**
  in LEP/LHC tunnel

Possible addition:

- ***p-e*** **(*FCC-he*) option**



From what we know today :
the way by FCC-ee is probably the fastest and cheapest way to 100 TeV.
That combination also produces the most physics. It is the assumption in the following.

also a good start for μC!

From European Strategy in 2013: “ambitious post-LHC accelerator project”
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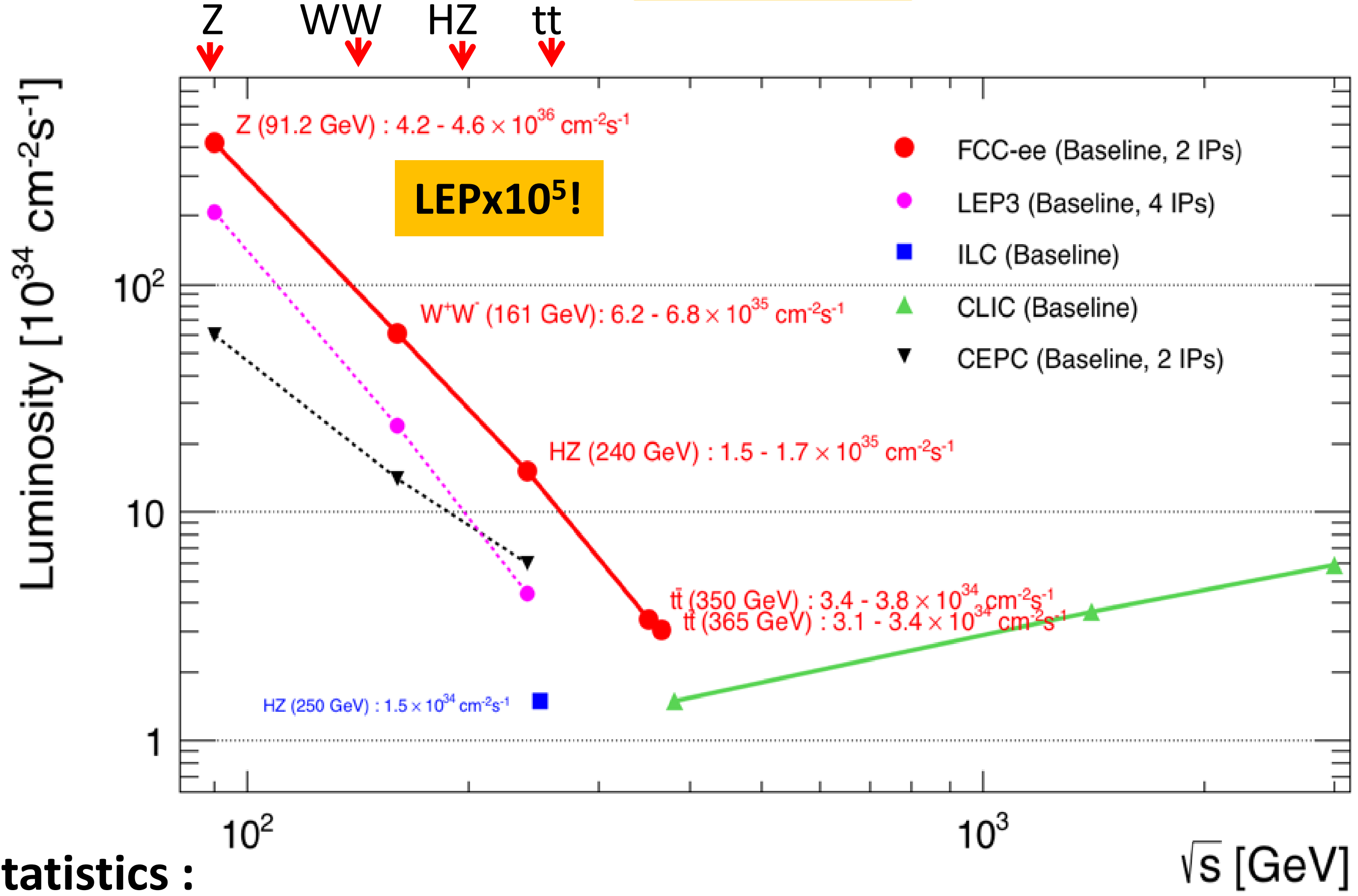
FCC-ee



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Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$ e+e- → Z	LEP x 10^5	100 keV
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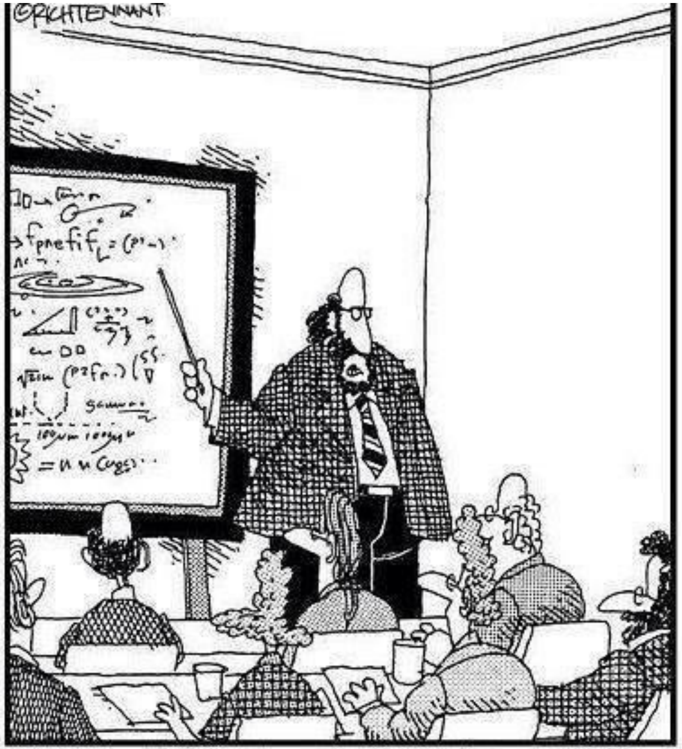
$t\bar{t}$ threshold	E_{cm} : 350 GeV	10^6 e+e- → $t\bar{t}$	Never done	2 MeV

Great energy range for the heavy particles of the Standard Model.

Electroweak eigenstates

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



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

rs

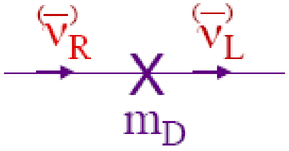
Right handed neutrinos
are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –

Also called 'sterile'

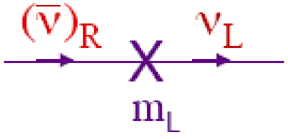
Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term

$m_D \nu_L \overline{\nu}_R$ $m_D \overline{\nu}_L \nu_R$



implies adding a right-handed neutrino.
Nothing prevents adding then a term like

$m_M \overline{\nu_R^{\,c}}\, \nu_R$



and this simply means that a neutrino turns into a antineutrino
(the charge conjugate of a right handed antineutrino is a left handed neutrino!)

this does not violate spin conservation since a left handed field has a component of the opposite helicity (and vice versa)

$\nu_L \approx \nu_- + \nu_+\, m/E$ (mass is what allows to flip the helicity)

Mass eigenstates

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\ \bar{N}_R^c)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

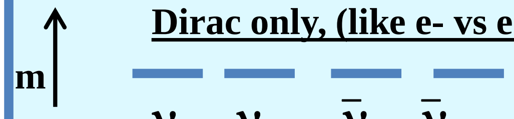
$$\tan 2\theta = \frac{2\,m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0+M_R) - \sqrt{(0-M_R)^2 + 4\,m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0+M_R) + \sqrt{(0-M_R)^2 + 4\,m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

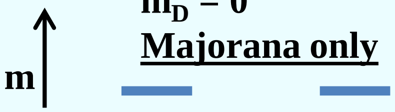


ν_L ν_R $\bar{\nu}_L$ $\bar{\nu}_R$
$I_{weak}=$ ½ 0 ½ 0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only



ν_L $\bar{\nu}_R$
$I_{weak}=$ ½ ½

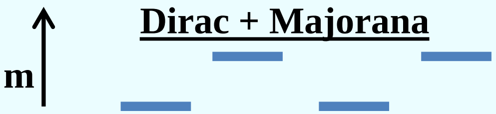
2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$

see-saw

Dirac + Majorana



dominantly: ν N $\bar{\nu}$ $\bar{N}$
$I_{weak}=$ ½ 0 ½ 0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

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

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

what is produced in W, Z decays is:

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

ν = light mass eigenstate
N = heavy mass eigenstate
$\neq \nu_L$, active neutrino which couples to weak inter.
and $\neq N_R$, which does'nt.

-- 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 $E=m_N/2$
-- 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 $H \rightarrow \nu_i \bar{N}_i$ and $Z \rightarrow \nu_i \bar{N}_i$, $W \rightarrow l_i \bar{N}_i$
    ➔ also in K, charm and b decays via $W^* \rightarrow l_i^\pm \bar{N}$, $N \rightarrow l_j^\pm$
        with any of six sign and lepton flavour combination
    ➔ violation of unitarity and lepton universality in Z, W or τ decays
    -- etc... etc...
-- Couplings are very small (m_ν / m_N) *(but who knows?)* and generally seem out of reach at high energy colliders.

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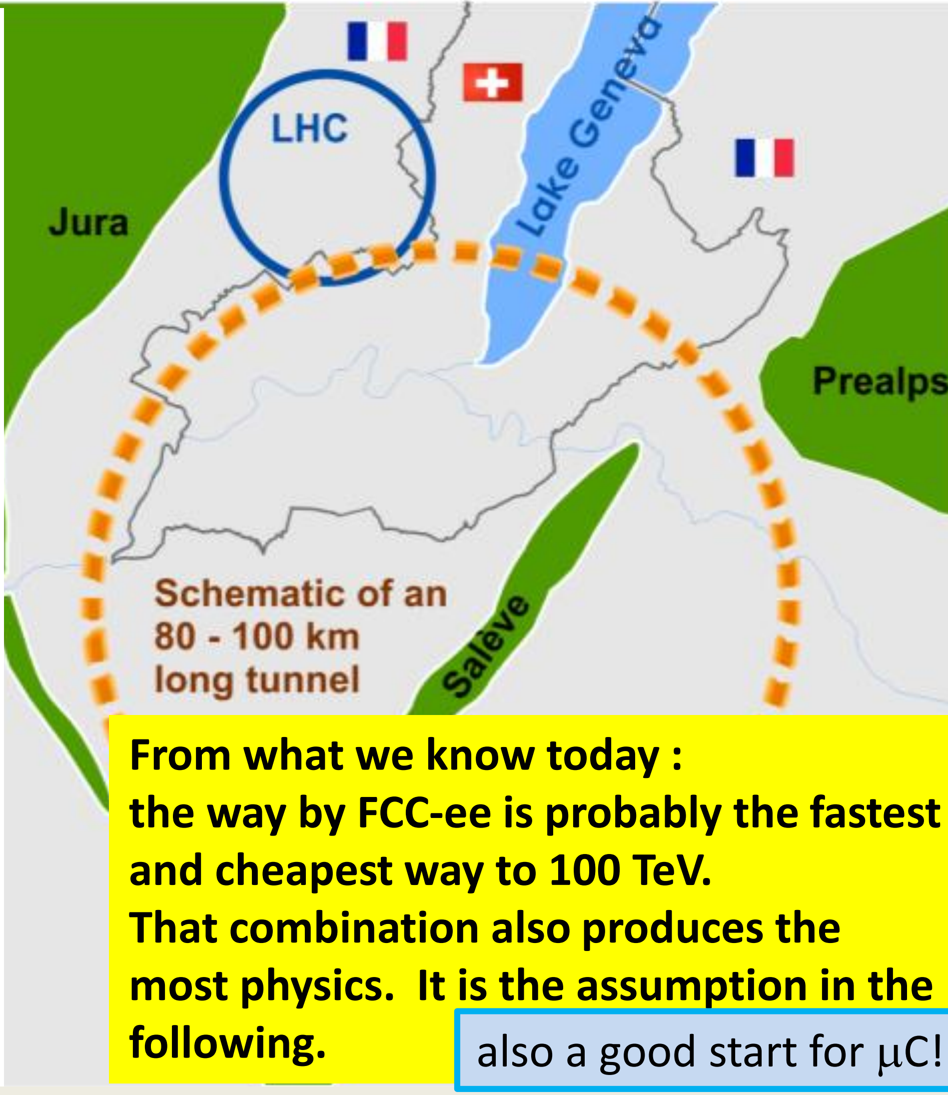

Schematic of an 80 - 100 km long tunnel

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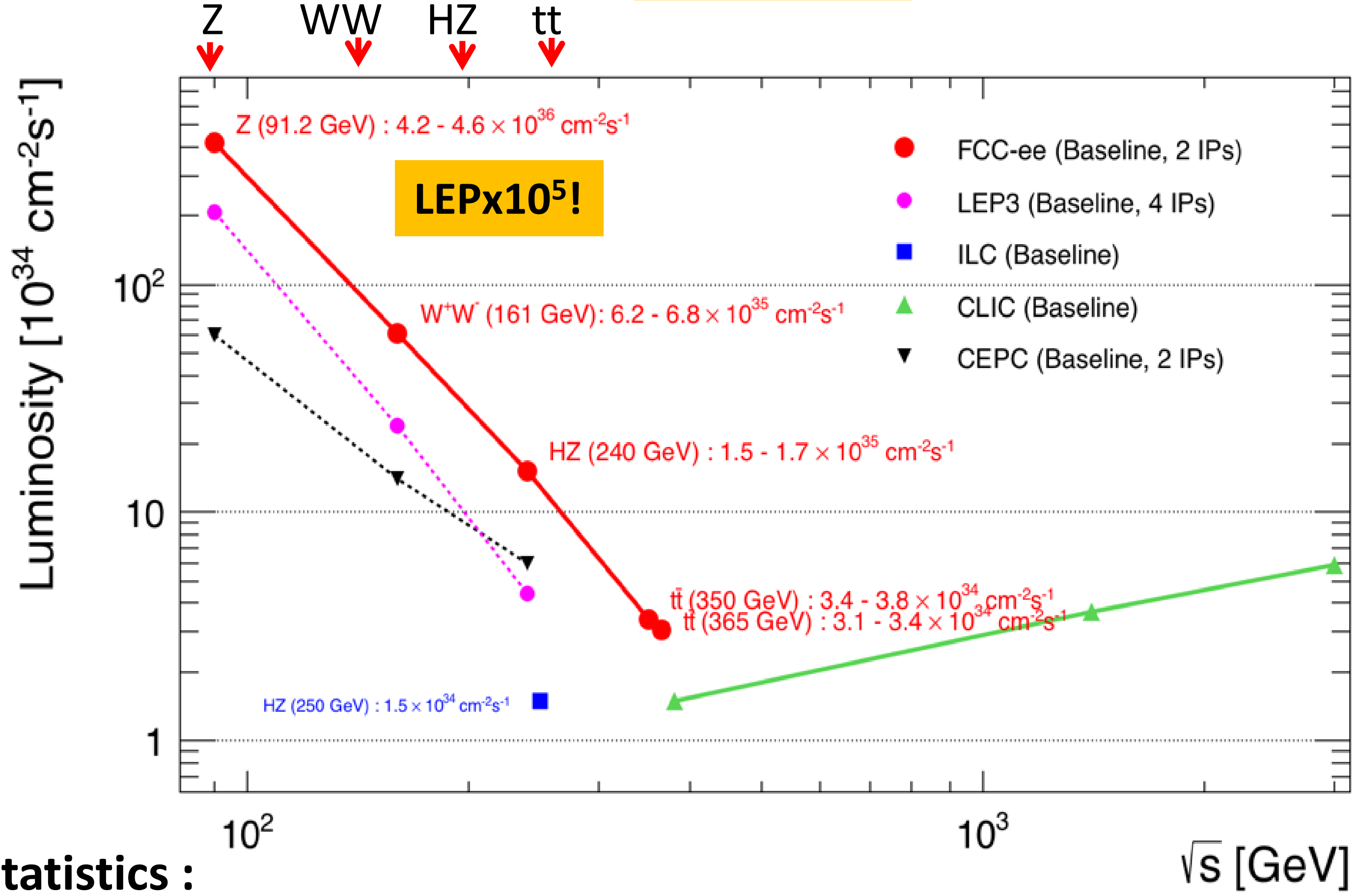

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Hadron collider parameters (*pp*)

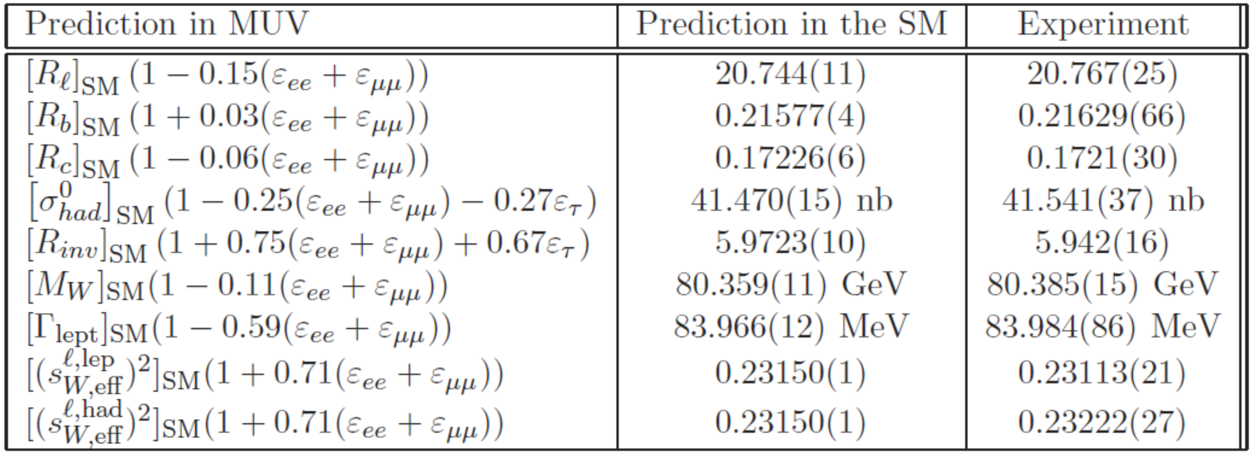
parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

(indirect) Effect of right handed neutrinos on EW precision observables

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 mu 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



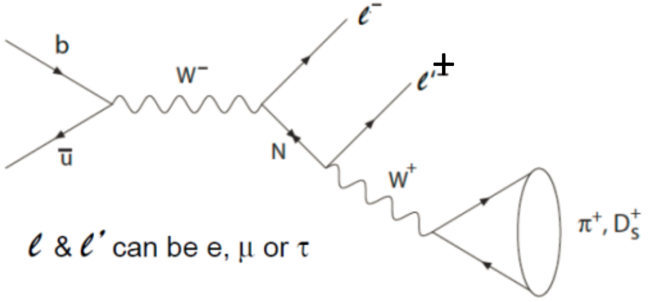
Prediction in MUV	Prediction in the SM	Experiment
$[R_\ell]_{\text{SM}}\,(1 - 0.15(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\text{SM}}\,(1 + 0.03(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.21577(4)	0.21629(66)
$[R_c]_{\text{SM}}\,(1 - 0.06(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.17226(6)	0.1721(30)
$[\sigma^0_{had}]_{\text{SM}}\,(1 - 0.25(\varepsilon_{ee} + \varepsilon_{\mu\mu}) - 0.27\varepsilon_\tau)$	41.470(15) nb	41.541(37) nb
$[R_{inv}]_{\text{SM}}\,(1 + 0.75(\varepsilon_{ee} + \varepsilon_{\mu\mu}) + 0.67\varepsilon_\tau)$	5.9723(10)	5.942(16)
$[M_W]_{\text{SM}}(1 - 0.11(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	80.359(11) GeV	80.385(15) GeV
$[\Gamma_{\text{lept}}]_{\text{SM}}(1 - 0.59(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	83.966(12) MeV	83.984(86) MeV
$[(s^{\ell,\text{lep}}_{W,\text{eff}})^2]_{\text{SM}}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[(s^{\ell,\text{had}}_{W,\text{eff}})^2]_{\text{SM}}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	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 $(s^{\ell,\text{lep}}_{W,\text{eff}})^2$ and $(s^{\ell,\text{had}}_{W,\text{eff}})^2$ are taken from Ref. [17].

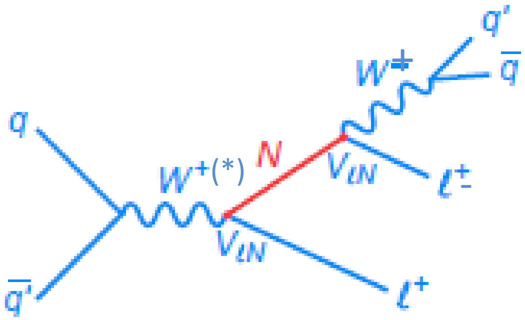
NB this is not decoupling

Detection of heavy right-handed neutrinos in collider experiments.

B factories



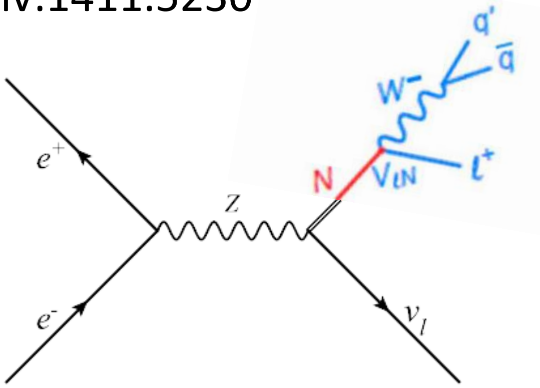
Hadron colliders



or $l^{\pm}\nu$

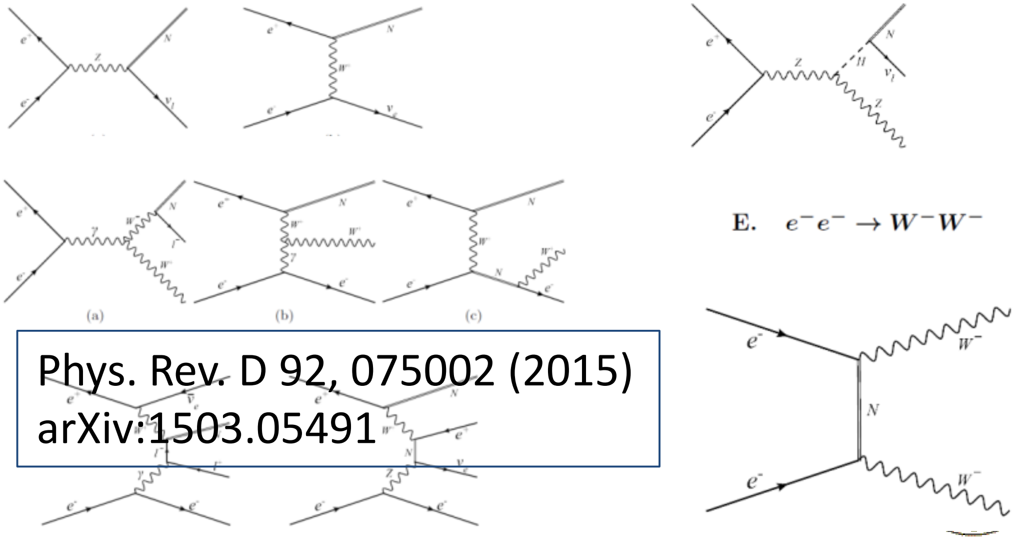
Z factory (FCC-ee, Tera-Z)

arXiv:1411.5230



or $l-\nu$

HE Lepton Collider (LEP2, CEPC, CLIC, FCC-ee, ILC, μμ)



Phys. Rev. D 92, 075002 (2015)
arXiv:1503.05491

RH neutrino production in Z decays

Production:

$$BR\left(Z^0 \to \nu_m \overline{\nu}\right) = BR\left(Z^0 \to \nu\bar{\nu}\right)|U|^2 \left(1 - \frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)^2 \left(1 + \frac{1}{2}\frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)$$

multiply by 2 for antineutrino and add contributions of 3 neutrino species (with different $|U|^2$)

Decay

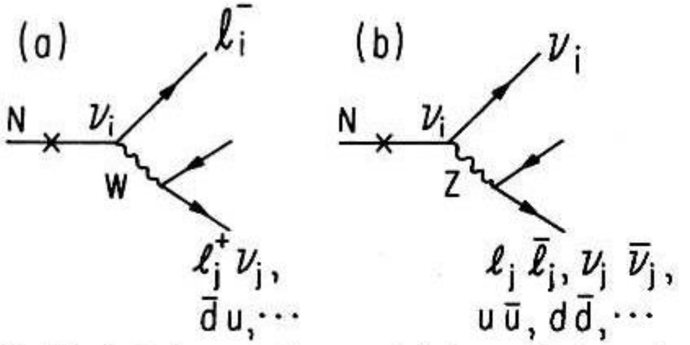


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

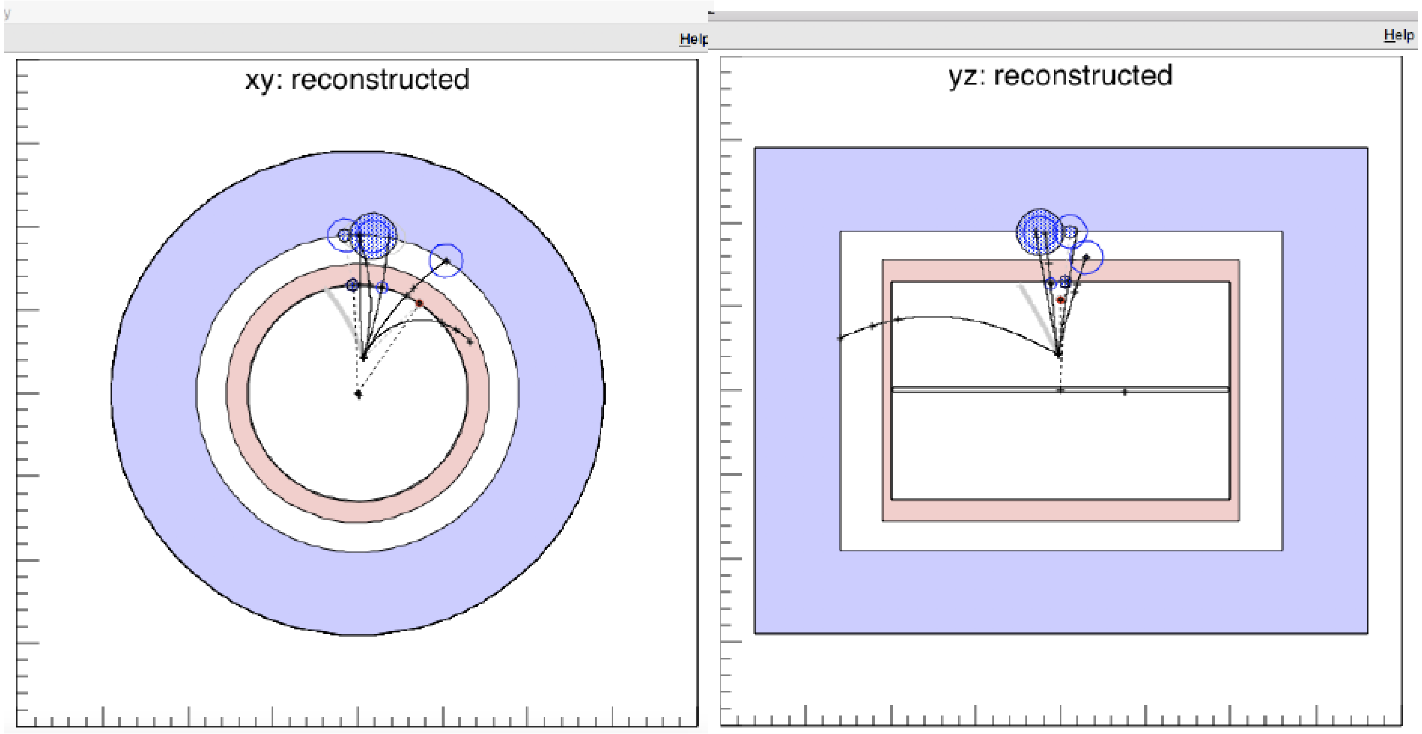
$$L \approx \frac{3\ \text{cm}}{|U|^2\left(m_{\nu_m}(\mathrm{GeV}/c^2)\right)^6}$$

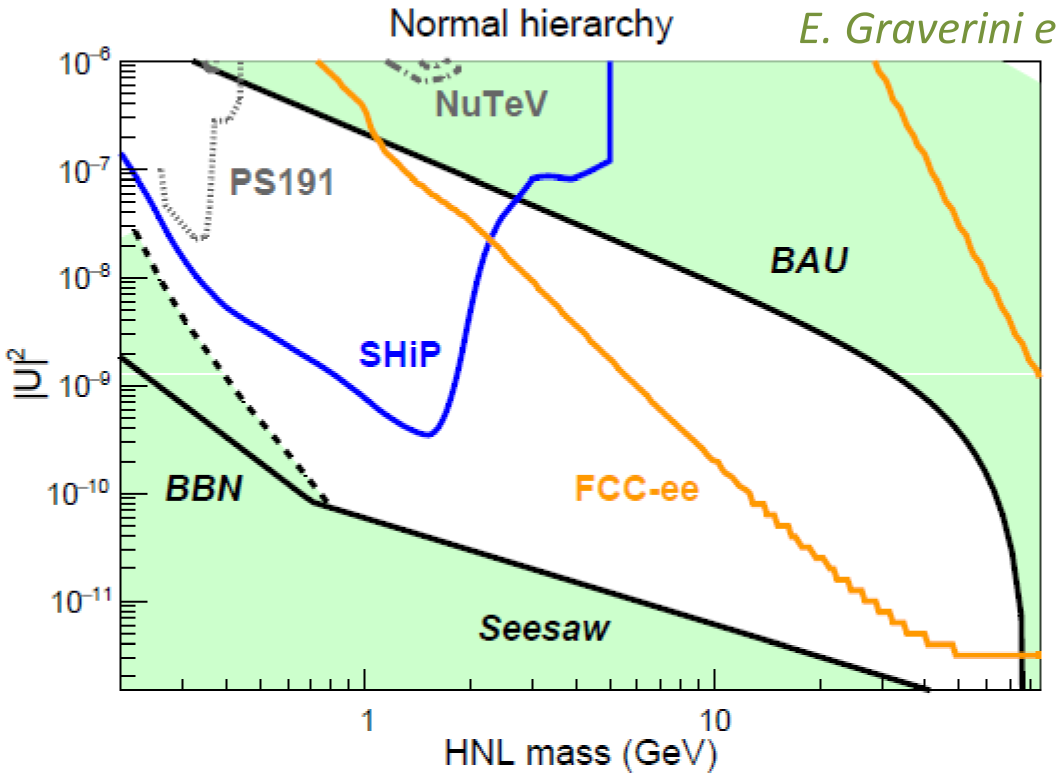
NB CC decay always leads to $\geq$ 2 charged tracks

Backgrounds : four fermion: e+e- → W^{*+} W^{*-} e+e- → Z*(vv) + (Z/γ)*

Long life time → detached vertex for ~<M_Z

Simulation of heavy neutrino decay in a FCC-ee detector



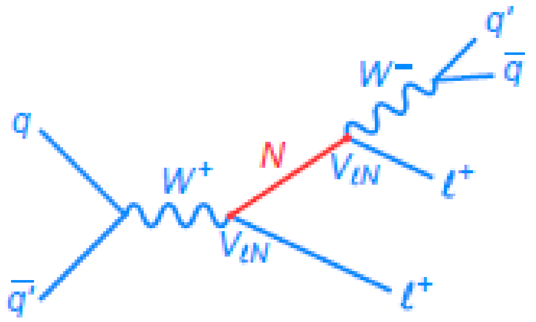


E. Graverini et al

(a) Decay length 500 μm to 2 m

with 5 10^{12} Z

Outlook for FCC-hh



We have seen that the Z factory offers a clean method
for detection of Heavy Right-Handed neutrinos
Ws are less abundant at the lepton colliders

At the 100 TeV pp 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
allows for a significant background reduction.

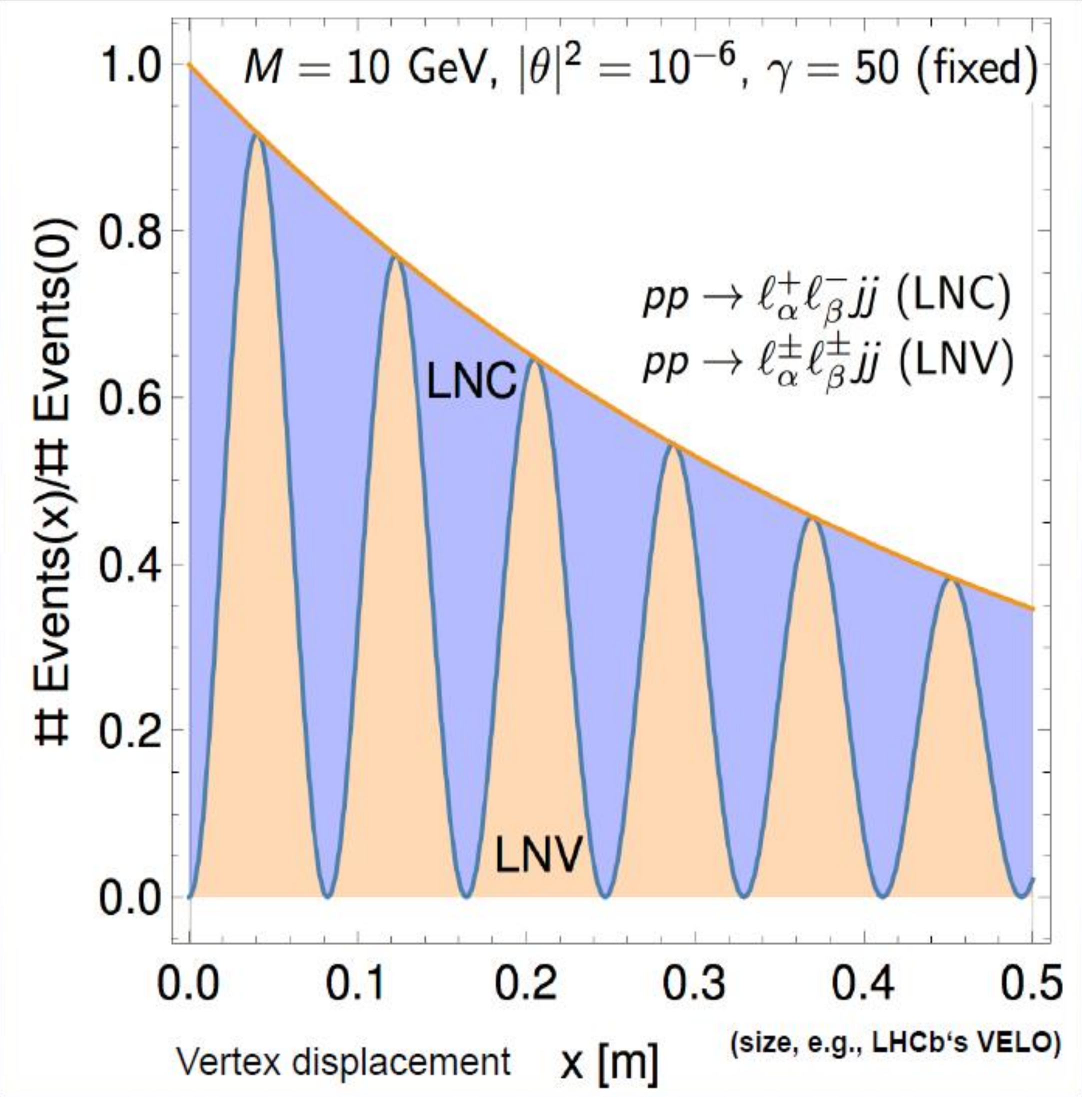
But it allows also a characterization both in flavour and charge of the produced neutrino, thus information of the flavour sensitive mixing angles and a test of the fermion violating nature of the intermediate (Majorana) particle.

VERY interesting...

Recent result: Heavy neutrino-antineutrino oscillations at colliders can be resolvable

Example:
Linear seesaw (inverse mass ordering)

(using the prediction for ΔM in the minimal linear seesaw model for inverse neutrino mass ordering)



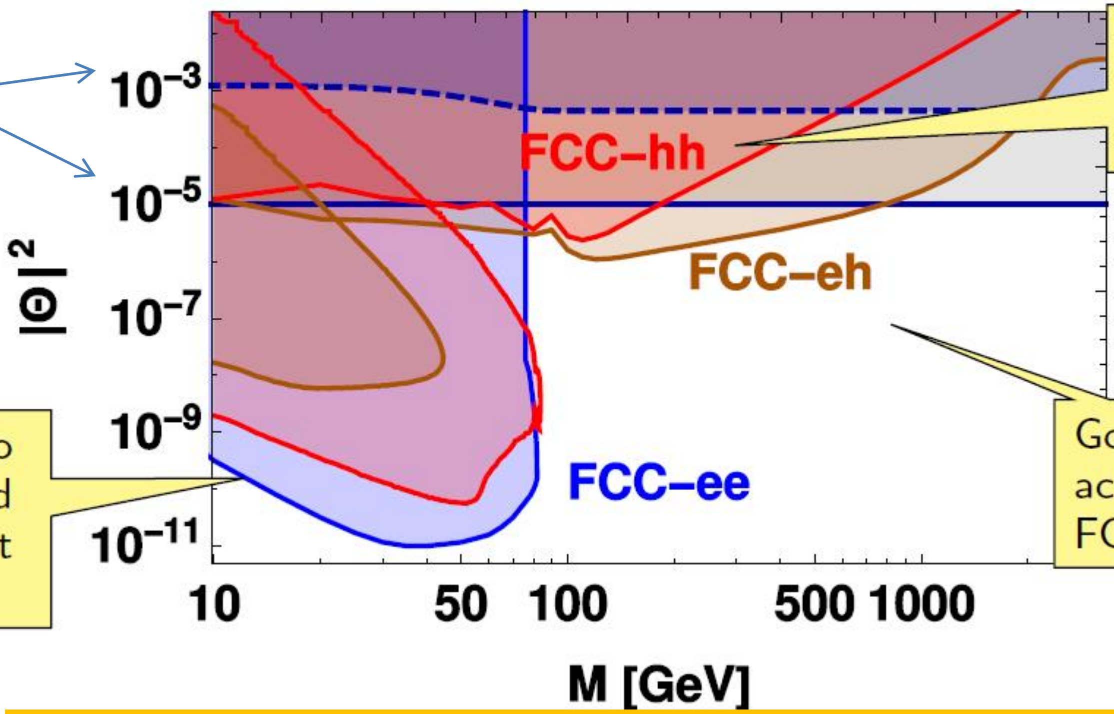
S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

Summary

Another example of Synergy
while ee covers a large part of space very cleanly ,
its either 'white' in lepton flavour or the result of EWPOs etc
Observation at FCC –hh or eh would test flavour mixing matrix!

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search

EWPO



FCC-hh able to test all flavour combinations.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Good sensitivity reach from FCC-hh & FCC-eh.

detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

CONCLUSIONS

-- 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

-- The right-handed neutrino search and study is not, as we thought 5 years ago, desperate. It is also a very interesting example of complementarity between the FCCs.

-- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities.