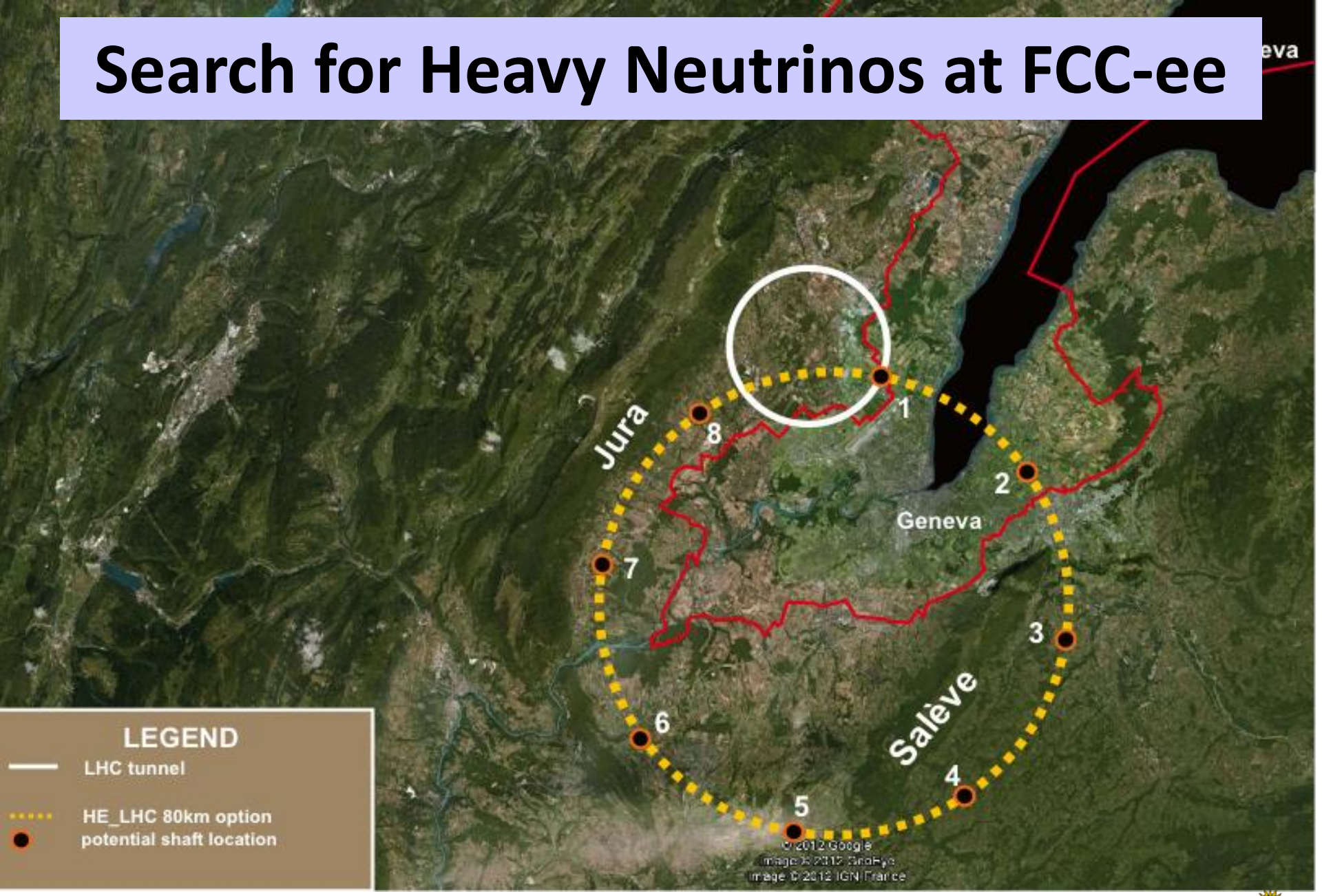
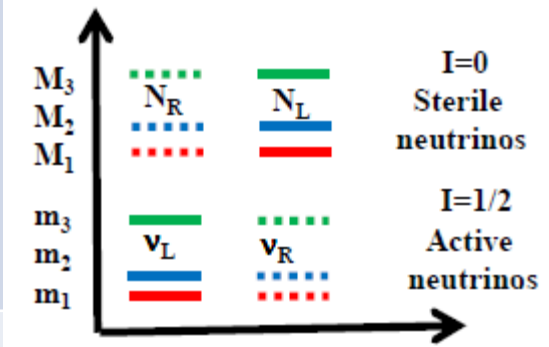
Search for Heavy Neutrinos at FCC-ee



Neutrinos : the New Physics there is… and a lot of it!

forgive the confusion between fields and particle notations

SM	Dirac mass term only ≡ «Yukawa»	Majorana mass term only	Dirac AND Majorana mass terms
ν_L $\bar{\nu}_R$ I= ½ ½	ν_L ν_R $\bar{\nu}_R$ $\bar{\nu}_L$ ½ 0 ½ 0	ν_L ‘ $\bar{\nu}_R$ ‘ ½ ½	
X 3 Families	X 3 Families	X 3 Families	
6 massless states **wrong**	3 masses 12 states 3 active neutrinos 3 active antinu’s **6 sterile neutrinos…** 3 mixing angles 1 CP violating phase **$0\nu\beta\beta = 0$**	3 masses 6 active states **No steriles** 3 mixing angles 3 CP violating phases **$0\nu\beta\beta \neq 0$**	6 masses (Majorana) 12 states 6 active states **6 sterile neutrinos…** More mixing angles and CPV phases **$0\nu\beta\beta \neq 0$** (different than pure Majorana case if m_N<100 MeV) ➔ **Leptogenesis and Dark matter**

Mass hierarchies are all unknown except $m_1 < m_2$

Preferred scenario has both Dirac and Majorana terms …

… many physics possibilities and experimental challenges

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 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 (Serguei)
  ➔ Higgs and Z visible exotic decays $H \rightarrow \nu_i \; \bar{N}_i$ and $Z \rightarrow \nu_i \; \bar{N}_i$ also $W \rightarrow l_i \; \bar{N}_i$
  ➔ violation of unitarity and lepton universality in Z, W or τ decays
  -- etc... etc...

-- Couplings are small (m_ν / m_N) *(but who knows?)* and generally out of reach of hadron colliders (but this deserves to be revisited for detached vertices @LHC, HL-LHC, FCC-hh)

some REFERENCES

PHYSICAL REVIEW D VOLUME 29, NUMBER 11 1 JUNE 1984

Extending limits on neutral heavy leptons

Michael Gronau*
Department of Physics, Syracuse University, Syracuse, New York 13210

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arxiv:1208.3654

Higgs Decays in the Low Scale Type I See-Saw Model

C. Garcia Cely[a], A. Ibarra[a], E. Molinaro[b] and S. T. Petcov[c,d] [1]

ois 60510

EAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–PPE/96–195

18 December 1996

Search for Neutral Heavy Leptons Produced in Z Decays

DELPHI Collaboration

theories of the electroweak strong interactions. At presen
and mixings with ordinary neutrinos of these leptons are v

The Role of Sterile Neutrinos in Cosmology and Astrophysics

Alexey Boyarsky*†, Oleg Ruchayskiy‡ and Mikhail Shaposhnikov‡

The νMSM, Dark Matter and Neutrino Masses

Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov

Institut de Théorie des Phénomènes Physiques,

I-1015 Lausanne, Switzerland

5)

Phys.Lett.B631:151-156,2005
arXiv:hep-ph/0503065

Preprint typeset in JHEP style - HYPER VERSION

FERMILAB-PUB-08-086-T, NSF-KITP-08-54, MADPH–06–1466, DCPT/07/198, IPPP/07/99

The Search for Heavy Majorana Neutrinos

Anupama Atre[1,2], Tao Han[2,3,4], Silvia Pascoli[5], Bin Zhang[4*]

RHASnu's production in Z decays

Production:

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

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

Decay

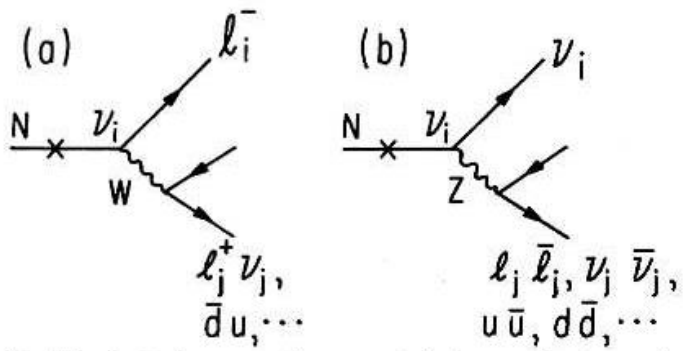


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

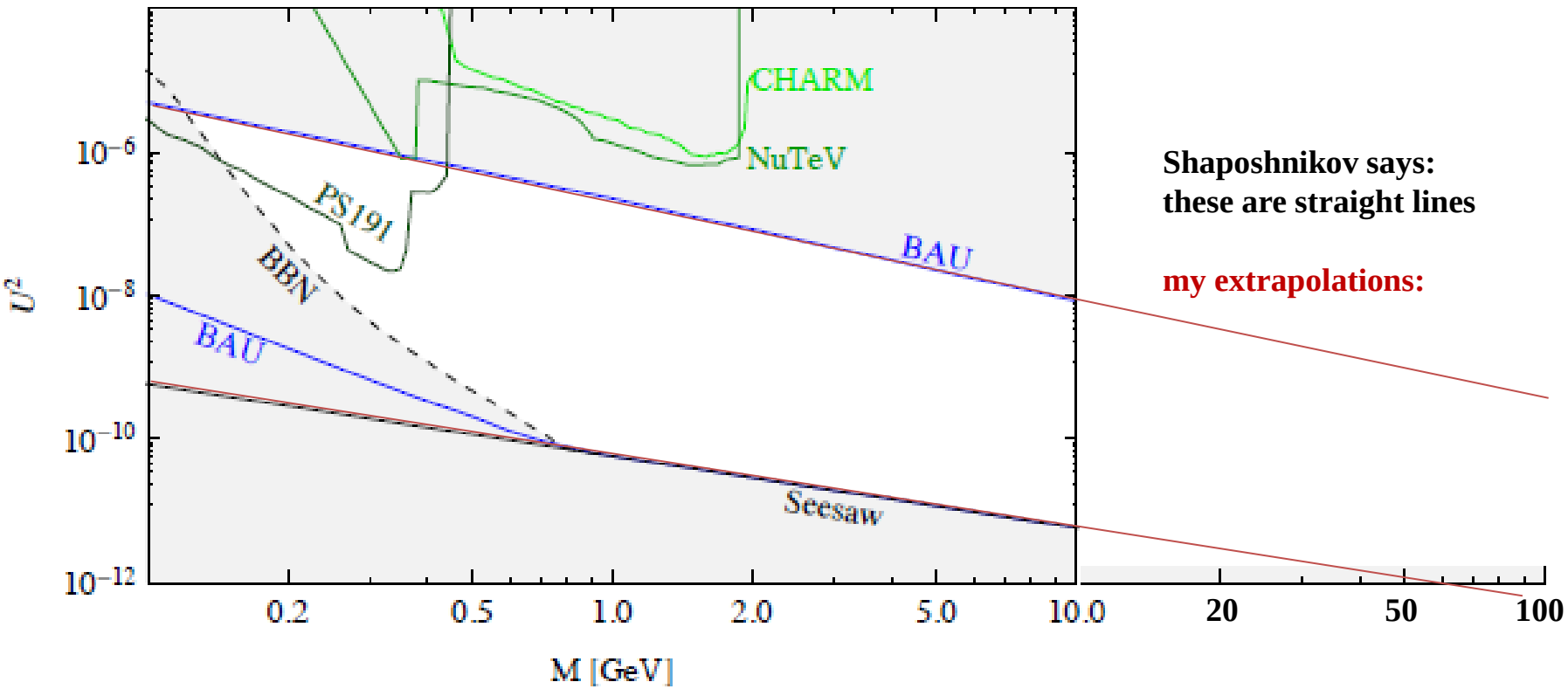
$$L \approx \frac{3\ \text{cm}}{|U|^2\,(m_{\nu_m}(\text{GeV}/c^2))^6}$$

NB CC decay always leads to ≥ 2 charged tracks

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

Typical Interesting Region (from Shaposhnikov)

➔ $|U|^2 \sim 10^{-9}$ to 10^{-12} @ 50 GeV

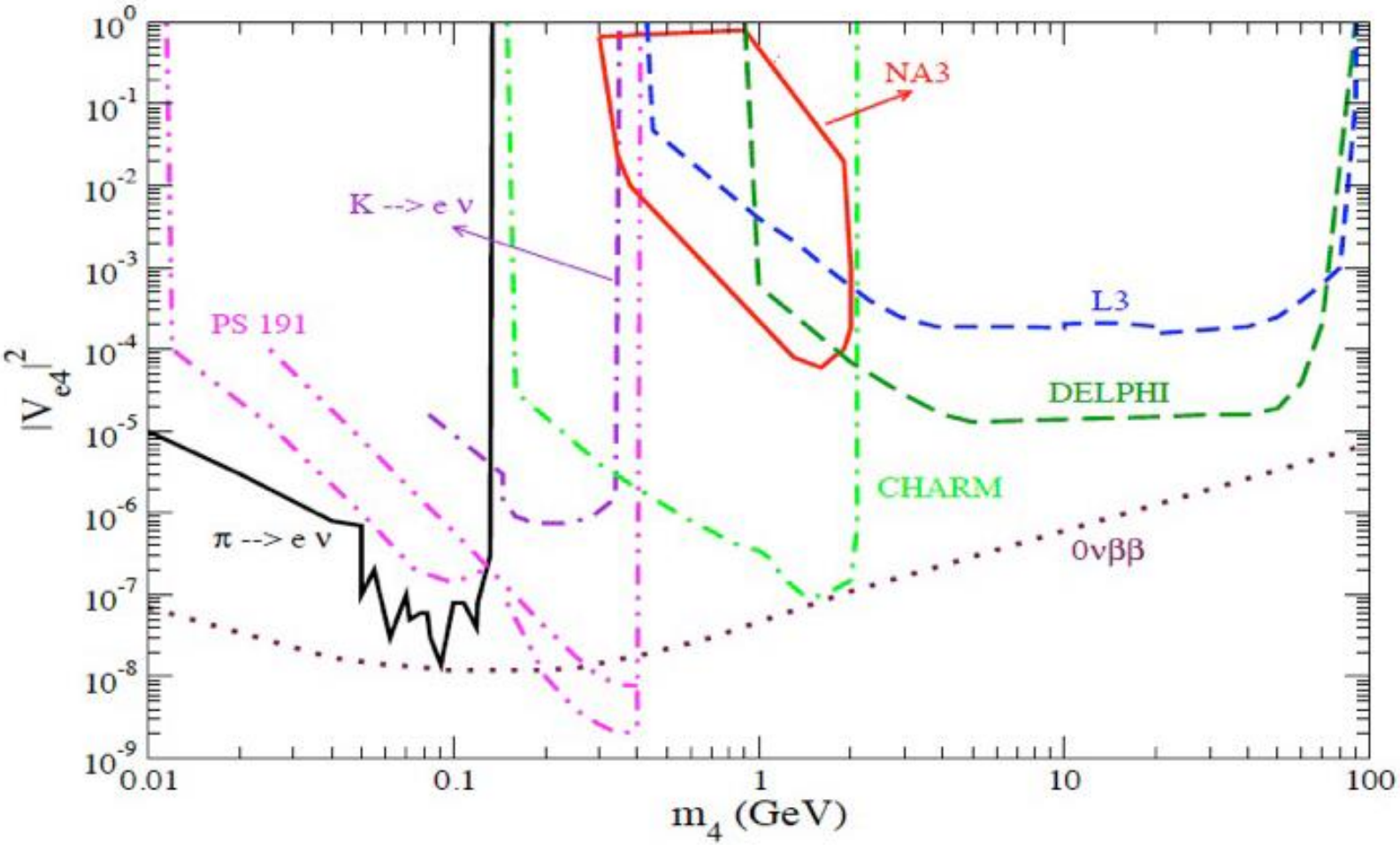


Shaposhnikov says: these are straight lines

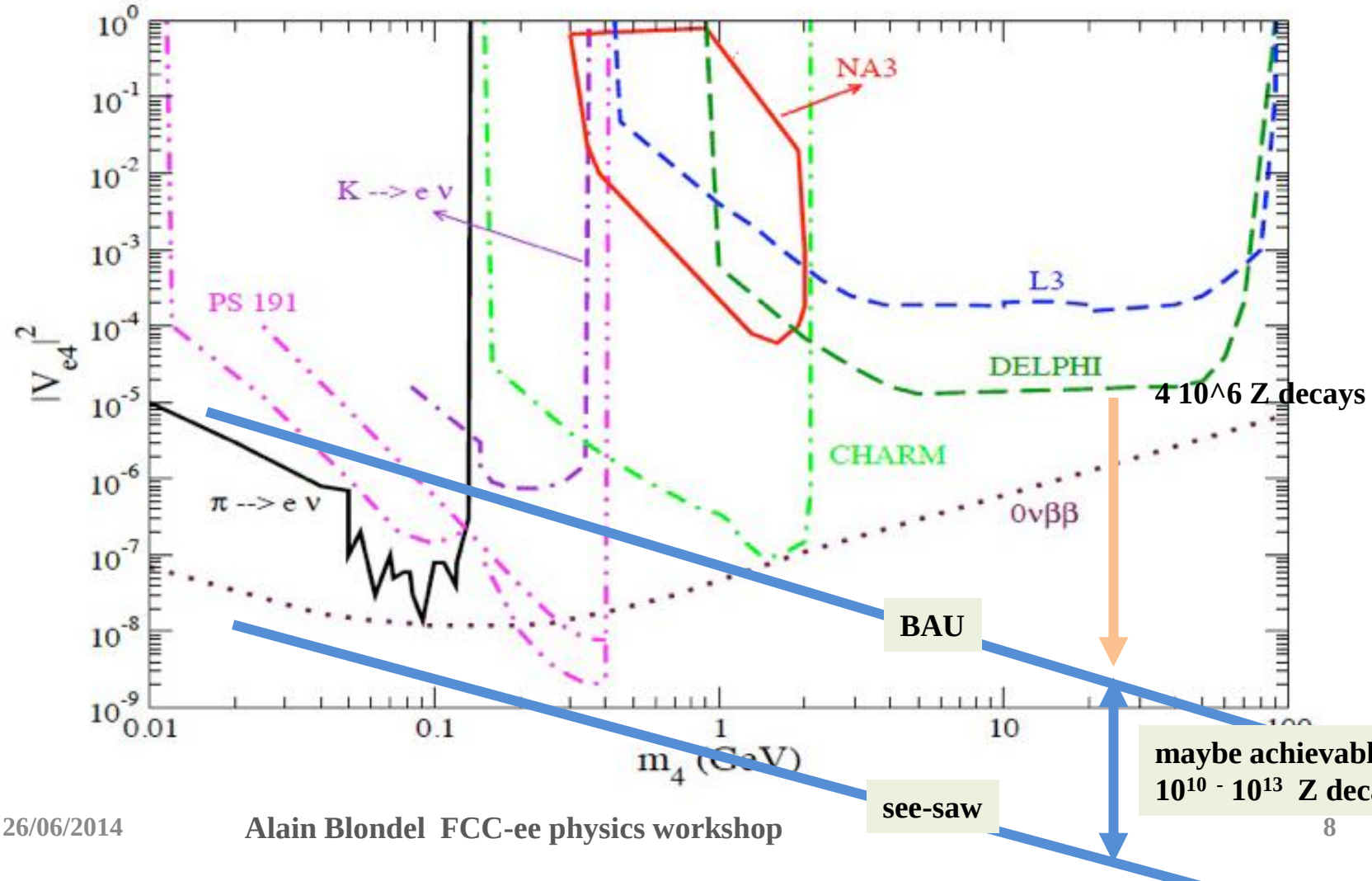
my extrapolations:

heavy neutrino mass ~ M

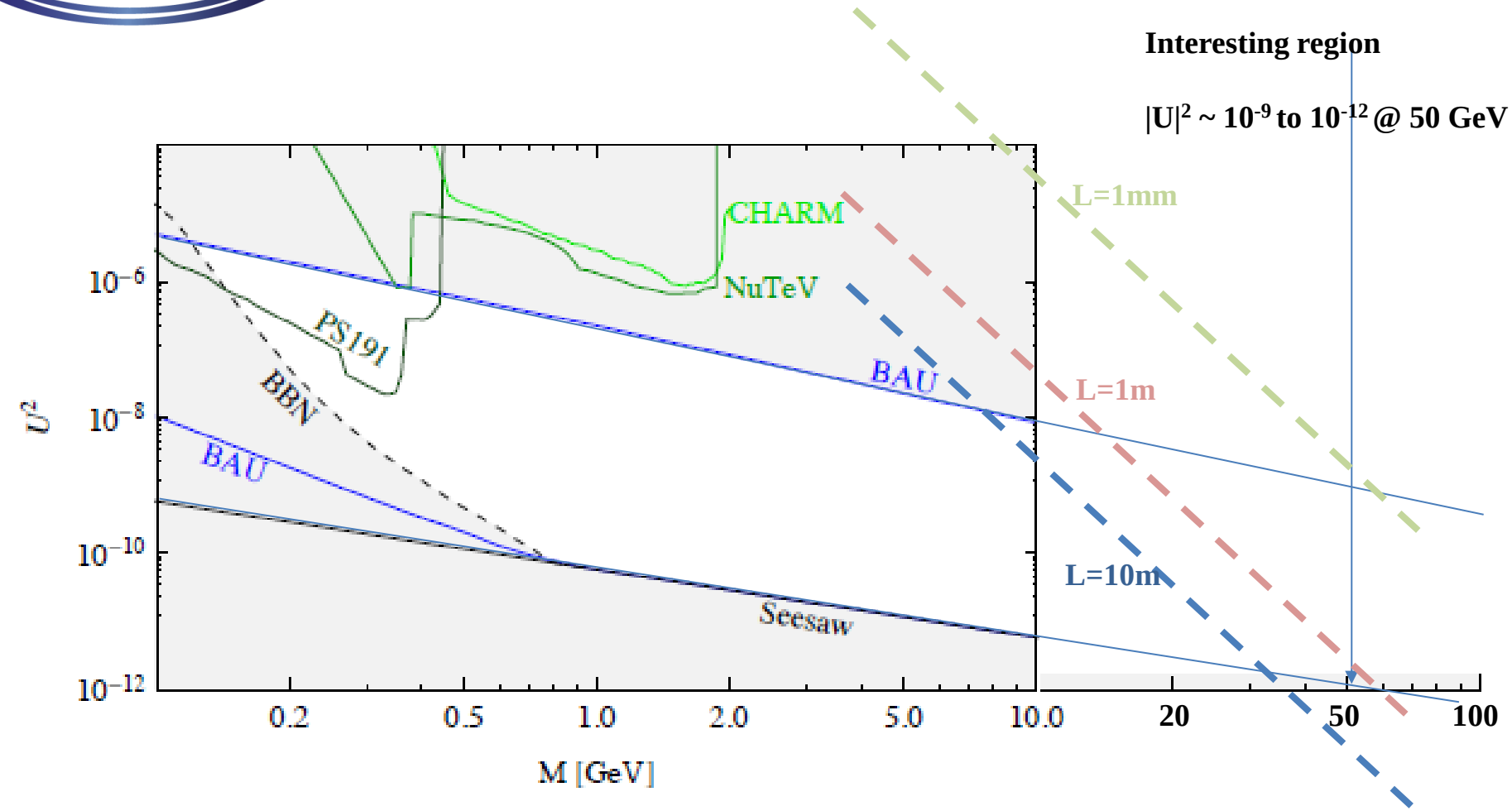
Existing limits



Order-of-magnitude extrapolation of existing limits



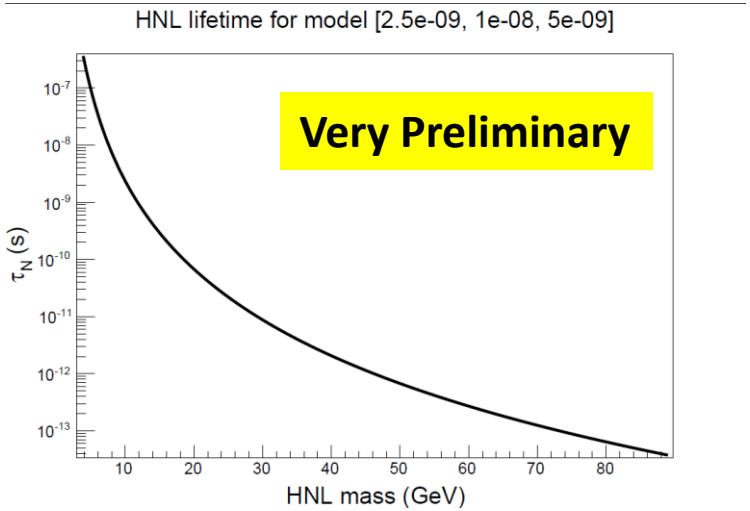
Decay length

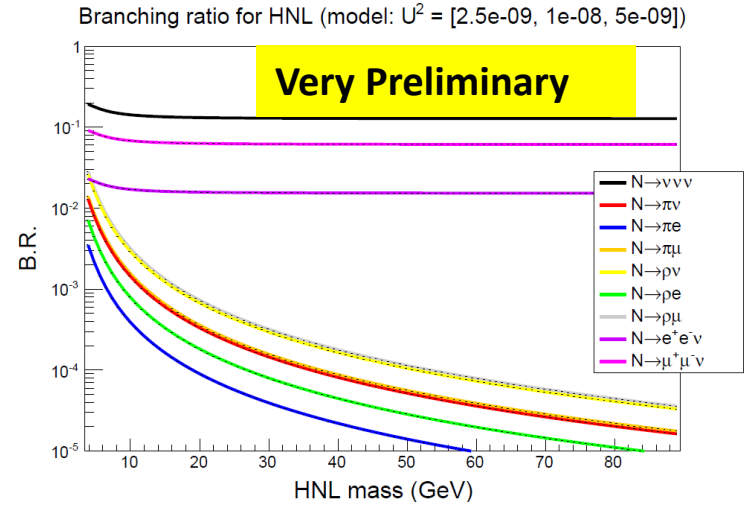


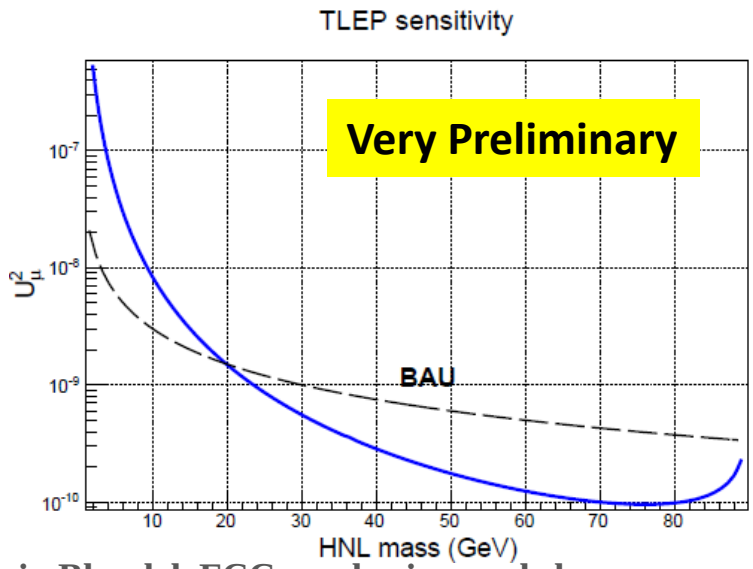
heavy neutrino mass ~ M

IFF this is correct, a large part of the interesting region will lead to detached vertices ... ➔very strong reduction of background!

More 'professional' study started this morning (Nicola Serra) with 3 neutrino scenario (first plots for fun with 10^{12} Z decays)







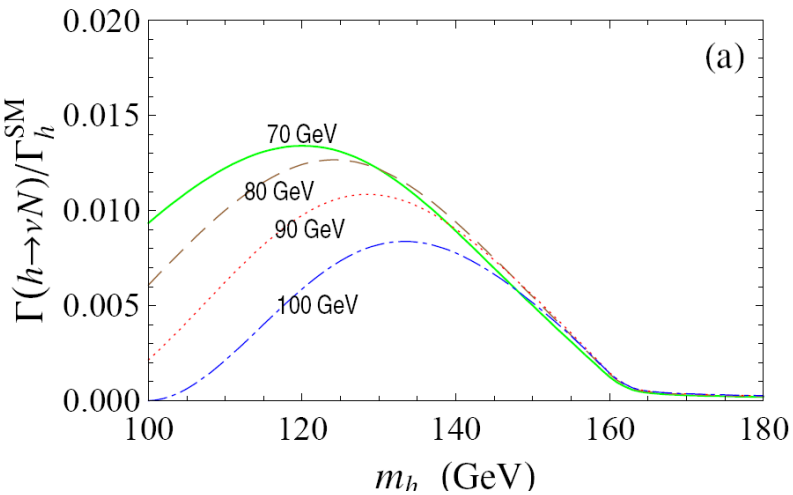
Indicates one would be able to enter BAU region with FCC-ee

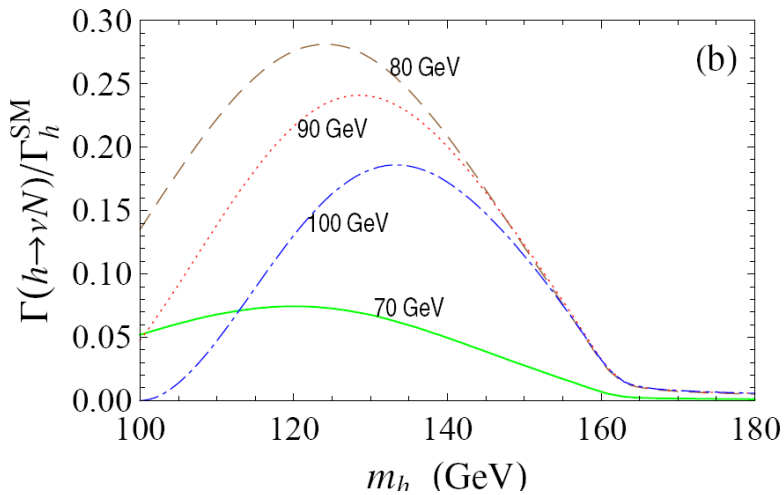
Higgs Decay into nu + N

$h \to \nu N$ allowed if N is light enough

Lepton universaility constraints must be met

$$\theta_{\nu_e - N} < 0.05, \quad \theta_{\nu_\mu - N} < 0.05, \quad \theta_{\nu_\tau - N} < 0.08$$





NB neutrino is the only particle that does not couple prop. to its mass!

Chen, He, Tandean, Tsai (2011)

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arxiv:1208.3654

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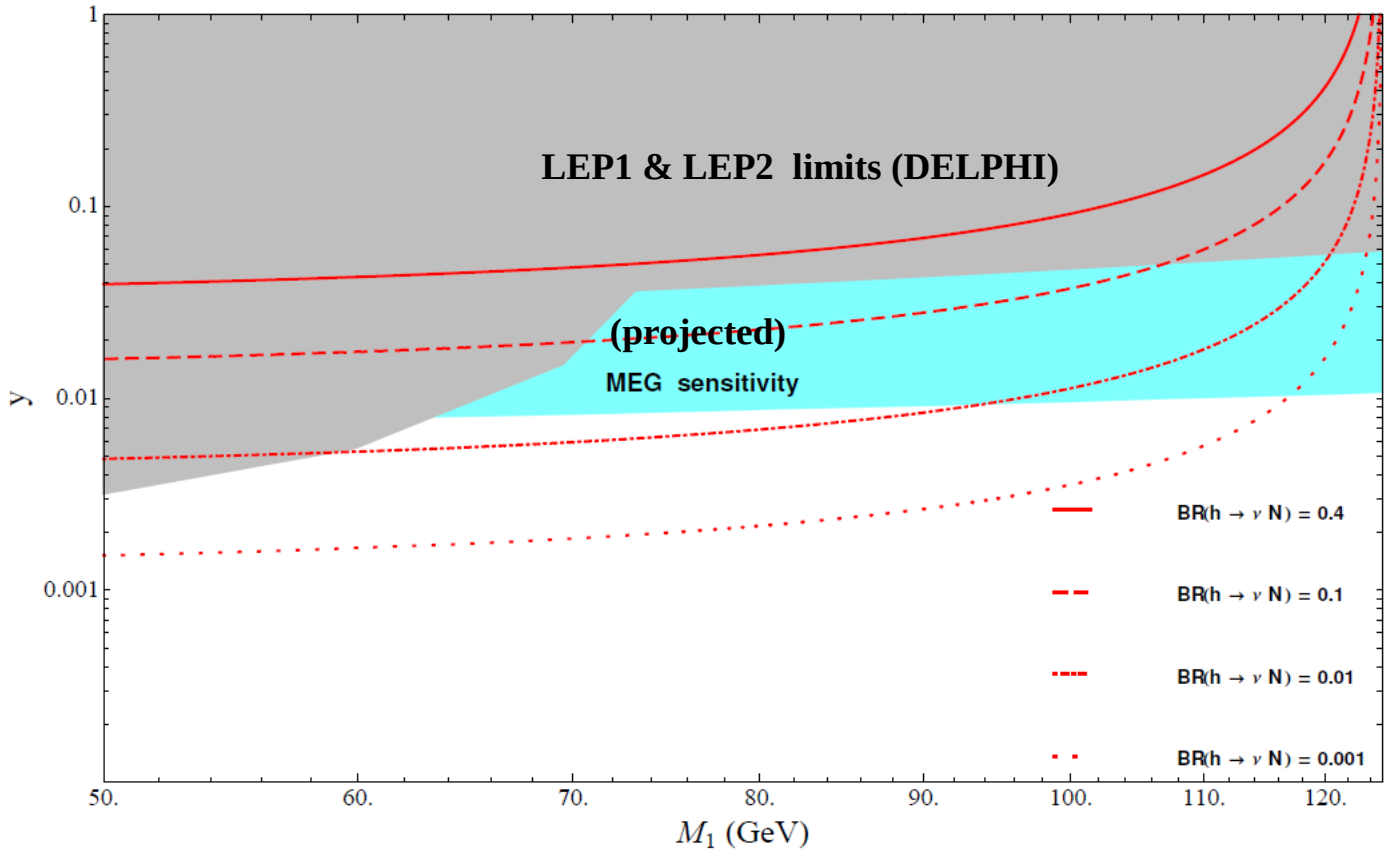

Also directly in e+e- annihilations for higher masses, and related to μ→eγ , and μ→e

Conclusion and suggestion

The direct search for Heavy Neutral Leptons decays seems promising at FCC-ee !

In particular may lead to spectacular 'detached vertex' signatures in Z-> neutrino decays

needs

- **firm up the numbers taking into account neutrino mixing**
- **simulate the signal and the 4 fermion background at Z peak**
- **see what is the effect of known neutrino mixing (was not known in 1997)**
- **include study in H → νN decays (not helicity-suppressed)**

<u>May motivate running at Z peak for longer than just one year.</u>

What about an 'invisible' phenomenology/exp (sub)working group for the FCC study?