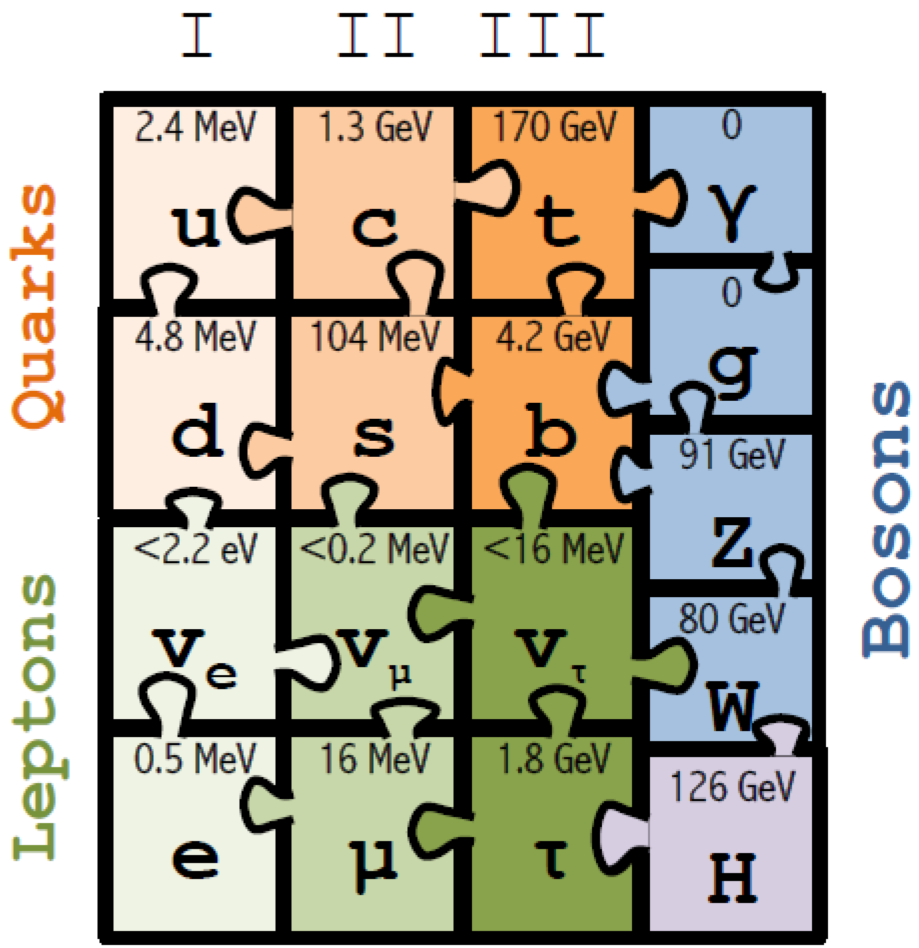
The Hunt for Heavy Neutrinos at the Z & H factory

Alain Blondel University of Geneva
with many thanks to
S. Ganjour, M. Mitra, S. Pascoli, N. Serra, M. Shaposhnikov

courtesy J. Wenninger

8/15/2014

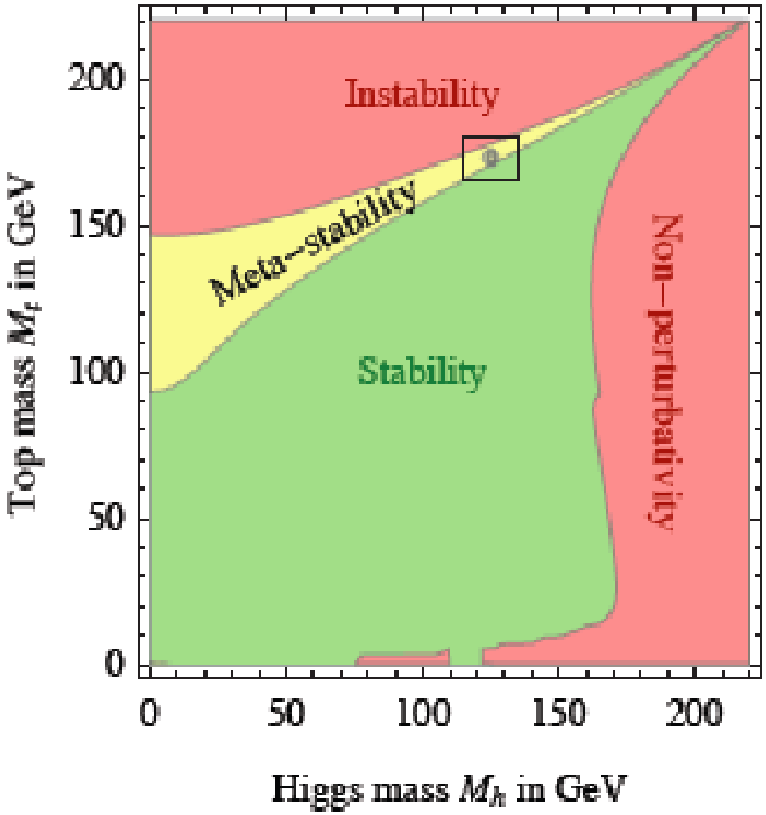
1997-2013 Higgs boson mass cornered (LEP H, M_Z etc +Tevatron m_t , M_W)
Higgs Boson discovered (LHC)
Englert and Higgs get Nobel Prize



SM is «complete»?

(c) Sfyrla

Is it the end?



many discussions on naturalness etc…

Is it the end?

Certainly not!

-- Dark matter

-- Baryon Asymmetry in Universe

-- Neutrino masses

are experimental proofs that there is more to understand.

New Physics → New particles…

But Where Is Everybody?

Nima

But Where Is Everybody?

Nima

At higher masses -- or at smaller couplings?

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 132

FLAVOUR(267104)-ERC-23 TUM-HEP 850/12 SISSA 25/2012/EP CFTP/12-013

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]

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

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First look at the physics case of TLEP

arxiv:1308.6176

The TLEP Design Study Working Group

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G. Coignet,[d] M. Delmastro,[d] T. Alexopoulos,[e] C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J. He,[i] K. Potamianos,[j] S. Haug,[k] A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Gomez-Ceballos,[o] M. Klute,[o] M. Zanetti,[o] L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Glover,[r] F. Krauss,[r] A. Lenz,[r] M. Syphers,[s]

CERN–PPE/96–195

18 December 1996

Search for Neutral Heavy Leptons Produced in Z Decays

DELPHI Collaboration

The Role of Sterile Neutrinos in Cosmology and Astrophysics

Alexey Boyarsky*†, Oleg Ruchayskiy‡ and Mikhail Shaposhni

The νMSM, Dark Matter and Neutrino Masses

Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov

Institut de Théorie des Phénomènes Physiques,
CH-1015 Lausanne, Switzerland
2005)

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

FCC design study and FCC-ee http://cern.ch/fcc-ee
and presentations at *FCC-ee physics workshop*
http://indico.cern.ch/event/313708/

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

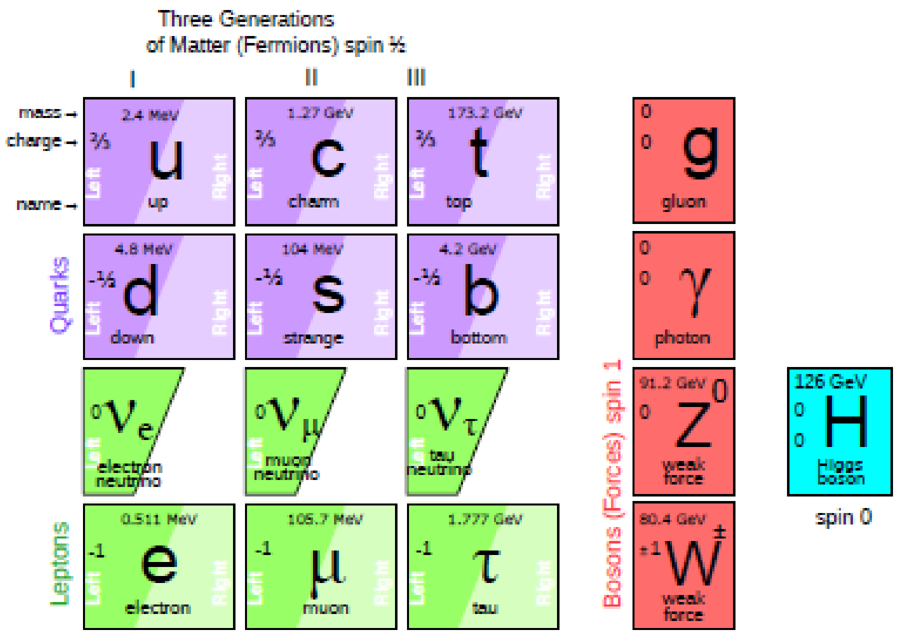
The Search for Heavy Majorana Neutrinos

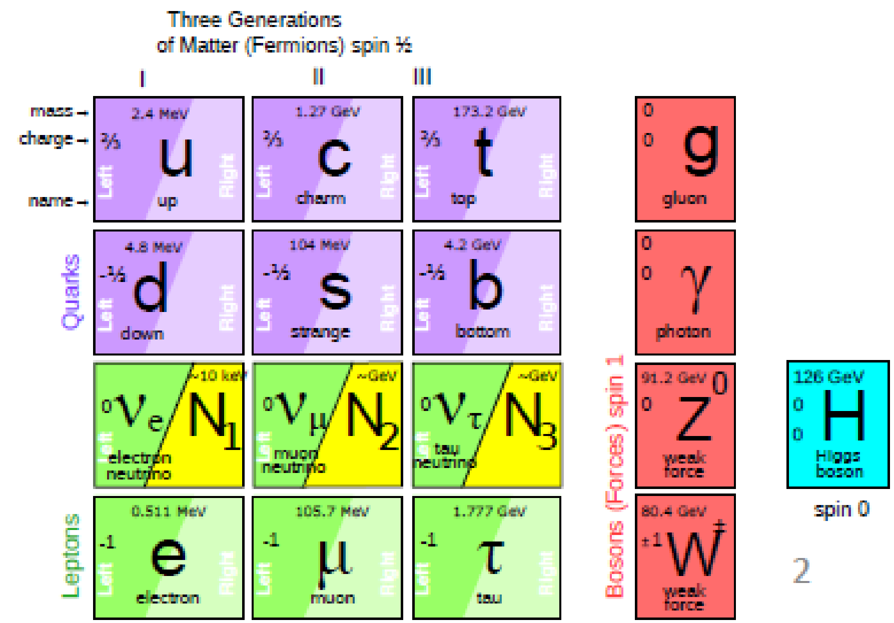
Anupama Atre[1,2], Tao Han[2,3,4], Silvia Pascoli[5], Bin Zhang[4*]

talks by Maurizio Pierini (BSM), Manqi Ruan (Higgs)
Roberto Tenchini (Top & Precision) tomorrow,
posters tonight at Future accelerator session

THE STANDARD MODEL IS COMPLETE .....

But at least 3 pieces are still missing





neutrinos have mass...

and this very probably implies new degrees of freedom

➔ Right-Handed, Almost «Sterile» (*very* small couplings) Neutrinos completely unknown masses (meV to ZeV), nearly impossile to find.

.... but could perhaps explain all: DM, BAU, ν-masses

Electroweak eigenstates

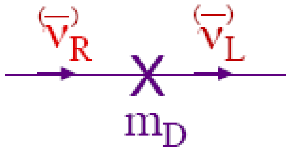
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0
I = 1/2	I = 0	

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

can't produce them
can't detect them
-- so what? --

Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term (Yukawa coupling)

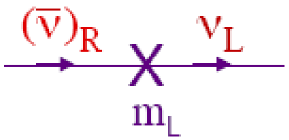
$m_D \nu_L \overline{\nu}_R$ $m_D \overline{\nu}_L \nu_R$



implies adding a right-handed neutrino (new particle)

<u>No SM symmetry</u> 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!)

It is perfectly conceivable ('natural'?) that both terms are present → 'see-saw'

Mass eigenstates

See-saw in a general way :

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

$M_R \neq 0$
$m_D \neq 0$
<u>Dirac + Majorana mass terms</u>

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

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

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

general formula — if $m_D \ll M_R$

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

m ↑

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

4 states of equal masses

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

$M_R \neq 0$
$m_D = 0$
<u>Majorana only</u>

m ↑

	ν_L	$\bar{\nu}_R$
I_{weak}=	½	½

2 states of equal masses

All have I=1/2 (active)

---

see-saw

$M_R \neq 0$
$m_D \neq 0$
<u>Dirac + Majorana</u>

m ↑

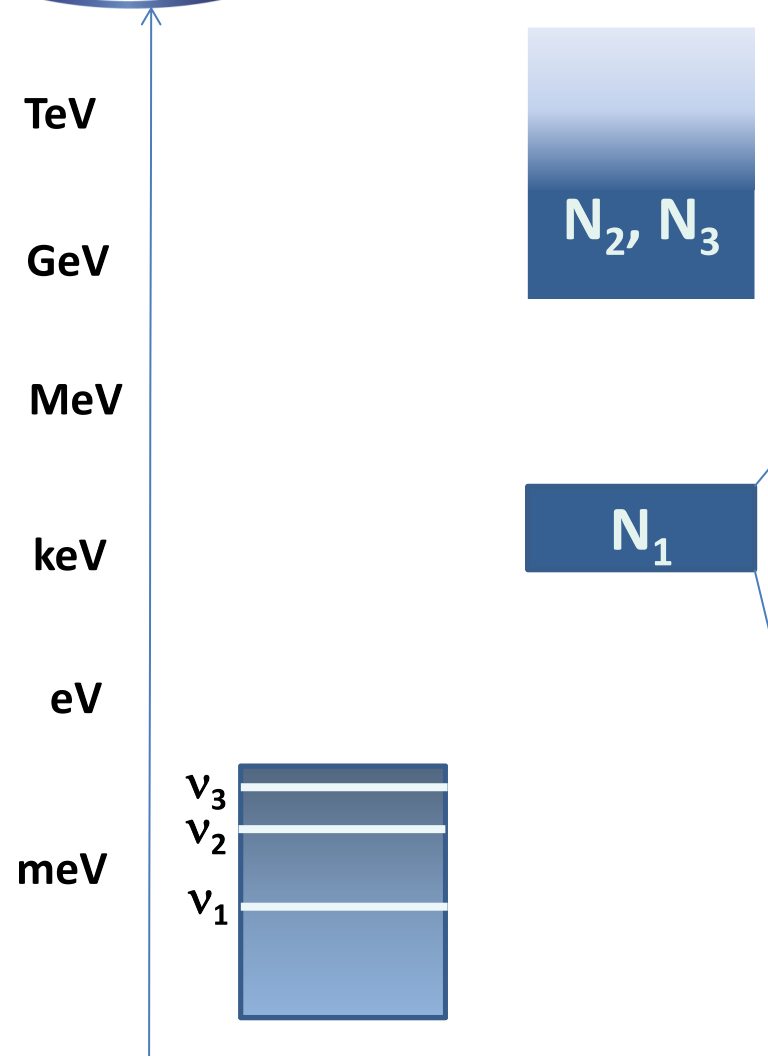
	ν_L	N_R	$\bar{\nu}_R$	$\bar{N}_L$
I_{weak}=	½	0	½	0

4 states , 2 mass levels

m1 have I=1/2 (~active)
m2 have I=0 (~sterile)

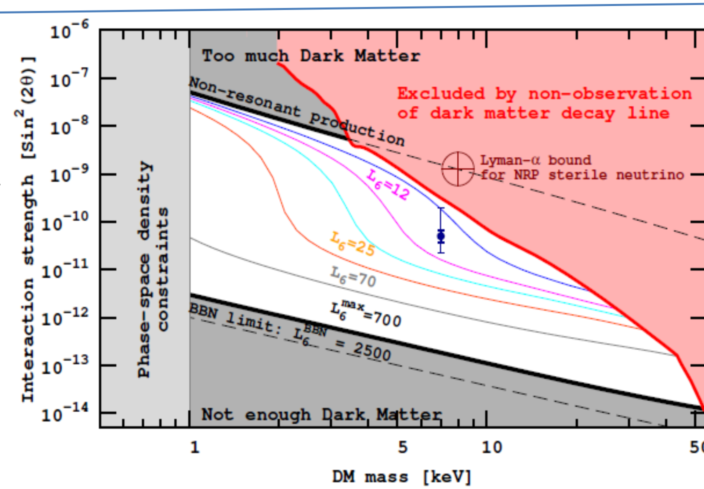
There even exists a scenario that explains everything: the νMSM

Shaposhnikov et al

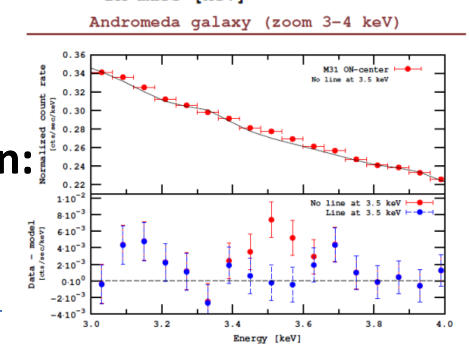


can generate Baryon Asymmetry of Universe if $m_{N2,N3}$ > 140 MeV

constrained:
mass: 1-50 keV
mixing :
10^{-7} to 10^{-13}
decay time:
$\tau_{N1} > \tau_{Universe}$



$N_1 \rightarrow \nu \gamma$
***may* have been seen:**
arxiv:1402:2301
arxiv:1402.4119



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.

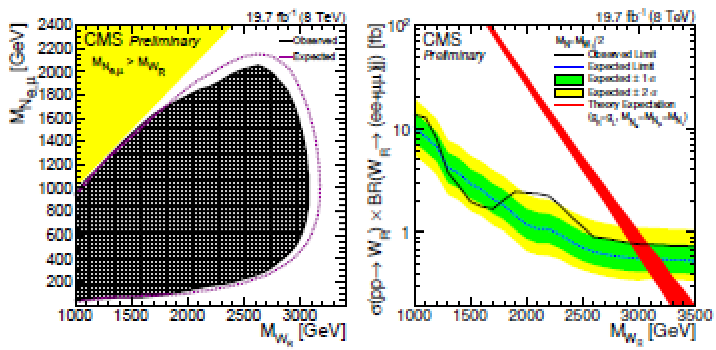
-- mixing with active neutrinos leads to various observable consequences
  -- if very light (eV) , possible effect on neutrino oscillations
  -- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$

-- 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 and Z 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 charm and b decays via $W^* \rightarrow l_i \bar{N}_i$
  → 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)

The minimal scenario νMSM is very beautiful but impossible to explore at the LHC
(I believe this statement should be revisited!)

Non minimal scenarios (e.g. involving pair production or W_R N_R production) can be investigated



CMS PAS EXO-13-008

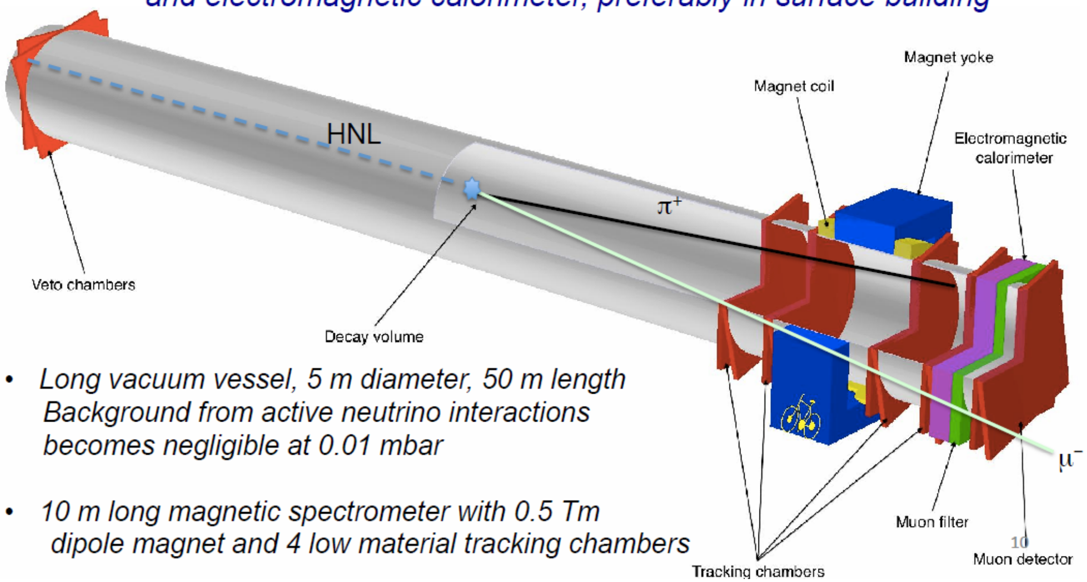
Figure 5: The 95% CL exclusion region in the (M_{W_R}, M_{N_ℓ}) plane (left), and as a function of W_R boson mass with $M_N = \frac{1}{2}M_{W_R}$ (right) obtained combining the electron and muon channels. The signal cross section PDF uncertainties (red band surrounding the theoretical W_R-boson production cross section curve) are included for illustration purposes only.

Detector concept

(based on existing technologies)

- *Reconstruction of the HNL decays in the final states:* $\mu^-\pi^+$, $\mu^-\rho^+$ & $e^-\pi^+$

→ *Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building*



- *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*
- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

Proposal to search for Heavy Neutral Leptons at the SPS

(CERN-SPSC-2013-024 / SPSC-EOI-010)

Disclaimer: It is not a classical neutrino physics experiment

On behalf of:

W. Bonivento[1,2], A. Boyarsky[3], H. Dijkstra[2], U. Egede[4], M. Ferro-Luzzi[2], B. Goddard[2], A. Golutvin[4], D. Gorbunov[5], R. Jacobsson[2], J. Panman[2], M. Patel[4], O. Ruchayskiy[6], T. Ruf[2], N. Serra[7], M. Shaposhnikov[6], D. Treille[2 (‡)]

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[2] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[3] Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[4] Imperial College London, London, United Kingdom
[5] Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
[6] Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[7] Physik-Institut, Universität Zürich, Zürich, Switzerland
(‡) retired

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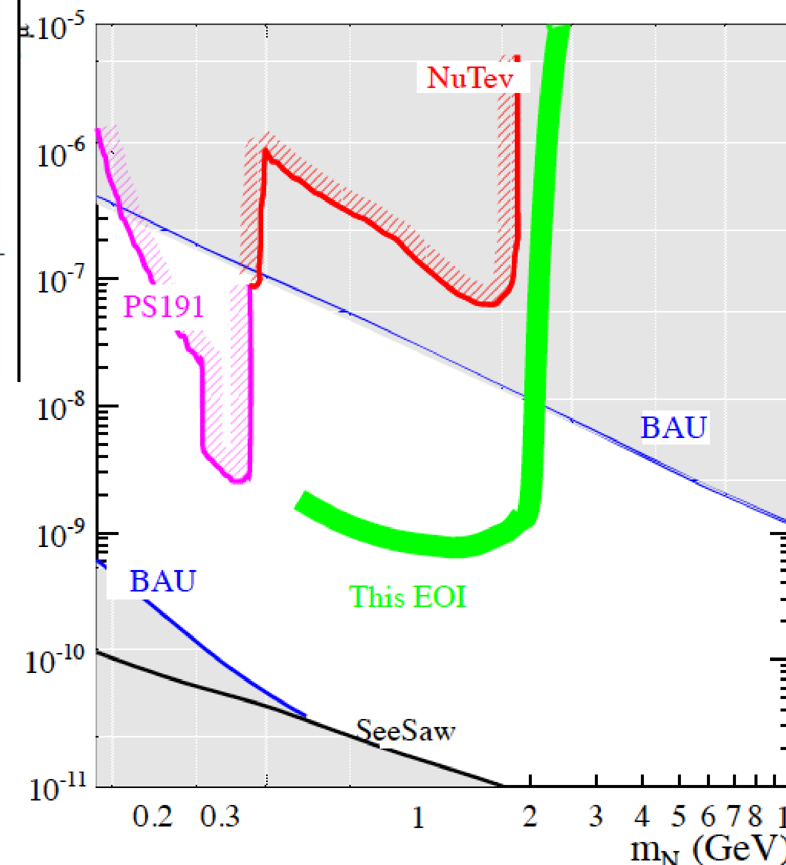
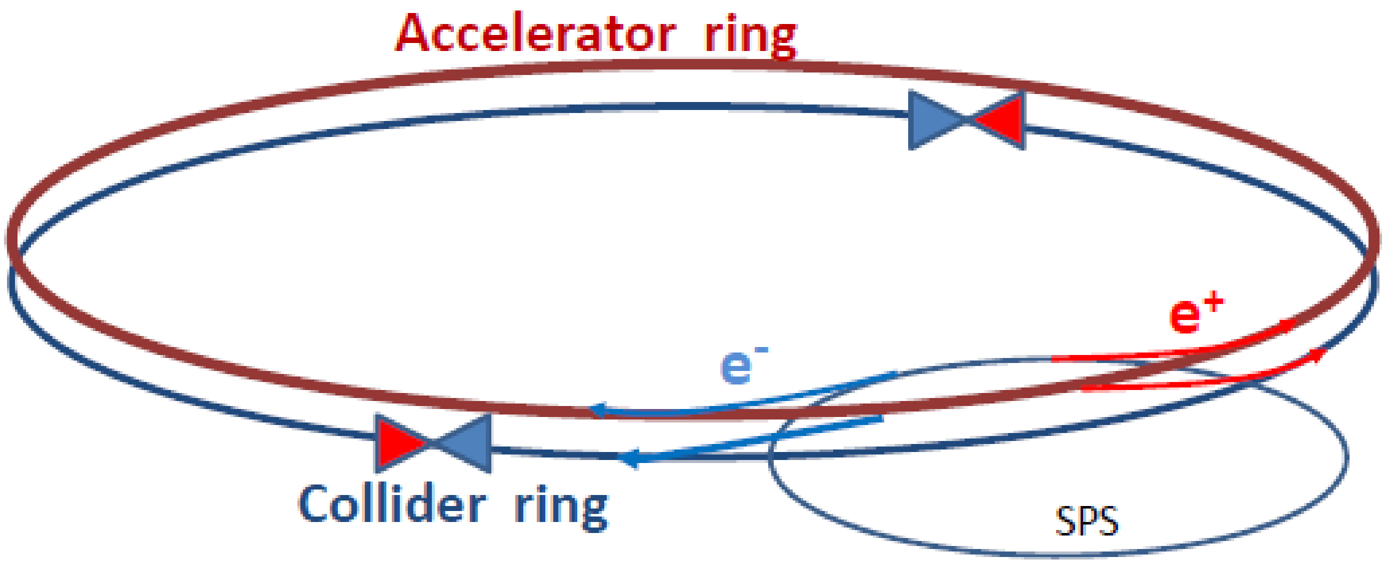


Back to the future

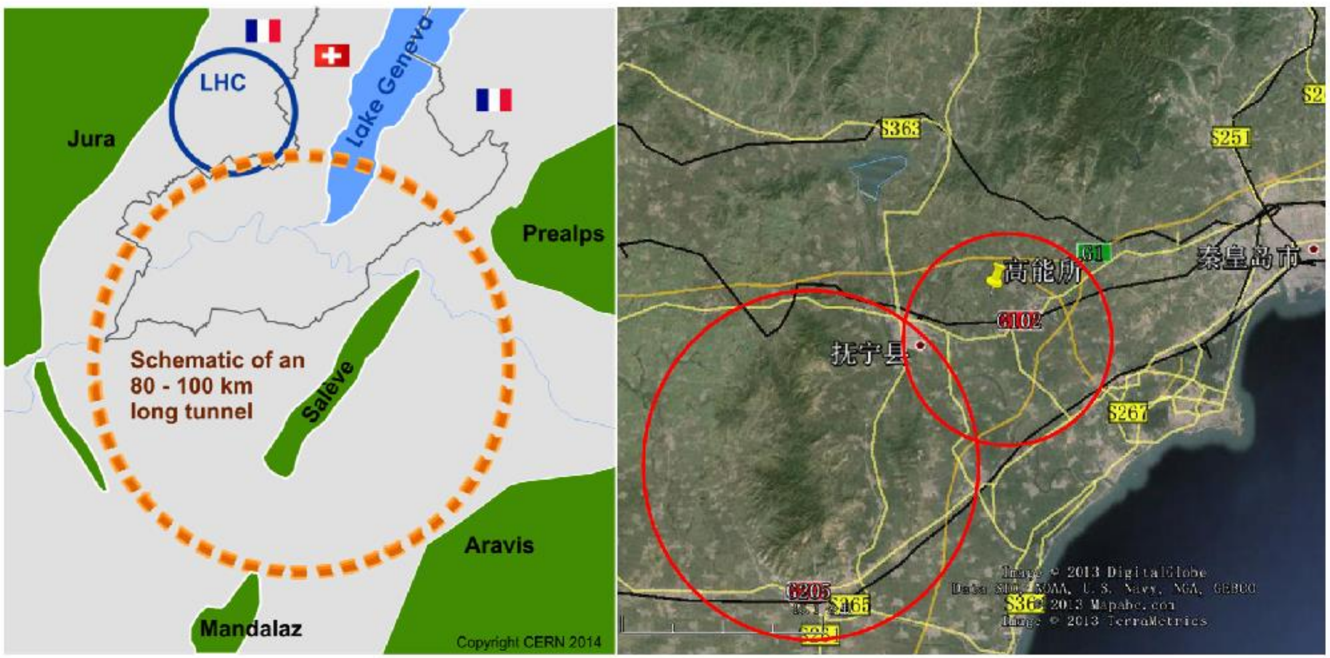


30 years later and with experience gained on LEP, LEP2 and the B factories we can propose a Z,W,H,t factory of many times the luminosity of LEP, ILC, CLIC

CERN is launching a 5 years international design study of Circular Colliders
100 TeV pp collider (FCC-hh) and high luminosity e+e- collider (FCC-ee)

IHEP in China is studying CEPC a 50-70 km ring with e+e- Higgs factory followed by HE pp.

FCCee & CEPC



LHC
Lake Geneva
Jura
Prealps
Schematic of an
80 - 100 km
long tunnel
Salève
Aravis
Mandalaz
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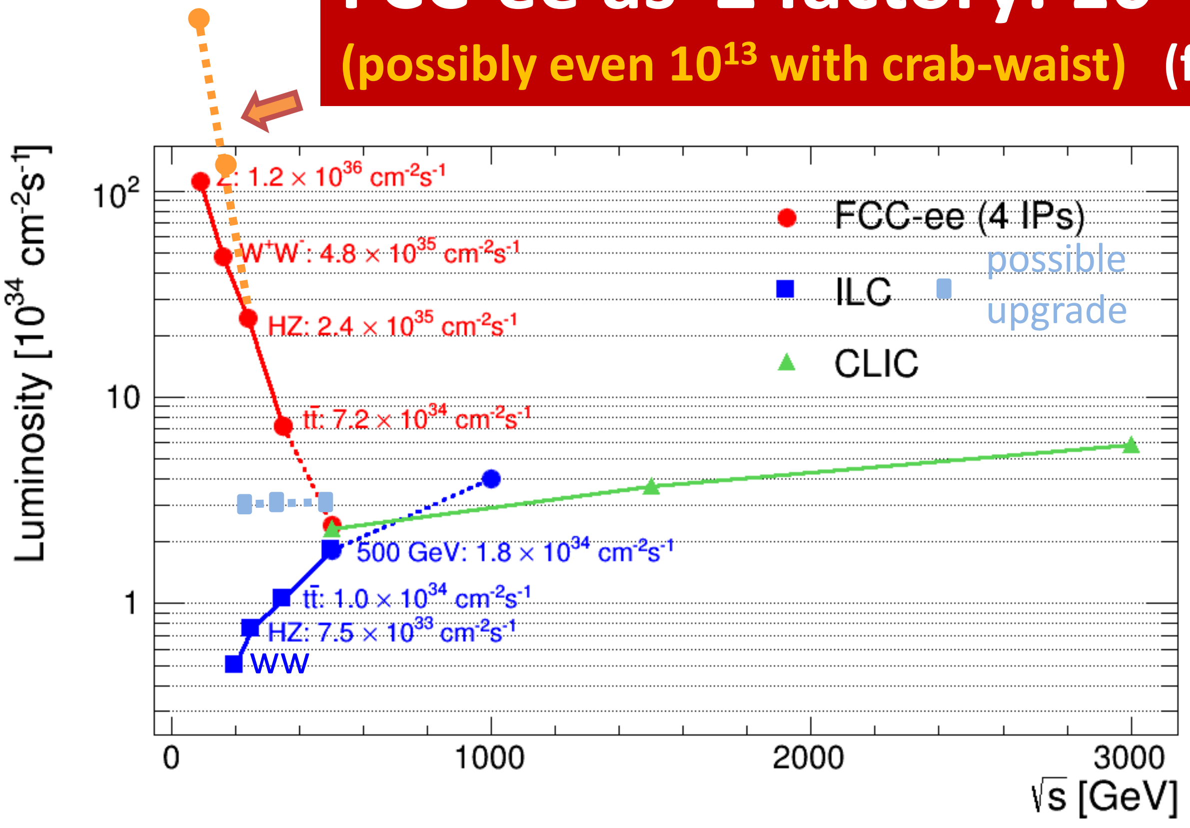
Goal performance of e+ e- colliders

FCC-ee as Z factory: 10^{12} Z

(possibly even 10^{13} with crab-waist) (few years)



complementarity

NB: ideas for lumi upgrades:
ILC arxiv:1308.3726 (not in TDR. Upgrade at 250GeV by reconfiguration after 500 GeV running; under discussion)
FCC-ee (crab waist)

NEUTRINO COUNTING AT THE Z-PEAK AND RIGHT-HANDED NEUTRINOS

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and Department of Physics, University of Stockholm, S-113 46 Stockholm, Sweden

Received 20 February 1990

We consider the implications of extending the minimal standard model, with n families of quarks and leptons, by introducing an arbitrary number of right-handed neutrinos, for neutrino-counting via the "invisible width" of the Z. It is shown that the effective number of neutrinos, $\langle n \rangle$, satisfies, the inequality $\langle n \rangle \leqslant n$, where $\langle n \rangle$ is defined by $\Gamma(Z \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0$ and Γ_0 is the standard width for one massless neutrino. Thus, in the case of three families, the neutrino-counting can give a result which is less than three, if there are right-handed neutrinos.

Theorem.

In the standard model, with n left-handed lepton doublets and $N-n$ right-handed neutrinos, the effective number of neutrinos, $\langle n \rangle$, defined by

$$\Gamma(Z \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0 ,$$

where Γ_0 is the standard width for one massless neutrino, satisfies the inequality

$$\langle n \rangle \leqslant n . \quad (15)$$

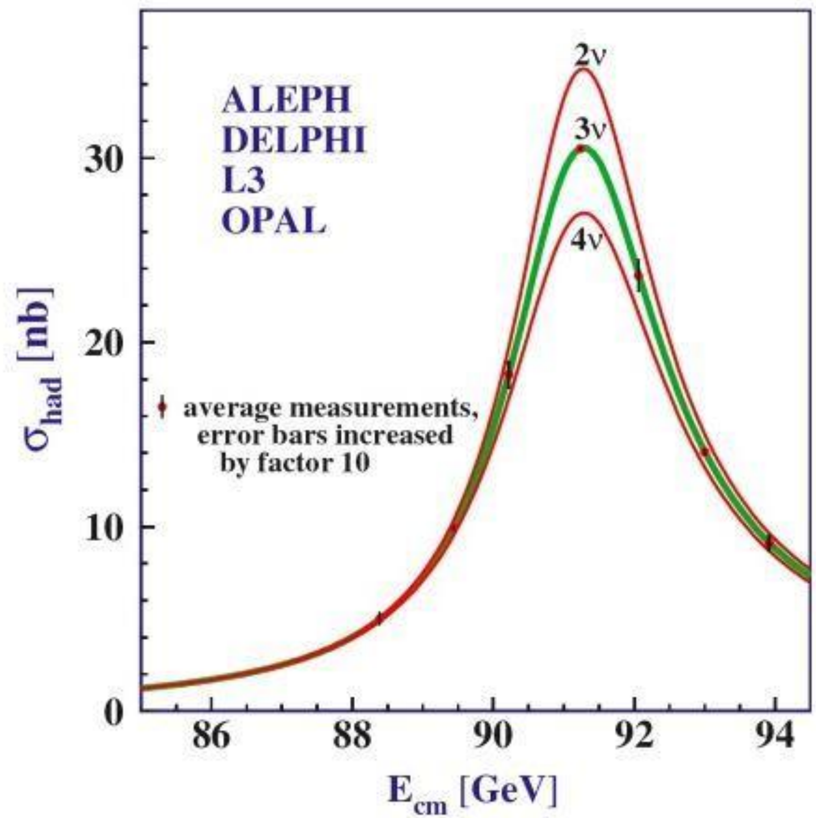
At the end of LEP:

Phys.Rept.427:257-454,2006

N_ν = 2.984 ±0.008

- 2 σ :^) !!

This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum ➔



The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) which represents an error of ±0.0046 on N_ν

Improving on N_ν by more than a factor 2 would require a large effort to improve on the Bhabha cross-section calculation!

Neutrino counting at TLEP

given the very high luminosity, the following measurement can be performed

$$N_{\nu} = \frac{\dfrac{\gamma Z(inv)}{\gamma Z \to ee, \mu\mu}}{\dfrac{\Gamma_{\nu}}{\Gamma e, \mu}\ (SM)}$$

The common γ tag allows cancellation of systematics due to photon selection, luminosity etc. The others are extremely well known due to the availability of $O(10^{12})$ Z decays.

The full sensitivity to the number of neutrinos is restored , and the theory uncertainty on $\frac{\Gamma_{\nu}}{\Gamma e}\ (SM)$ is very very small.

A good measurement can be made from the data accumulated at the WW threshold where σ (γ Z(inv)) ~4 pb for $|\cos\theta_{\gamma}| < 0.95$

161 GeV (10^7 s) running at $1.6 \times 10^{35}/cm^2/s$ x 4 exp ➔ 3×10^7 γ Z(inv) evts, $\Delta N_{\nu}=0.0011$
adding 5 yrs data at 240 and 350 GeV .... $\Delta N_{\nu}=0.0008$

A better point may be 105 GeV (20pb and higher luminosity) may allow $\Delta N_{\nu}=0.0004$?

RHASnu's 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 anti neutrino and add contributions of 3 neutrino species (with different $|U|^2$)

Decay

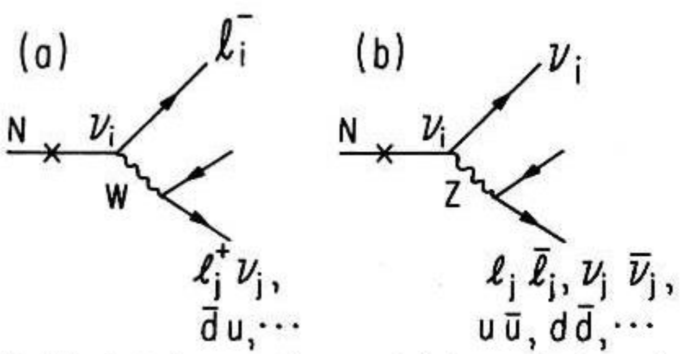


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

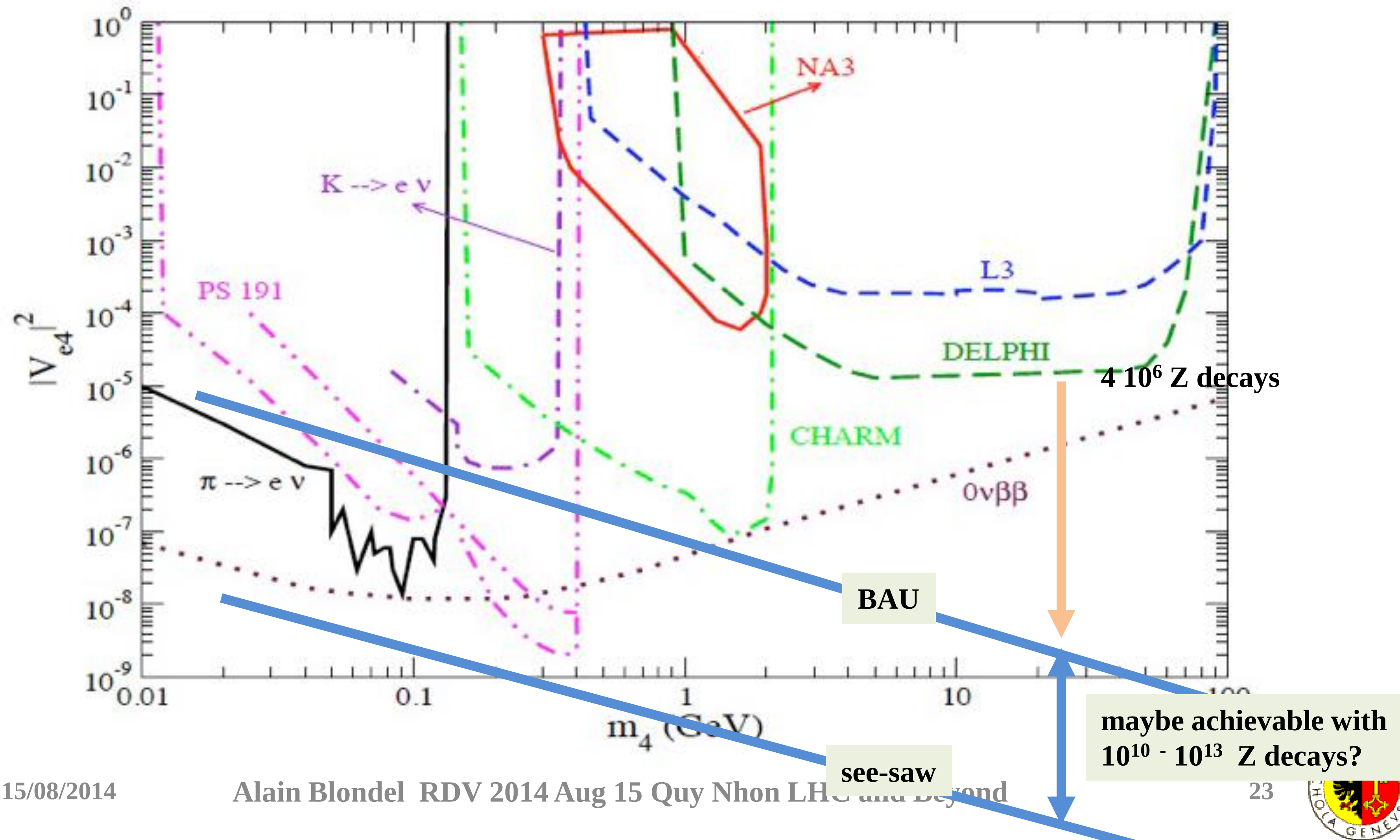
Decay length:

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

NB CC decay always leads to ≥ 2 charged tracks

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

Order-of-magnitude extrapolation of existing limits



Search for heavy neutral leptons

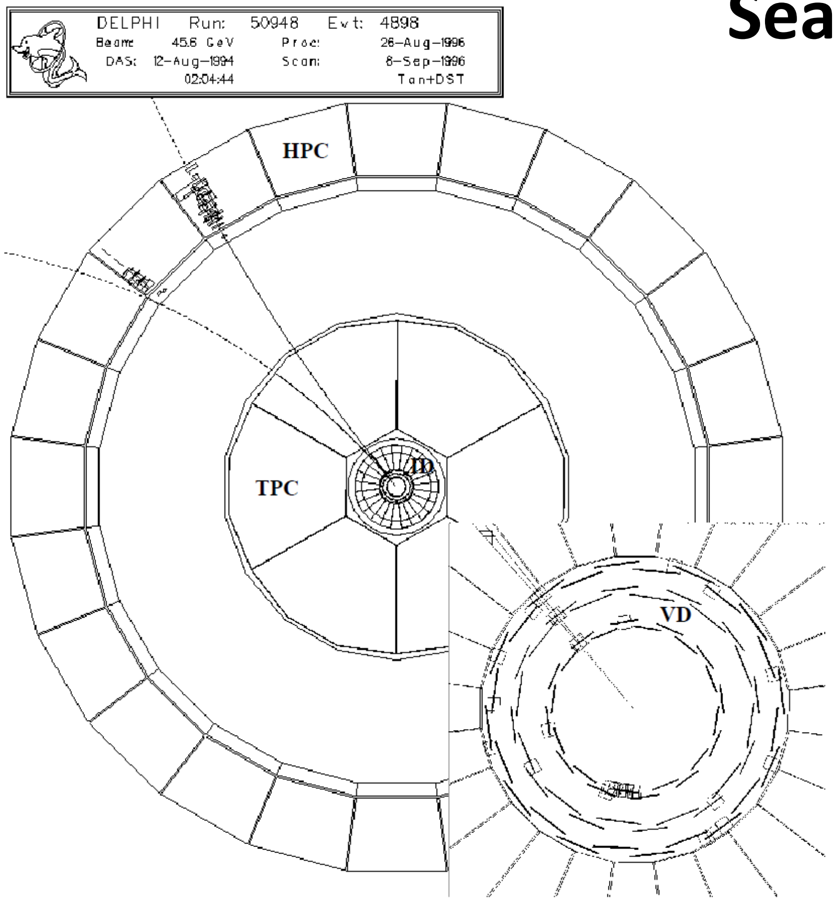
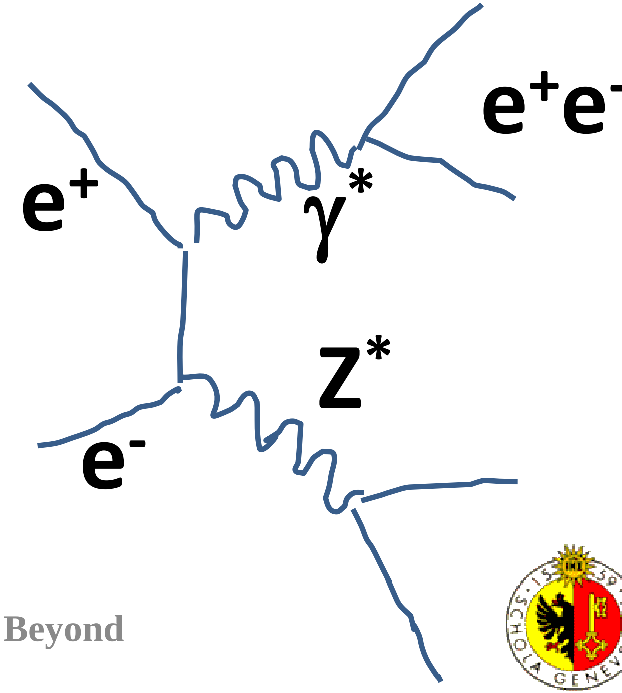


Fig. 3. Surviving event in the monojet search. It has an invariant mass of 300 MeV/c^2 and a missing p_t of 6 GeV/c and is probably an $e^+e^- \to e^+e^-\nu\bar{\nu}$ interaction

search $e^+ e^- \to \nu N$

$N \to \nu(\gamma/Z)^* \to$ monojet

Find: one event in 4x10^{6}Z:



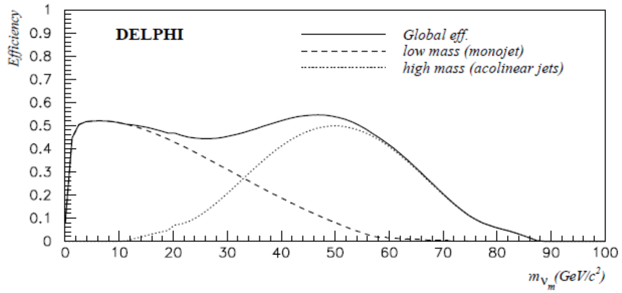
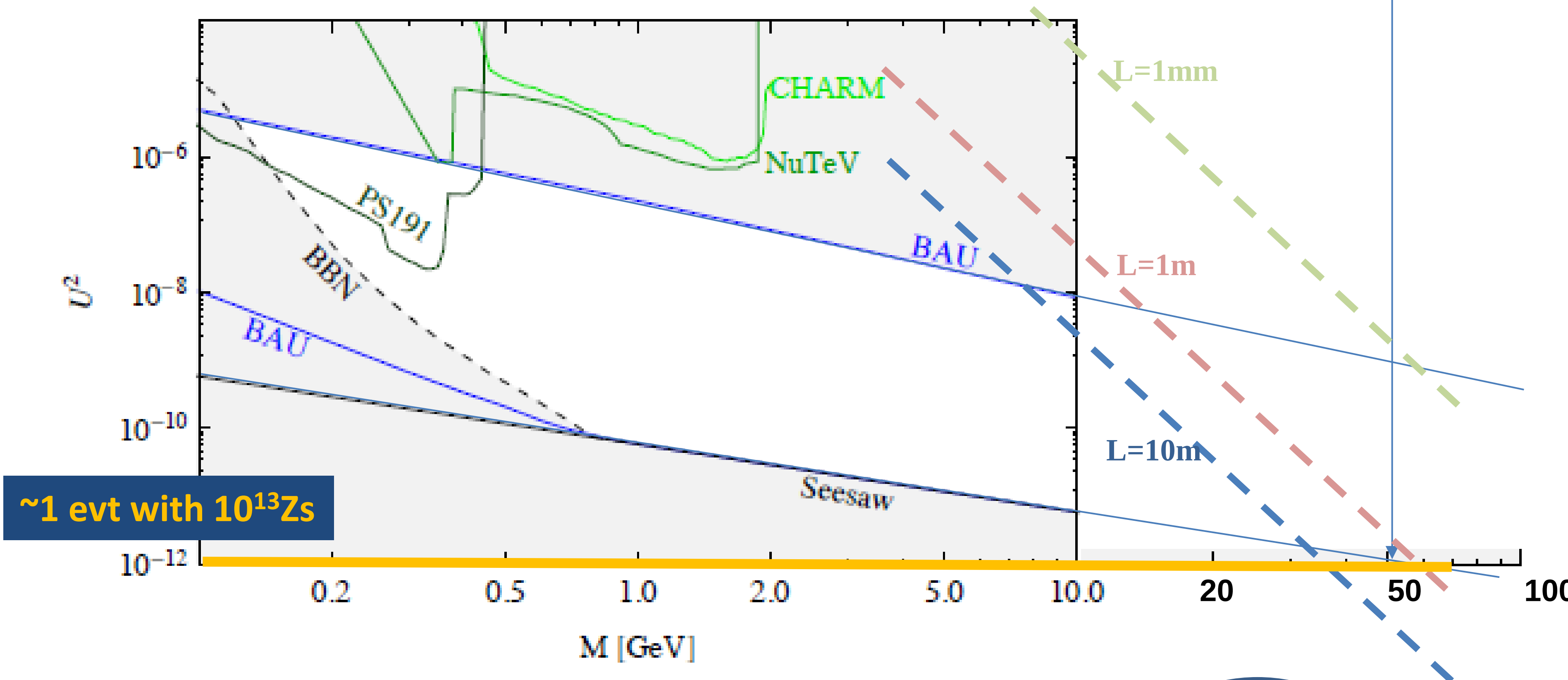


Fig. 4. Efficiency of the monojet search (Sect. 3) and the acollinear jets search (Sect. 4). The *full curve* shows the efficiency of the two searches combined

Decay length

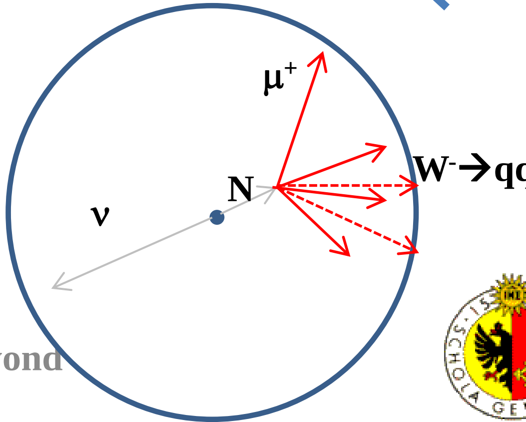
Interesting region
$|U|^2 \sim 10^{-9}$ to 10^{-12} @ 50 GeV



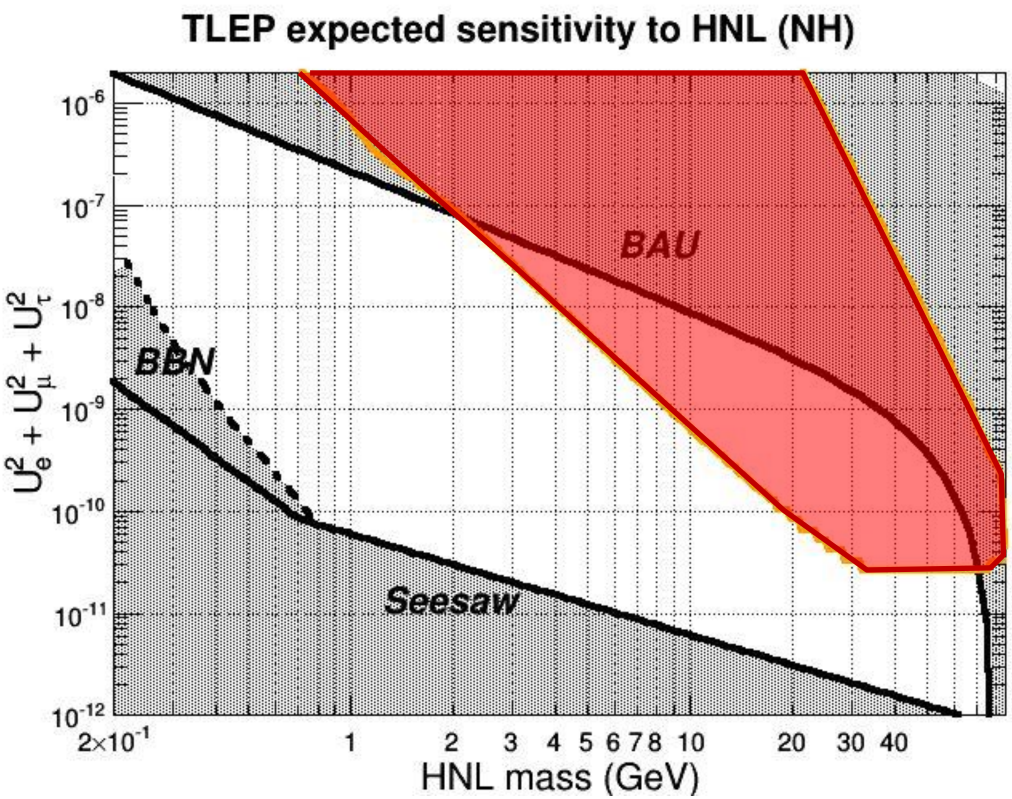
heavy neutrino mass ~ M

a large part of the interesting region will lead to detached vertices

... ➔very strong reduction of background!



Exact reach domain will depend on detector size and details of displaced vertex efficiency & background

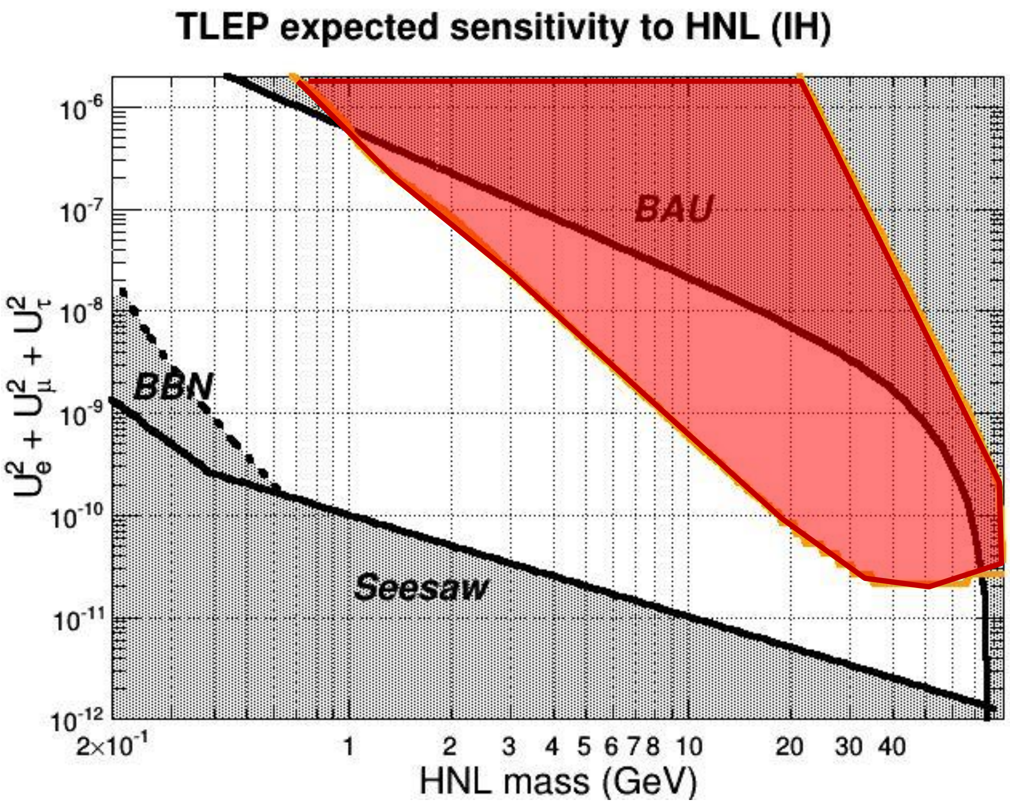


$N_Z = 10^{12}$ 1mm<L<1m

region of interest

FCC-ee sensitivity

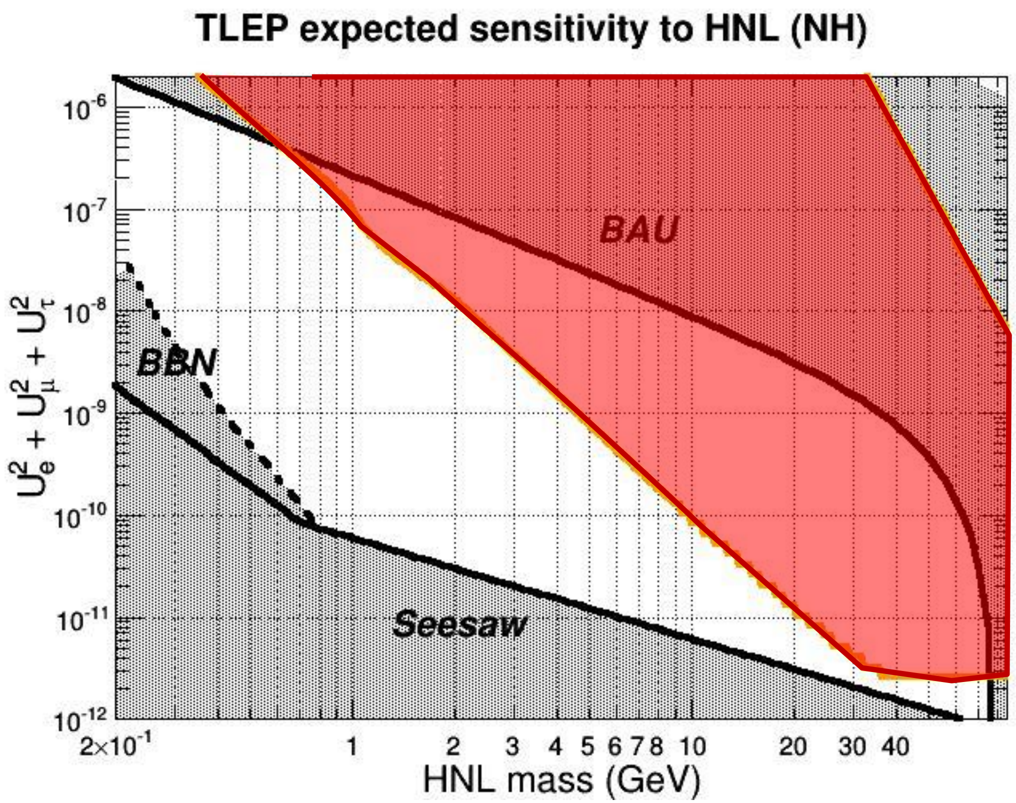
A.B, Elena Graverini, Nicola Serra, Misha Shaposhnikov



$N_Z = 10^{12}$ 1mm<L<1m

region of interest

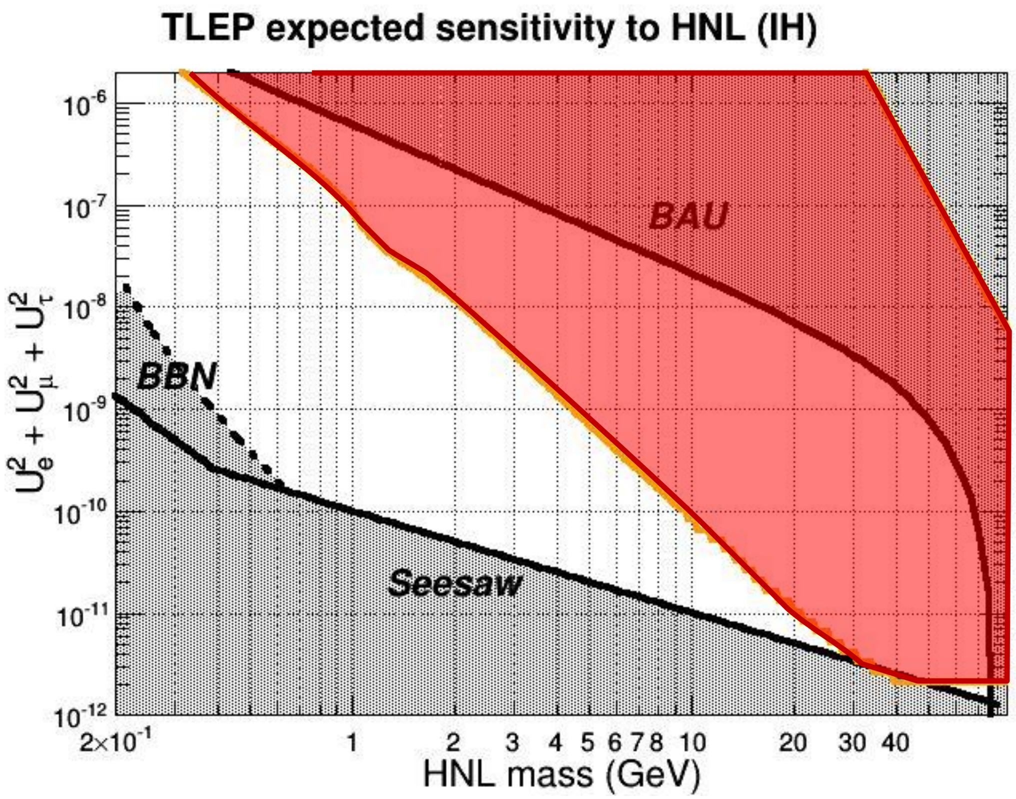
FCC-ee sensitivity



$N_Z = 10^{13}$ $100\mu m < L < 5m$

region of interest

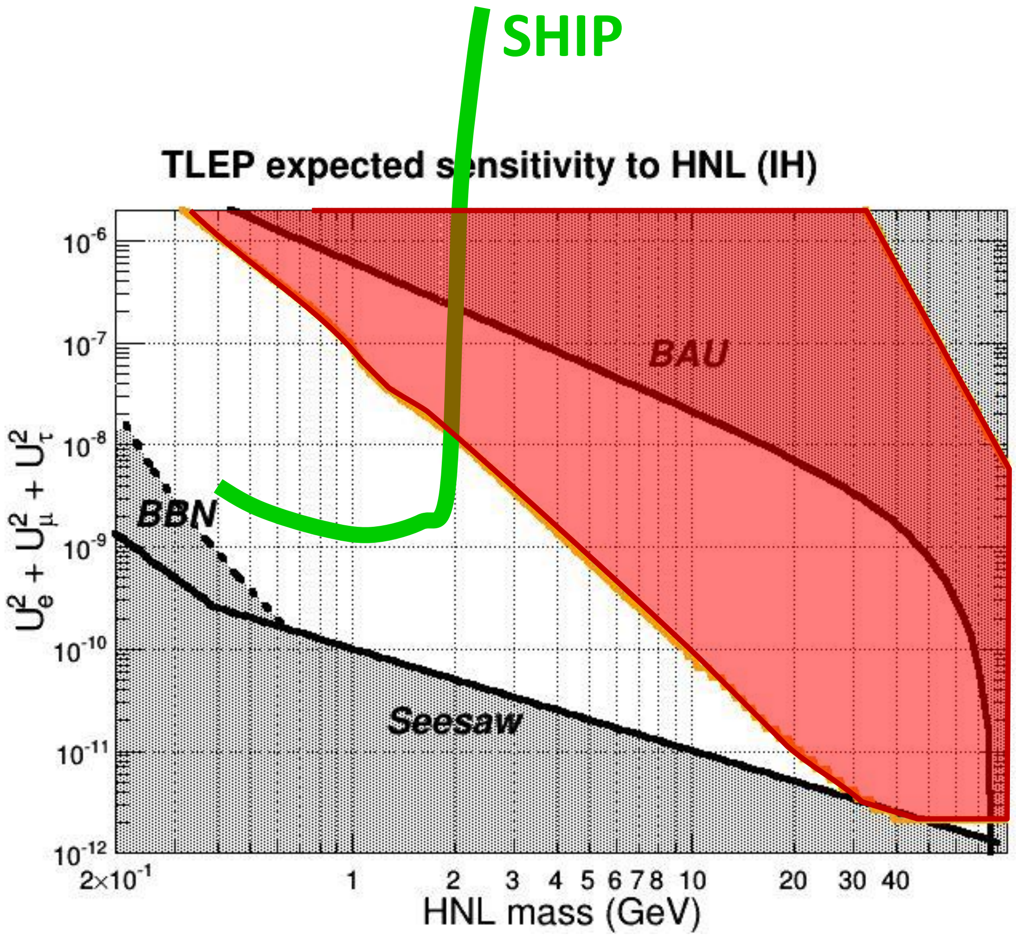
FCC-ee sensitivity



$N_Z = 10^{13}$ 100μm <L<5m

region of interest

FCC-ee sensitivity



$N_Z = 10^{13}$ $100\mu m < L < 5m$

region of interest

FCC-ee sensitivity

Conclusions

The quest for the

«Right-Handed-Almost-Sterile-See-saw-partners neutrinos»

(dextrinos? RHASnus? Heavy Neutral Leptons? Shaposhninos? heavinos?)

is not desperate at all

In particular it may lead to spectacular ‘detached vertex’ signatures in a beam dump experiment (SHIP) or in Z-> neutrino decays at a Tera-Z factory like FCC-ee

Join us: http://cern.ch/fcc-ee

SPARES

FLAVOUR(267104)-ERC-23 TUM-HEP 850/12 SISSA 25/2012/EP CFTP/12-013

arxiv:1208.3654

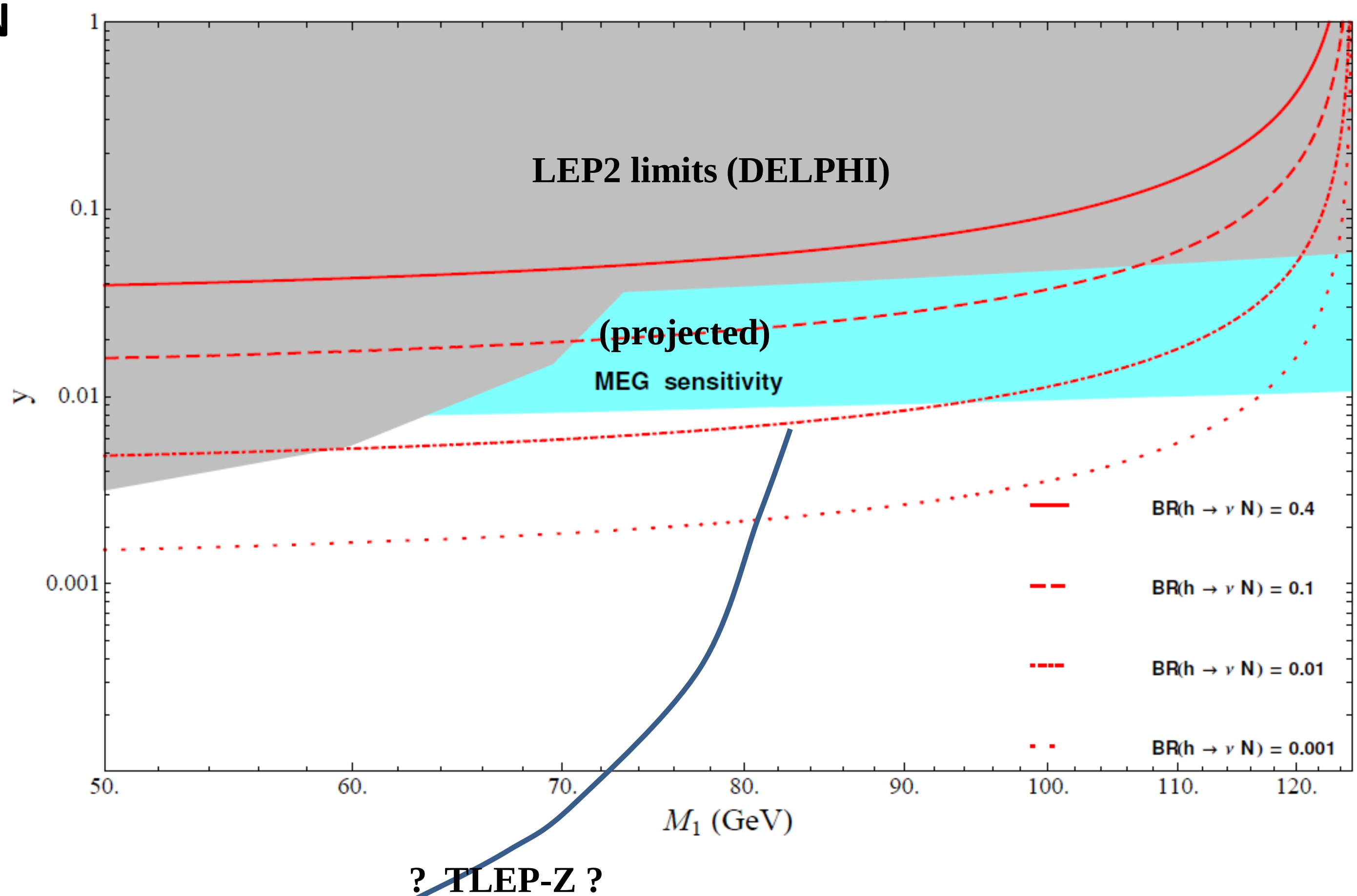
Higgs Decays in the Low Scale Type I See-Saw Model

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

H-> vN

or

Z-> vN



Another solution:

determine the number of neutrinos from the radiative returns

$e^+e^- \rightarrow \gamma\ Z\ (\rightarrow \nu\ \bar{\nu})$

CERN-TH.5528/89

NEUTRINO COUNTING

G. Barbiellini[1], X. Berdugo[2], G. Bonvicini[3], P. Colas[4], L. Mirabito[4], C. Dionisi[5], D. Karlen[6], F. Linde[7], C. Luci[8], C. Mana[8], C. Matteuzzi[9], O. Nicrosini[10], R. Ragazzon[1], D. Schaile[11], F. Scuri[1] and L. Trentadue*),[12]

in its original form (Karlen) the method only counts the 'single photon' events and is actually less sensitive than claimed. It has poorer statistics and requires running ~10 GeV above the Z pole. Systematics on photon selection are not small.

present result: N_ν= 2.92±0.05

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NEUTRINO COUNTING AT THE Z-PEAK AND RIGHT-HANDED NEUTRINOS

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We consider the implications of extending the minimal standard model, with n families of quarks and leptons, by introducing an arbitrary number of right-handed neutrinos, for neutrino-counting via the "invisible width" of the Z. It is shown that the effective number of neutrinos, $\langle n \rangle$, satisfies, the inequality $\langle n \rangle \leqslant n$, where $\langle n \rangle$ is defined by $\Gamma(\mathrm{Z} \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0$ and Γ_0 is the standard width for one massless neutrino. Thus, in the case of three families, the neutrino-counting can give a result which is less than three, if there are right-handed neutrinos.

Theorem.

In the standard model, with n left-handed lepton doublets and $N-n$ right-handed neutrinos, the effective number of neutrinos, $\langle n \rangle$, defined by

$$\Gamma(\mathrm{Z} \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0 ,$$

where Γ_0 is the standard width for one massless neutrino, satisfies the inequality

$$\langle n \rangle \leqslant n . \qquad (15)$$