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
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

(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?
But Where Is Everybody?

At higher masses -- or at smaller couplings?
some REFERENCES

15/08/2014

arxiv:1208.3654

Higgs Decays in the Low Scale Type I See-Saw Model
C. García Cely$^{a)}$, A. Ibarra$^{a)}$, E. Molinaro$^{b)}$ and S. T. Petcov$^{c,d)}$

The Role of Sterile Neutrinos in Cosmology and Astrophysics
Alexey Boyarsky$^{a)}$, Oleg Ruehlsayskiy$^{a)}$ and Mikhail Shaposhnikov

The $\nu$MSM, Dark Matter and Neutrino Masses
Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov

The Search for Heavy Majorana Neutrinos
Anupama Atre$^{1,2}$, Tao Han$^{3,4}$, Silvia Pascoli$^{5}$, Bin Zhang$^{4}$

Search for Neutral Heavy Leptons Produced in Z Decays
DELPHI Collaboration

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

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

arxiv:1308.6176

First look at the physics case of TLEP

CERN-PPE/96–195

19 December 1996


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 impossible to find.

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

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I = 1/2  
Q = -1

I = 0  
Q = 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)

\[ m_D \bar{v}_L v_R \quad m_D \bar{v}_L v_R \]

implies adding a right-handed neutrino (new particle)

No SM symmetry prevents adding then a term like

\[ m_M \bar{v}_R^c v_R \]

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:

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

- \( M_R \neq 0 \)
- \( m_D \neq 0 \)
- Dirac + Majorana mass terms

**General formula**

\[ \tan 2\theta = \frac{2m_D}{M_R - 0} \ll 1 \]

\[ m_\nu = \frac{1}{2} \left[ (0 + M_R) - \sqrt{(0 - M_R)^2 + 4m_D^2} \right] \]

\[ M = \frac{1}{2} \left[ (0 + M_R) + \sqrt{(0 - M_R)^2 + 4m_D^2} \right] \]

- Dirac only, (like e- vs e+):
  - \( m_D \neq 0 \)
  - \( M_R = 0 \)
  - \( I_{\text{weak}} = \begin{pmatrix} \nu_L \\ \nu_R \\ \bar{\nu}_R \\ \bar{\nu}_L \end{pmatrix} \begin{pmatrix} 1/2 \\ 0 \\ 1/2 \\ 0 \end{pmatrix} \)
  - 4 states of equal masses
  - Some have \( I=1/2 \) (active)
  - Some have \( I=0 \) (sterile)

- Majorana only:
  - \( m_D = 0 \)
  - \( M_R \neq 0 \)
  - \( I_{\text{weak}} = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \begin{pmatrix} 1/2 \\ 1/2 \end{pmatrix} \)
  - 2 states of equal masses
  - All have \( I=1/2 \) (active)

- Dirac + Majorana:
  - \( m_D \neq 0 \)
  - \( M_R \neq 0 \)
  - \( I_{\text{weak}} = \begin{pmatrix} \nu_L \\ \nu_R \\ \bar{\nu}_R \\ \bar{\nu}_L \end{pmatrix} \begin{pmatrix} 1/2 \\ 0 \\ 1/2 \\ 0 \end{pmatrix} \)
  - 4 states, 2 mass levels
  - \( m_1 \) have \( I=1/2 \) (~active)
  - \( m_2 \) have \( I=0 \) (~sterile)
There even exists a scenario that explains everything: the $\nu$MSM

$\nu_1 \rightarrow \nu \gamma$
may have been seen:
arxiv:1402:2301
arxiv:1402.4119
Manifestations of right handed neutrinos

\[ \nu = \nu_L \cos \theta - N_R^c \sin \theta \]
\[ N = N_R \cos \theta + \nu_L^c \sin \theta \]

what is produced in W, Z decays is:
\[ \nu_L = \nu \cos \theta + N \sin \theta \]

-- 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 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 \( \tau \) decays
  -- etc... etc...

-- Couplings are small \( (m_\nu / m_N) \) (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 vMSM 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
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:

2. Instituto de Fisica Casaccia, Rome, Italy
3. European Organization for Nuclear Research (CERN), Geneva, Switzerland
4. Instituto de Fisica, ETSI, University of Zaragoza, Zaragoza, Spain
5. Imperial College London, London, United Kingdom
6. Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
7. Ecole Polytechnique, Federale Lausanne (EPFL), Lausanne, Switzerland
8. Physik-Institut, Universität Zürich, Zürich, Switzerland
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

Schematic of an 80 - 100 km long tunnel
Goal performance of e+ e- colliders

FCC-ee as Z factory: $10^{12}$ Z
(possibly even $10^{13}$ with crab-waist) (few years)

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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 \( \langle n \rangle \leq n \), where \( \langle n \rangle \) is defined by \( \Gamma(Z \rightarrow \text{neutrinos}) = \langle n \rangle \Gamma_0 \) and \( \Gamma_0 \) 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

\[
\Gamma(Z \rightarrow \text{neutrinos}) = \langle n \rangle \Gamma_0 ,
\]

where \( \Gamma_0 \) is the standard width for one massless neutrino, satisfies the inequality

\[
\langle n \rangle \leq n .
\]

(15)
At the end of LEP:

N_\nu = 2.984 \pm 0.008

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 \pm 0.0046 on N_\nu.

Improving on N_\nu 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

\[ N_\nu = \frac{\gamma Z(\text{inv})}{\gamma Z \rightarrow ee, \mu\mu} \frac{\Gamma_\nu}{\Gamma_{e,\mu}} \ (SM) \]

The common $\gamma$ 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 $\sigma (\gamma Z(\text{inv})) \sim 4\; \text{pb}$ for $|\cos\theta_\gamma| < 0.95$

161 GeV ($10^7$ s) running at $1.6 \times 10^{35} / \text{cm}^2 / \text{s} \times 4\; \text{exp} \rightarrow 3 \times 10^7 \gamma Z(\text{inv})$ 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:**

\[
\text{BR} (Z^0 \rightarrow \nu_m \bar{\nu}) = \text{BR} (Z^0 \rightarrow \nu \bar{\nu}) \ |U|^2 \left(1 - \frac{m_{\nu_m}^2}{m_{Z^0}^2}\right)^2 \left(1 + \frac{1}{2} \frac{m_{\nu_m}^2}{m_{Z^0}^2}\right)
\]

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

**Decay**

![Decay Diagram]

**Decay length:**

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

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

**Backgrounds:** four fermion:

\[
e^+e^- \rightarrow W^+ W^- \quad e^+e^- \rightarrow Z^*(\gamma\nu) + (Z/\gamma)^*
\]
Order-of-magnitude extrapolation of existing limits

4 \times 10^6 Z decays

maybe achievable with $10^{10} \cdot 10^{13} Z$ decays?

BAU

see-saw
Search for heavy neutral leptons

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

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

Find: one event in $4 \times 10^6 Z$:

$e^+ e^- \rightarrow \nu N$

$N \rightarrow \nu (\gamma/Z)^*$ \rightarrow monojet
Interesting region
$|U|^2 \sim 10^{-9}$ to $10^{-12}$ @ 50 GeV

Decay length

~1 evt with $10^{13} Zs$

heavy neutrino mass $\sim M$

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

Alain Blondel  RDV 2014 Aug 15 Quy Nhon LHC and Beyond

\[ N_z = 10^{12} \quad 1\text{mm}<l<1\text{m} \]
$N_z = 10^{12}$, $1 \text{mm} < L < 1 \text{m}$

TLEP expected sensitivity to HNL (IH)

- Region of interest
- FCC-ee sensitivity

$U_e^2 + U_\mu^2 + U_\tau^2$

HNL mass (GeV)
TLEP expected sensitivity to HNL (NH)

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

- **BBN**
- **Seesaw**
- **BAU**

region of interest

FCC-ee sensitivity

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

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
Higgs Decays in the Low Scale
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C. Garcia Cely\textsuperscript{a)}, A. Ibarra\textsuperscript{a)}, E. Molinaro\textsuperscript{b)} and S. T. Petcov\textsuperscript{c,d)}

\begin{align*}
\mathcal{H}^0 &\rightarrow vN \\
\mathcal{Z} &\rightarrow vN
\end{align*}

\textbf{LEP2 limits (DELPHI)}

\textbf{(projected)}

\textbf{MEG sensitivity}

\textbf{? TLEP-Z ?}

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Another solution:
determine the number of neutrinos from the radiative returns

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

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: \( N_\nu = 2.92 \pm 0.05 \)
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$$\langle n \rangle \leq n.$$ (15)