Fourth Generation Leptons

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Work with Arvind Rajaraman, and Daniel Whiteson

arXiv:1001.1229v1 [hep-ph]

arXiv:1005.4407 [hep-ph]

arXiv:1005.0628 [hep-ph]

arXiv:1010.1011 [hep-ph]

arXiv:1010.5502 [hep-ph]

Most General Fourth Generation Lepton Sector consists of a charged lepton with a Dirac Mass, and a neutrino with a Majorana and a Dirac Mass

The neutrino mass matrix is

$$\mathcal{L}_m = -\frac{1}{2}\overline{(Q_R^c N_R^c)}\begin{pmatrix} 0 & m_D \\ m_d & M \end{pmatrix}\begin{pmatrix} Q_R \\ N_R \end{pmatrix} + h.c.$$

Diagonalizing one gets

$$L_m = m_1 \bar{N}_1 N_1 + m_2 \bar{N}_2 N_2 + \sum_{i=1}^{4} m_e^i \bar{L}_i E_{Ri}$$

Define two mass eigen states

$$N_1 = \cos\theta \nu_{4L} + \sin\theta \nu_R^c \quad N_2 = \cos\theta \nu_R^c - \sin\theta \nu_{4L}$$

With mixing angle

$$t_\theta = -m_D/m_2 = (m_1/m_D)$$

And masses

$$m_1 = -(M/2) + \sqrt{m_D^2 + M^2/4}; m_2 = -(M/2) - \sqrt{m_D^2 + M^2/4}$$

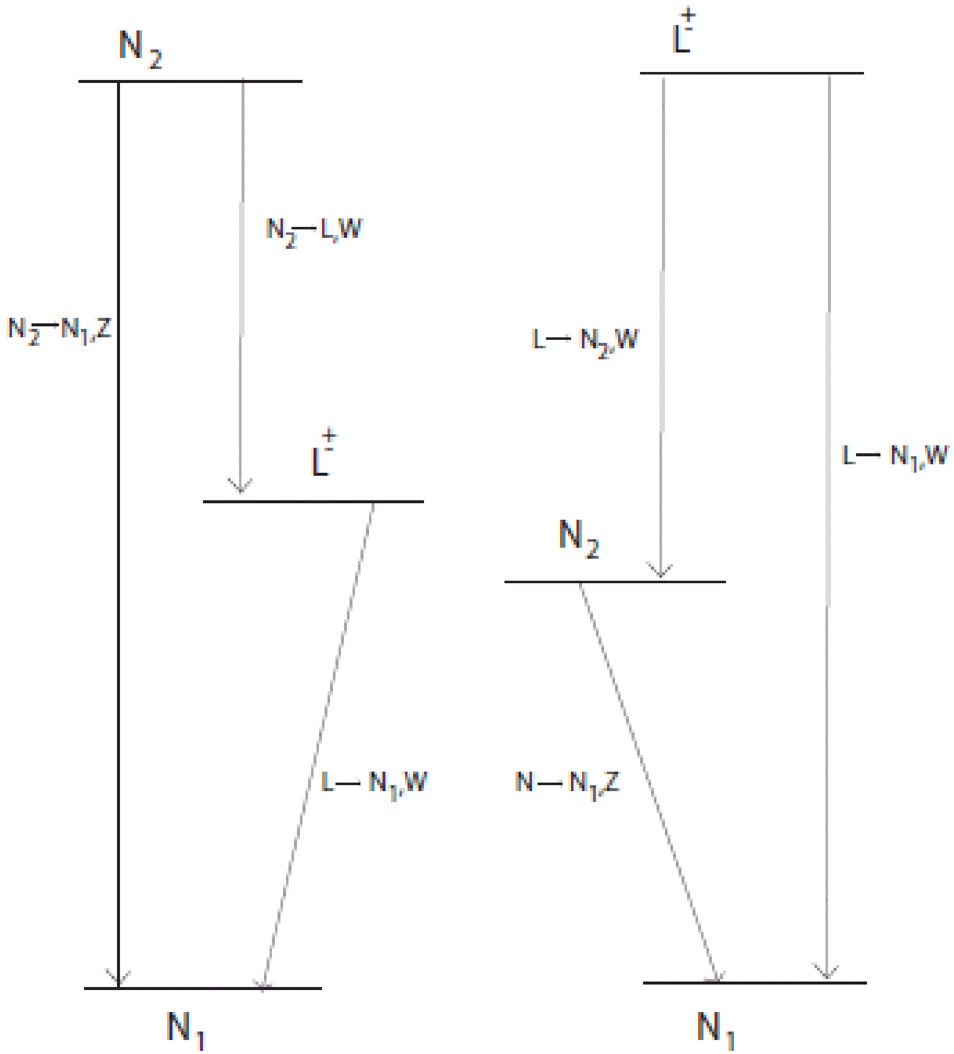
Leptons couple to the charged and neutral currents

$$\mathcal{L} = gZ_\mu J^\mu + (gW_\mu^+ J^{\mu+} + c.c)$$

where

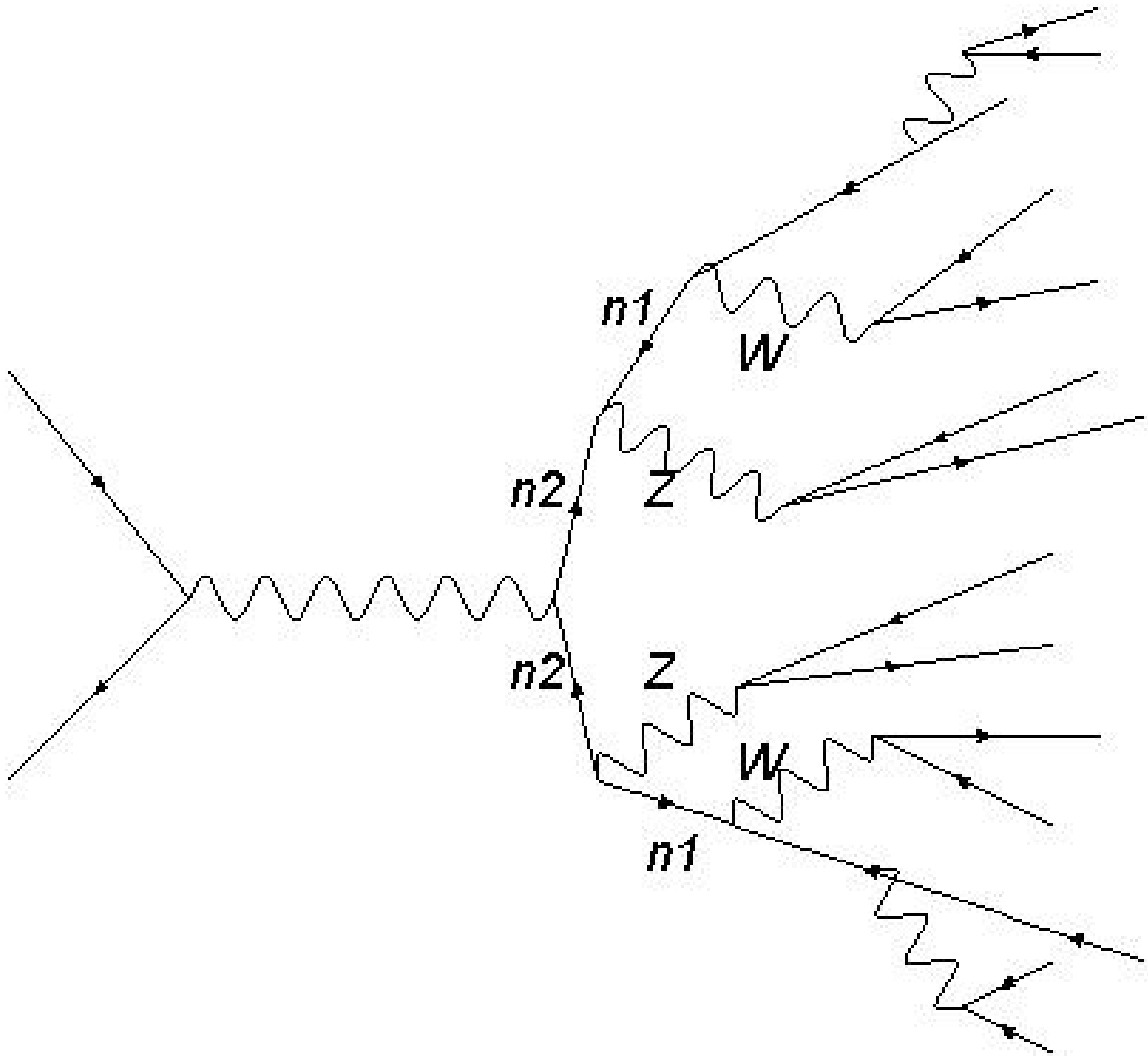
$$J^\mu = \frac{1}{2\cos\theta_W}(-c_\theta^2 \bar{N}_1 \gamma^\mu \gamma^5 N_1 - 2is_\theta c_\theta \bar{N}_1 \gamma^\mu N_2 - s_\theta^2 \bar{N}_2 \gamma^\mu \gamma^5 N_2))$$

$$J^{\mu+} = c_i \overline{(c_\theta N_1 - is_\theta N_2)} \gamma^\mu l_L^i \; + \frac{1}{\sqrt{2}} \overline{(c_\theta N_1 - is_\theta N_2)} \gamma^\mu L$$



N2
N2—L,W
N2—N1,Z
L±
L—N1,W
N1
L±
L—N2,W
L—N1,W
N2
N—N1,Z
N1

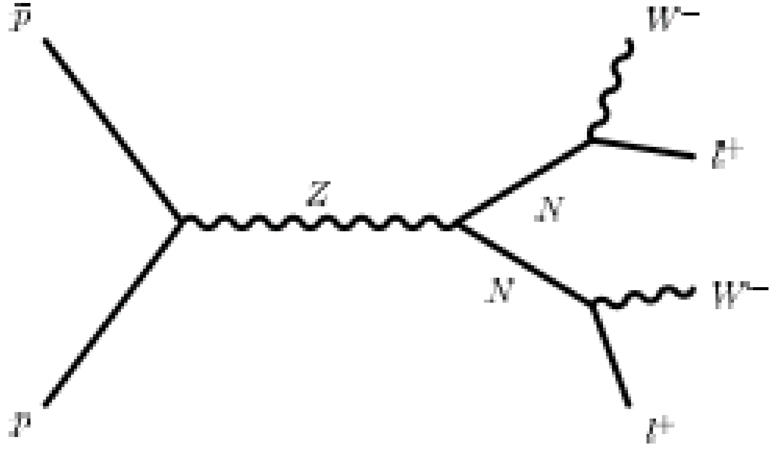
Possible Neutrino Event



Mass bounds are different in the case that the lightest leptons is stable or unstable.

In the case of unstable lightest neutrino, mass bounds are given by LEP 2

From the process



For mixed mass case the neutrino production cross section for the lightest state neutrinos is

$$(\sigma)_{CM} = \frac{1}{4}\frac{\left(E_{cm}^2/4 - m_{N_1}^2\right)^{3/2}}{(2\pi)E_{cm}}\left(\frac{g c_\theta}{\cos\theta_W}\right)^4 \left((-\frac{1}{2} + \sin^2\theta_W)^2 + \sin^4\theta_W\right)\frac{(10/3)}{(E_{cm}^2 - m_Z^2)^2}$$

Suppressed by the fourth power of the mixing angle. Heavy state pair production and heavy light production are suppressed by phase space. In this way we can lower the mass bound.

LEP search

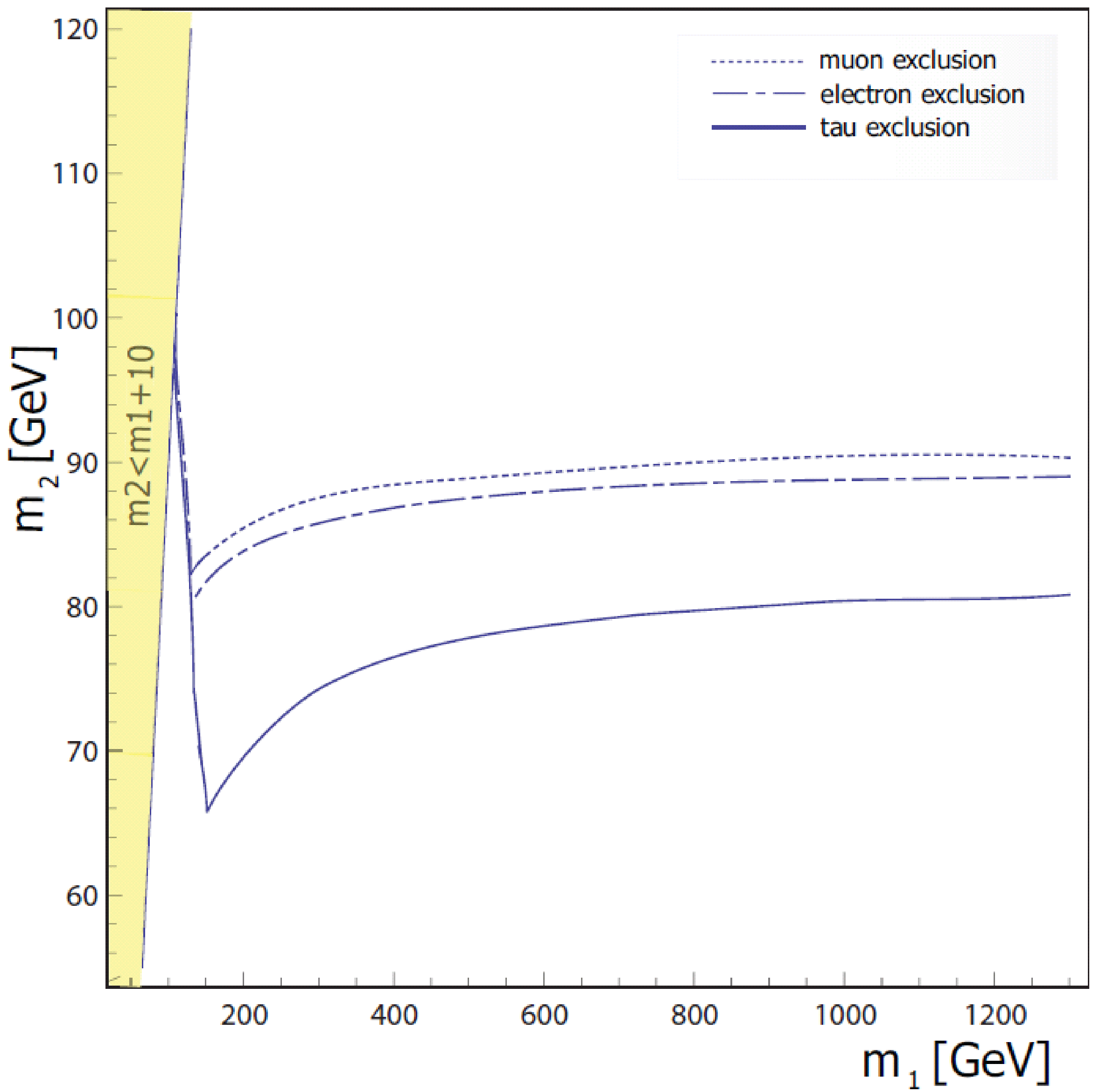
Relied on looking for 2 well isolated leptons of the same flavor.

Required isolation cone of 30 degrees around the hard leptons

Looked for 60 GeV of hadronic activity, mostly sensitive to hadronic decay of the Ws.

Assuming all 4th gen neutrinos decay to a single final lepton flavor, generate events with MADGRAPH, decay using BRIDGE, and shower events through PYTHIA to get estimated efficiencies for mixed mass search

	e, μ mode			τ mode		
N_1 mass	ϵ_{11}	ϵ_{12}	ϵ_{22}	ϵ_{11}	ϵ_{12}	ϵ_{22}
45	.162	.313	.331	.121	.149	.181
55	.188	.336	.338	.125	.151	.188
65	.224	.342	.384	.110	.147	.196
75	.251	.342	.369	.114	.149	.199
85	.234	.325	.352	.129	.155	.195


muon exclusion
electron exclusion
tau exclusion
m2<m1+10
120
110
100
90
80
70
60
m_2 [GeV]
200
400
600
800
1000
1200
m_1 [GeV]

The only bound on stable neutrinos is from the Z pole measurement of the Z invisible width. The Z invisible width may be corrected by 21 MeV*

PDG quotes 45 GeV for Dirac type and 39.9 for Majorana type stable neutrinos, (The Lower Majorana bound is from a phase space factor)

*(Particle Data Group), J. Phys. G 37, 075021 (2010)

P. Abreu *et al.* [DELPHI Collaboration], Phys. Lett. B274, 230-238 (1992)

Hadron Collider Searches for 4^{th} Generation Leptons

a) The case of unstable lightest neutrino

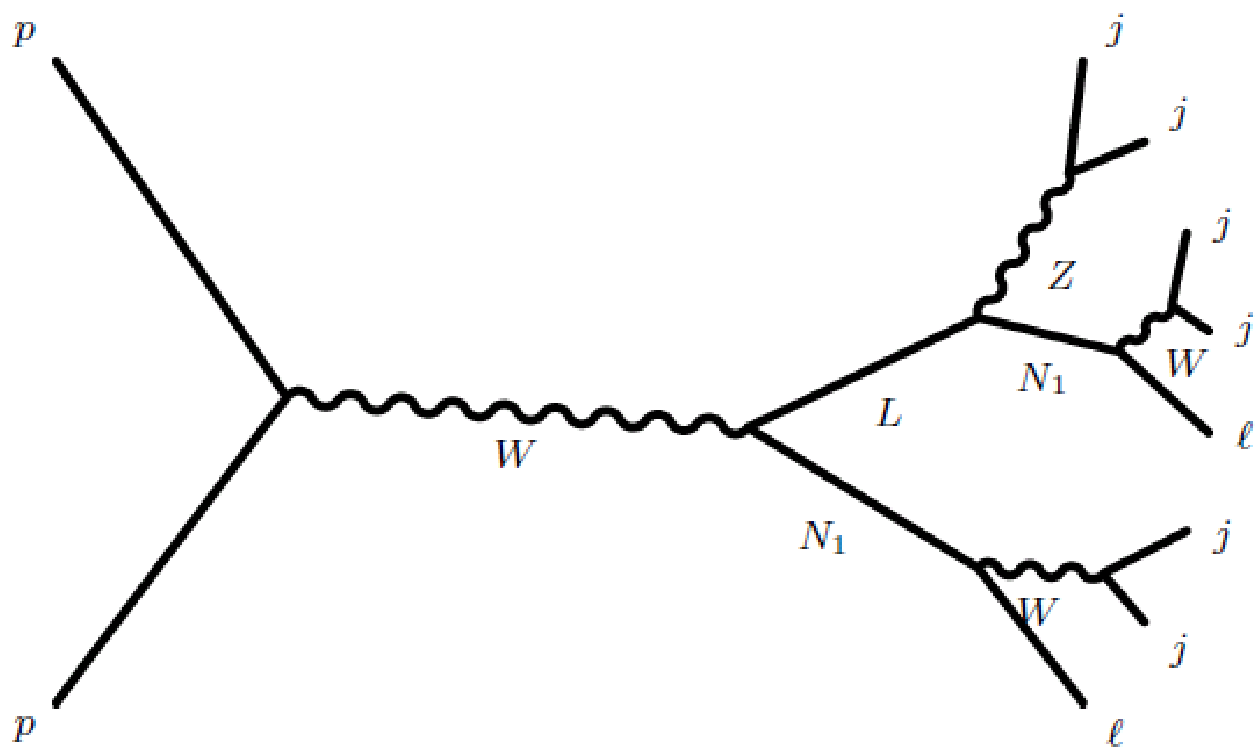
Looking for unstable leptons, One has events with many final state particles particles.

One must have something good to trigger on. Luckily, the signal for Majorana neutrinos is like sign dileptons, which is a very distinctive signal.

Searches for a charged lepton neutrino pair are easier than neutrino pair production b.c. one may produce a lepton and neutrino from a W rather than a neutrino pair from a Z.

The resulting cross section is almost two order of magnitude higher than neutrino pair production from a Z.

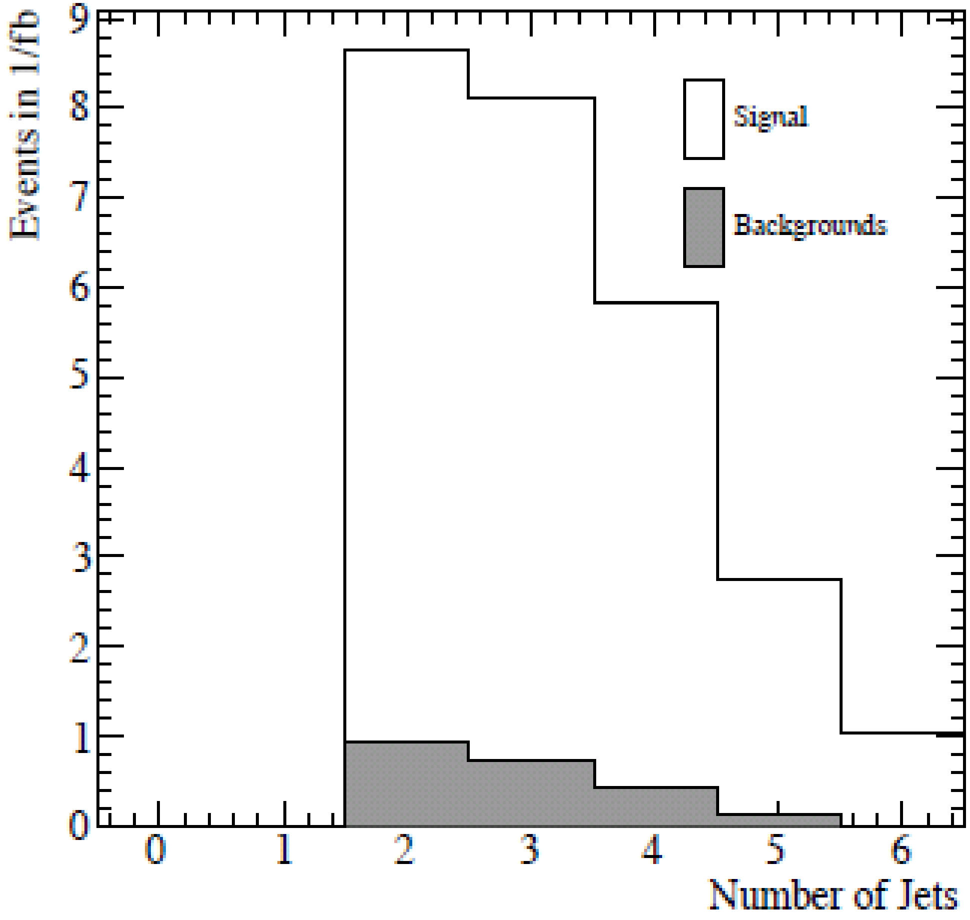
LHC event producing L N_1 pair



We use the following cuts

- two isolated like-sign leptons of the same flavor
- both lepton $p_T > 25$ GeV$/c$.
- at least two jets with $E_T > 20$ GeV

Benchmark point m_N=100 GeV m_L=200GeV

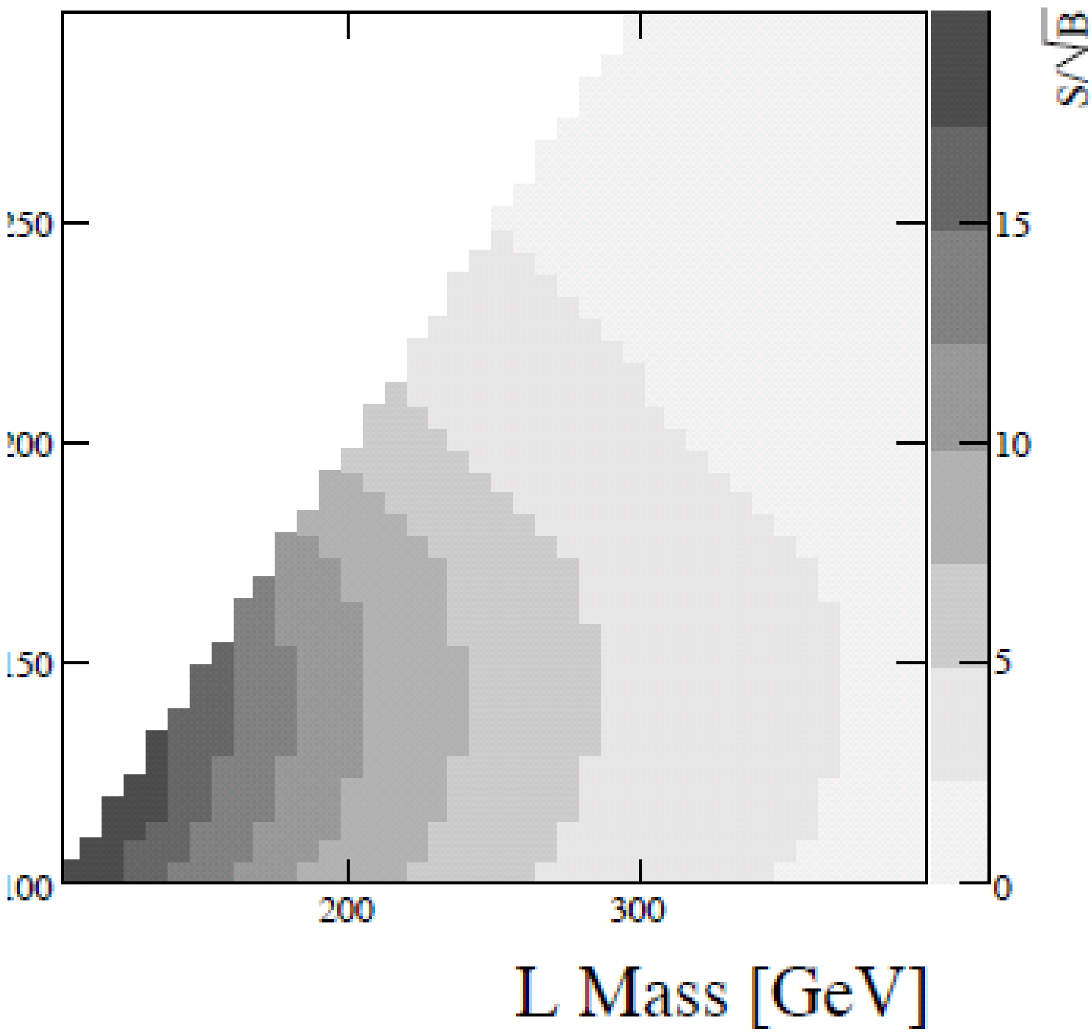


Events vs. Number of jets

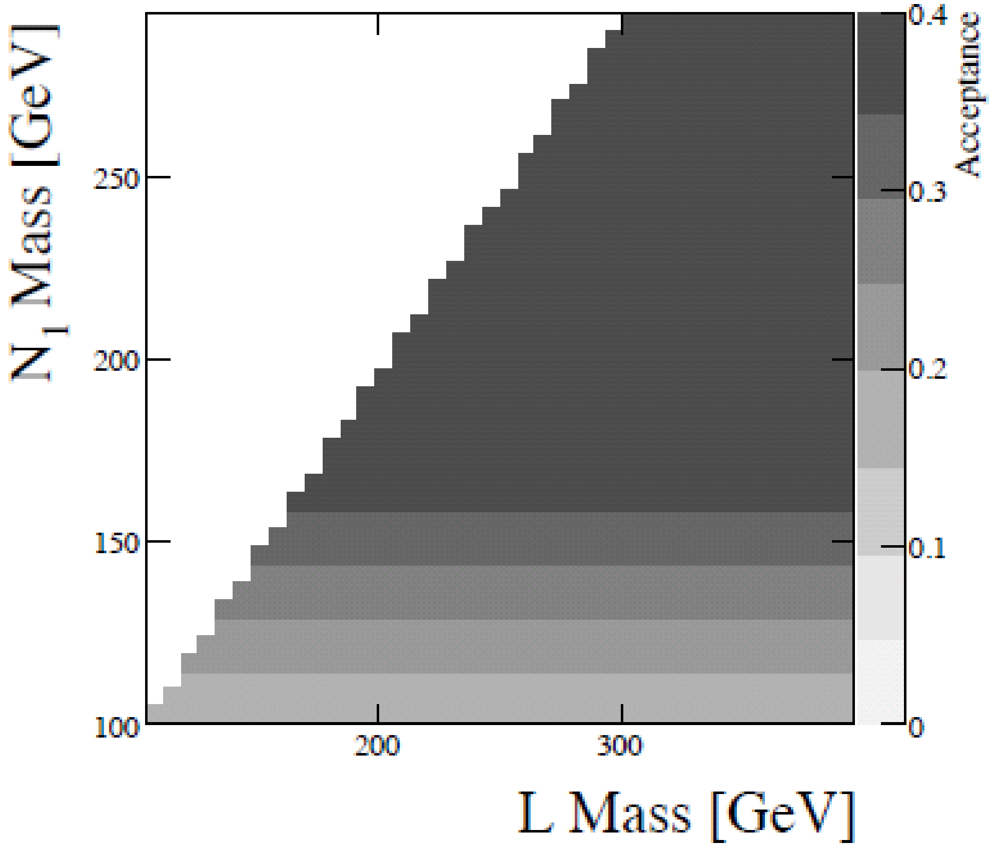
The production cross section is high, around .1pb

Backgrounds are low for like sign di-lepton events and are mostly from WZ or W photon or W+jets and ttbar with mistagged leptons.

Production cross section

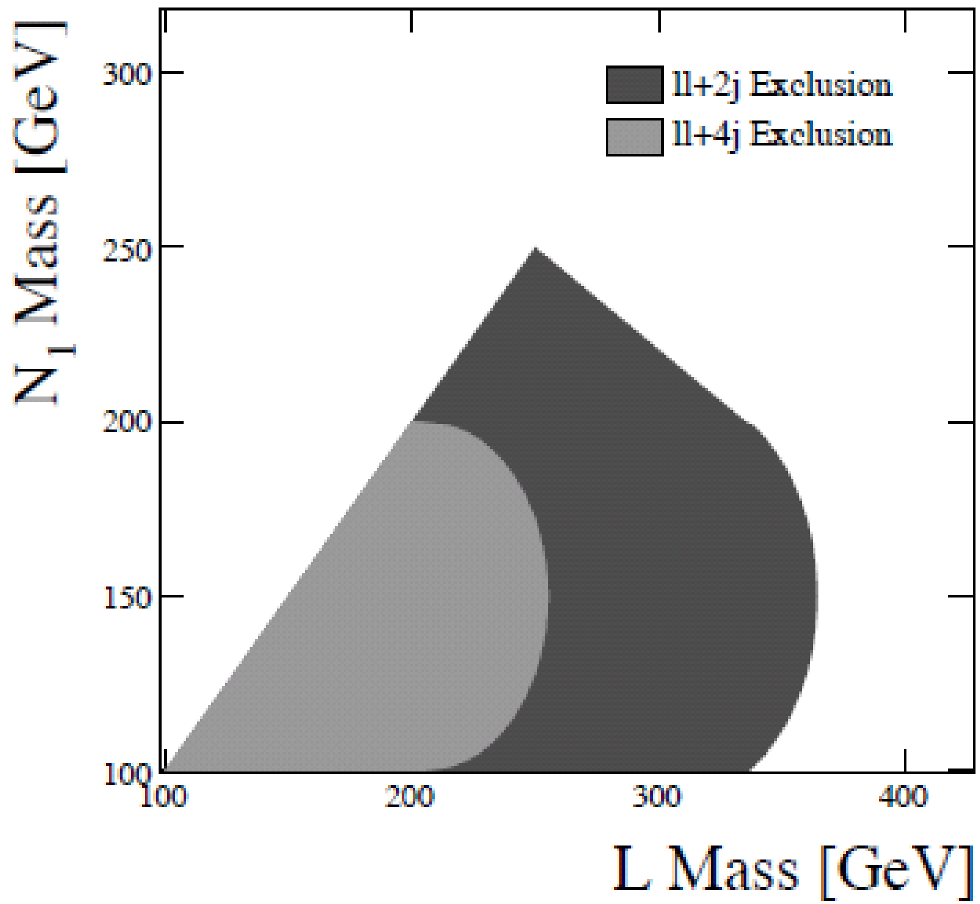


Plot of Acceptance



Note that acceptance drops as N1 decreases as its decay products get soft

Exclusion with 1 inverse fb at 7TeV

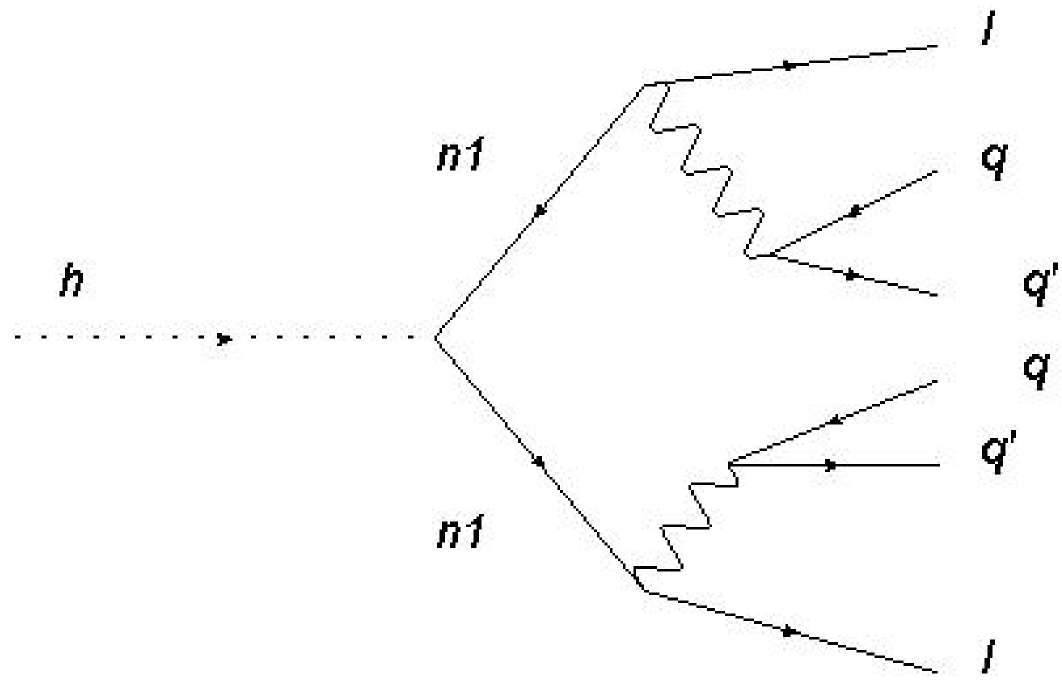


Possible exclusion at 95% c.l. for entire mass plane of charged lepton masses up to 250 GeV with 1 inverse fb at 7TeV.

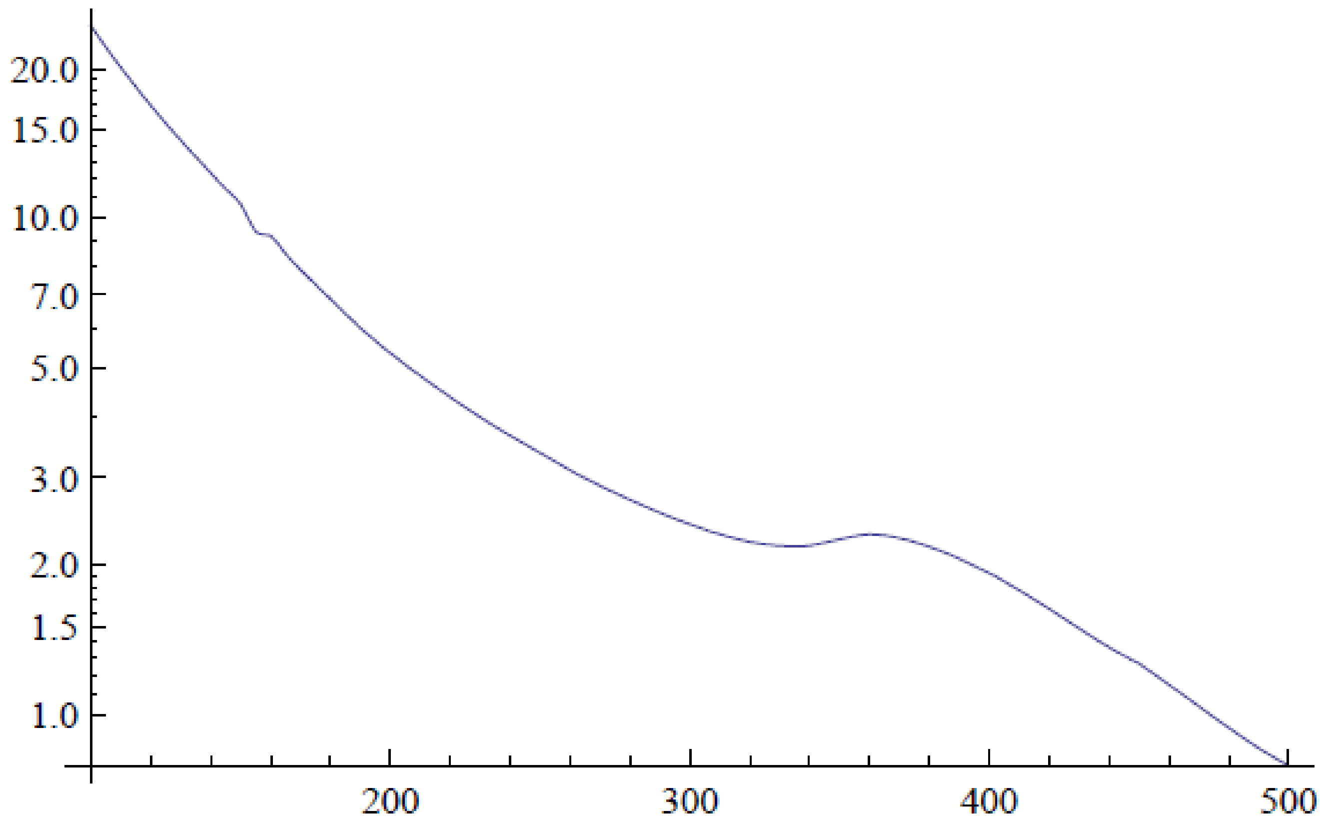
Maximum reach into the mass plane of 350 GeV for charged lepton masses.

Jet distribution can give a hint that the signal is indeed a charged lepton plus neutrino

A possible Higgs decay



Higgs production from gluon fusion at LHC



The Higgs decay width into Dirac fermions is given by

$$\Gamma_D = \frac{m_h y_D^2}{8\pi}(1 - \frac{4m_d^2}{m_h^2})^{3/2}$$

The ratio of Higgs decay widths of heavy neutrinos to b-quarks is thus

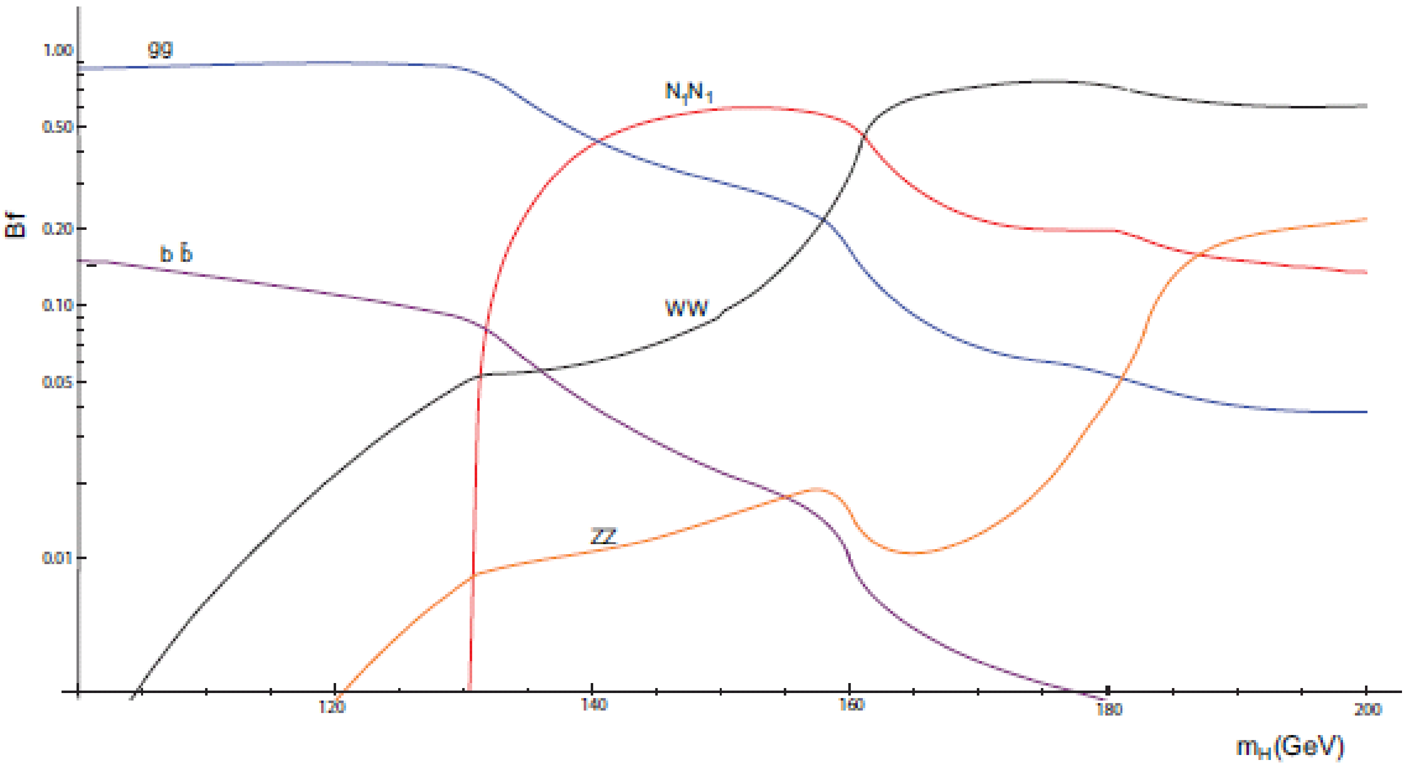
given by

$$\frac{m_{n1}^2 Sin(2\theta)}{m_b^2} \frac{(1 - \frac{4m_{n1}^2}{mh^2})^{3/2}}{(1 - \frac{4m_b^2}{mh^2})^{3/2}}$$

The Higgs decay width to gluons is given by

$$\frac{\alpha_s G_F m_h^3}{16\sqrt{2}\pi^3}\Sigma(\tau_i(1+(1-\tau_i)f(\tau_i))) \qquad \tau_i = \frac{4m_f^2}{m_h^2}, f(\tau_i) = (sin^{-1}\sqrt{1/\tau_i})^2$$

which is enhanced compared to the SM decay width to gluons by a substantial factor. Thus the Higgs production rate from gluon fusion is also enhanced



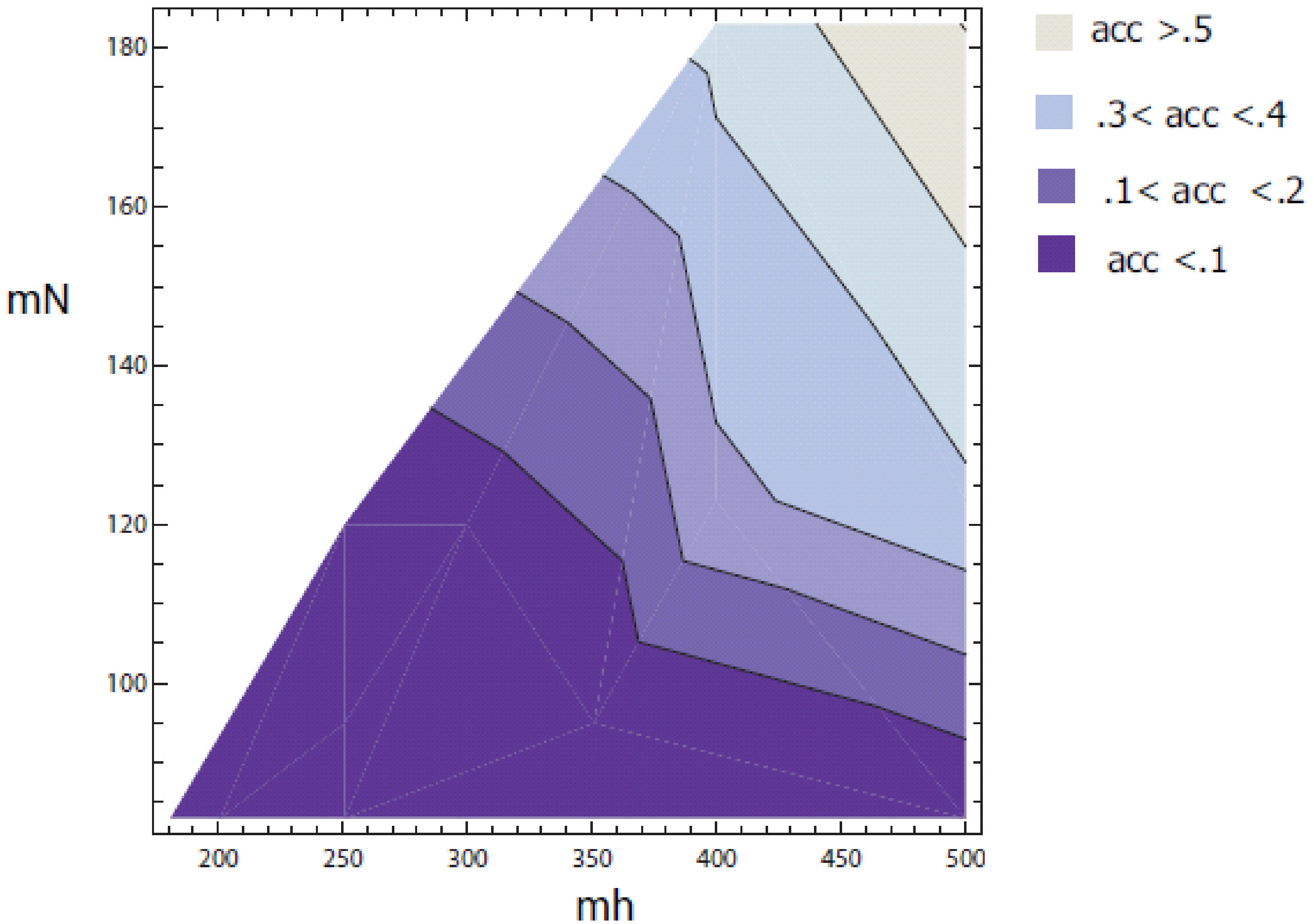
Bf
1.00
0.50
0.20
0.10
0.05
0.01
gg
b b̄
N_1N_1
WW
ZZ
120
140
160
180
200
m_H(GeV)

Consider an inclusive search for like-sign di-leptons at LHC at 7 TeV

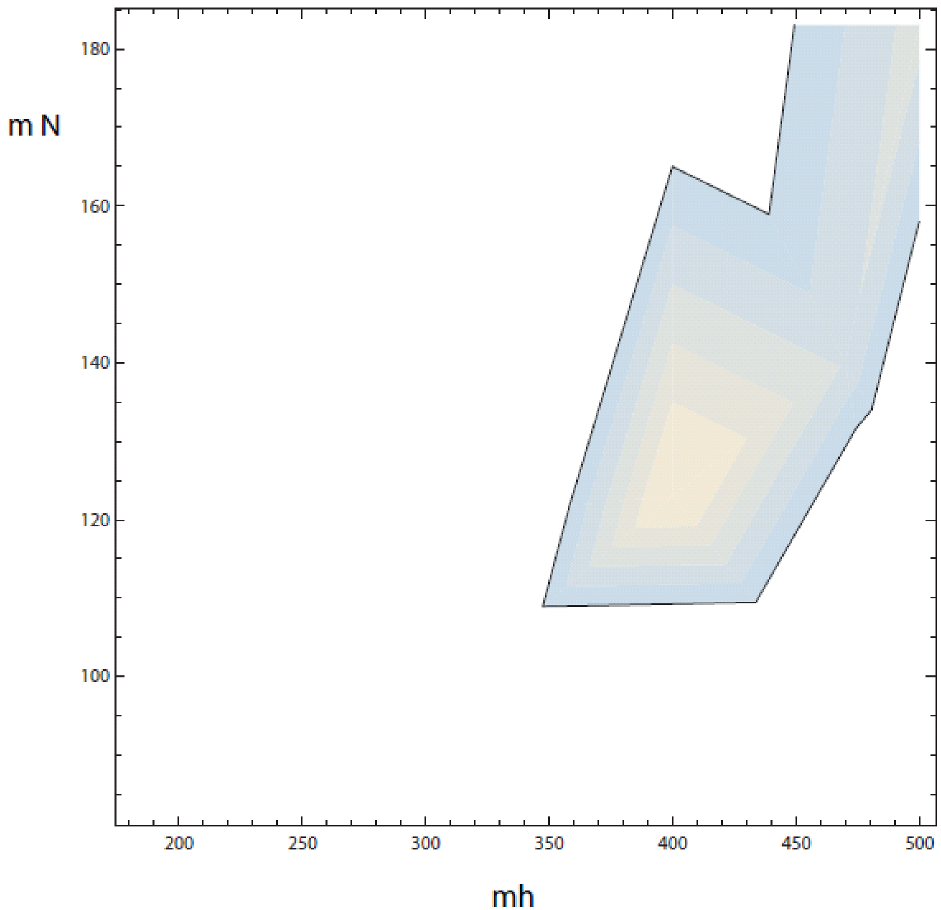
- 2 same sign muons
- with p_T >20 GeV
- $\eta_\mu < 2.5$
- isolation cone of $R > .4$ between muons and jets
- invariant mass of muons $110 GeV$

In 35 inverse pb of data this excludes production cross sections above 170 pb

Search acceptance in Higgs heavy neutrino mass pane



Exclusion in Higgs heavy neutrino mass plane



Some further work

Propose search strategy for an intermediate mass Higgs (130-160 GeV) where heavy neutrinos dominate the branching fractions, inclusive dilepton search or leptons + jets.

Summary

4 generation neutrinos are simple new physics with interesting signals at colliders

A striking feature of these neutrinos is decay into like sign di-leptons

The Higgs has significant b.f. into fourth generation neutrinos thus like sign di-leptons become a Higgs signal.

We may make significant progress ruling out these scenarios in the first inverse fb of LHC data.

Extra Slides

Under the assumption that final state leptons are all the same flavor these are LEP's exclusions.

Decay mode	Model	Dirac	Majorana
$L^0 \rightarrow eW$	Sequential	101.3	89.5
	Vector	102.6	–
	Mirror	100.8	89.5
$L^0 \rightarrow \mu W$	Sequential	101.5	90.7
	Vector	102.7	–
	Mirror	101.0	90.7
$L^0 \rightarrow \tau W$	Sequential	90.3	80.5
	Vector	99.3	–
	Mirror	90.3	80.5

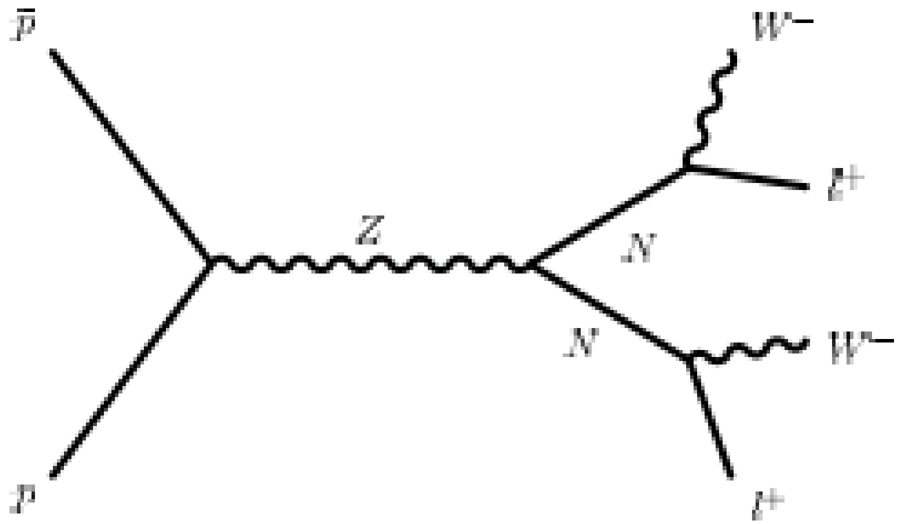
$e^+e^- \rightarrow L^0\bar{L}^0 \rightarrow \ell^+\ell^- W^+W^-$

$L^+L^- \rightarrow \nu_\ell\bar{\nu}_\ell\ W^+W^- \rightarrow \nu_\ell\bar{\nu}_\ell \ell \nu_\ell q\bar{q}'$

Decay mode	Model	
$L^\pm \rightarrow \nu W$	Sequential	100.8
	Vector	101.2
	Mirror	100.5
$L^\pm \rightarrow L^0 W$	Sequential	101.9
	Vector	102.1
	Mirror	101.9
Stable	Sequential	102.6
	Vector	102.6
	Mirror	102.6

arXiv:hep-ex/0107015v1

Look for neutrino pair production

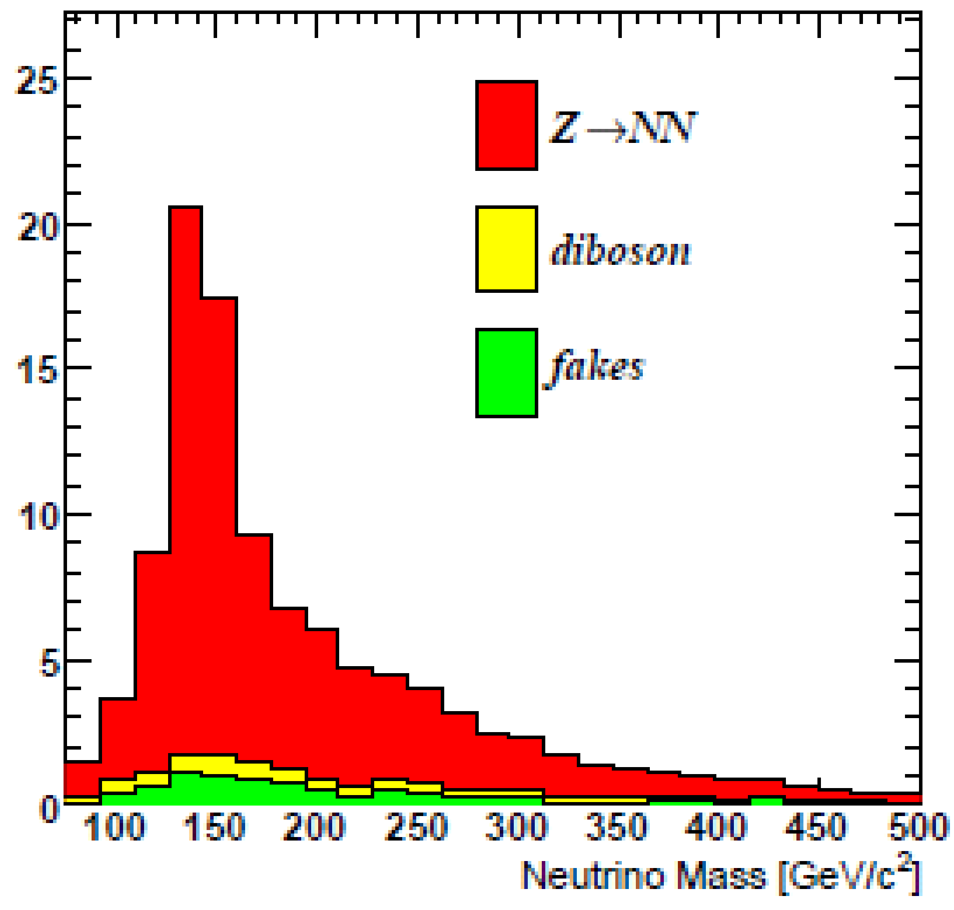


Half of the event will have same sign dileptons and Many event will have the final state

$$\ell^{\pm}\ell^{\pm}jj$$

For a dilepton search with proposed cuts

- two like-signed reconstructed leptons (e or μ), each with $p_T > 20$ GeV and $|\eta| < 2.0$
- at least two reconstructed jets, each with $p_T > 15$ GeV and $|\eta| < 2.5$



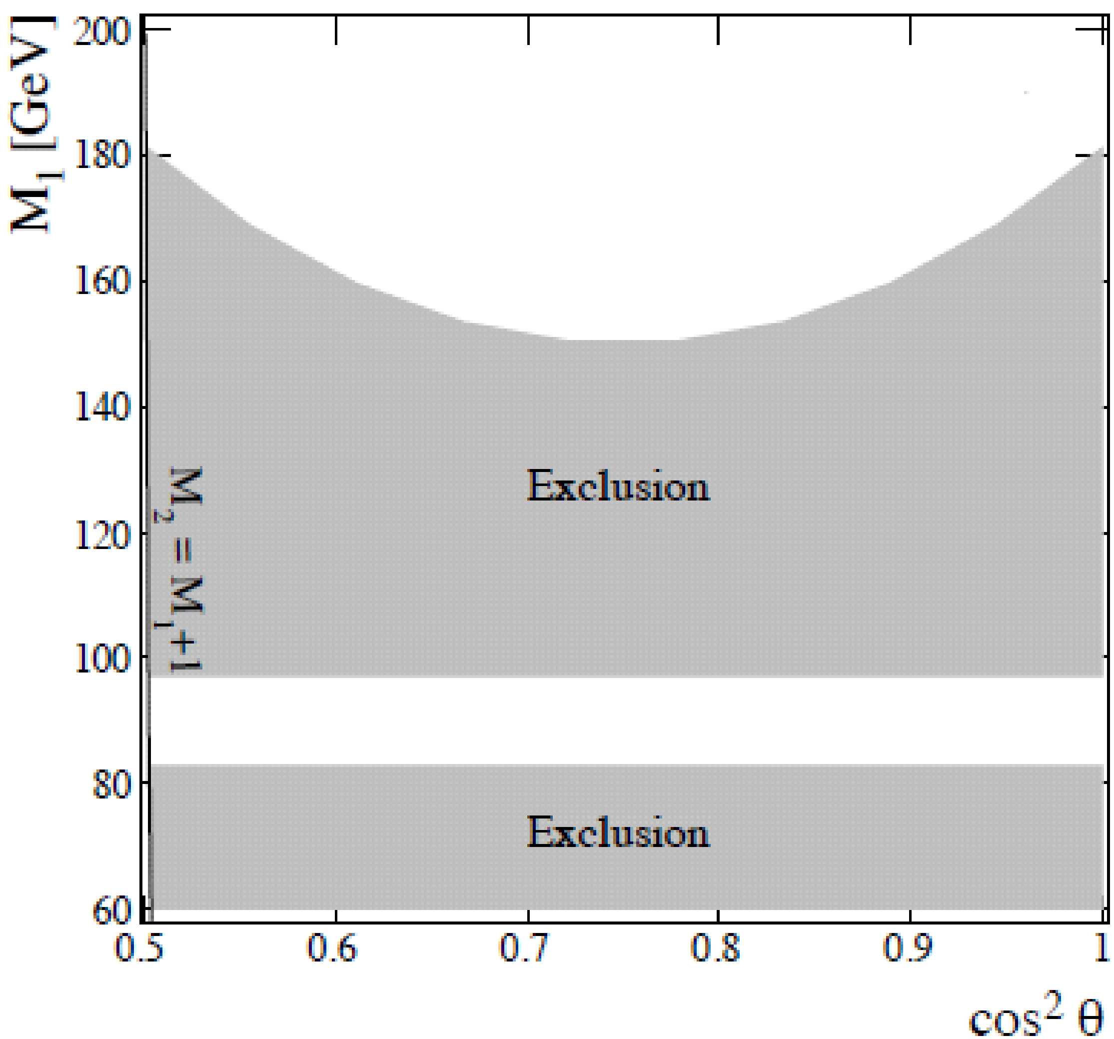
25
20
15
10
5
0
Z →NN
diboson
fakes
100
150
200
250
300
350
400
450
500
Neutrino Mass [GeV/c2]

One may produce estimated efficiencies

Tevatron						
Mass [GeV/c^2]	100	125	150	175	200	225
σ_{Theory}[fb]	26.7	9.8	4.1	1.8	0.9	0.4
ϵ	0.09	0.32	0.44	0.51	0.54	0.55
Yield	11.5	15.7	9.1	4.6	2.3	1.2
σ_{Limit}[fb]	8.3	2.5	2.0	1.8	1.6	1.0

LHC, 10 TeV							
Mass [GeV/c^2]	100	150	200	250	300	350	400
σ_{Theory}[fb]	195	39	12	5.2	2.3	1.2	0.6
ϵ	0.11	0.46	0.57	0.61	0.63	0.65	0.65
Yield	111.0	91.7	35.0	15.9	7.4	3.8	1.9
σ_{Limit}[fb]	10.7	4.5	2.7	2.6	2.3	2.0	1.5

With possible exclusion up to 300 GeV or with 5 inverse fb of data, 3 sigma discovery potential for 225GeV neutrinos.


M_1 [GeV]
200
180
160
140
120
100
80
60
0.5
0.6
0.7
0.8
0.9
1
cos^2 θ
Exclusion
Exclusion
M_2 = M_1+1