Phenomenology of Fourth Generation Neutrinos

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Constraints on a 4^{th} Generation

Z width from LEP Z pole measurements

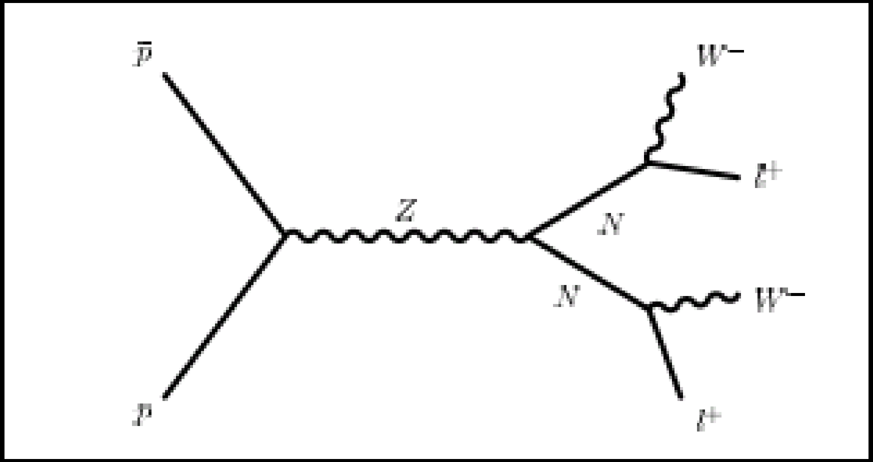
Direct search bounds

S and T EW precision measurements constrain fourth generation mass splittings

Mixing constrains between generations

Direct search mass bounds

Unstable fourth gen particles decay to SM fermion plus a W boson

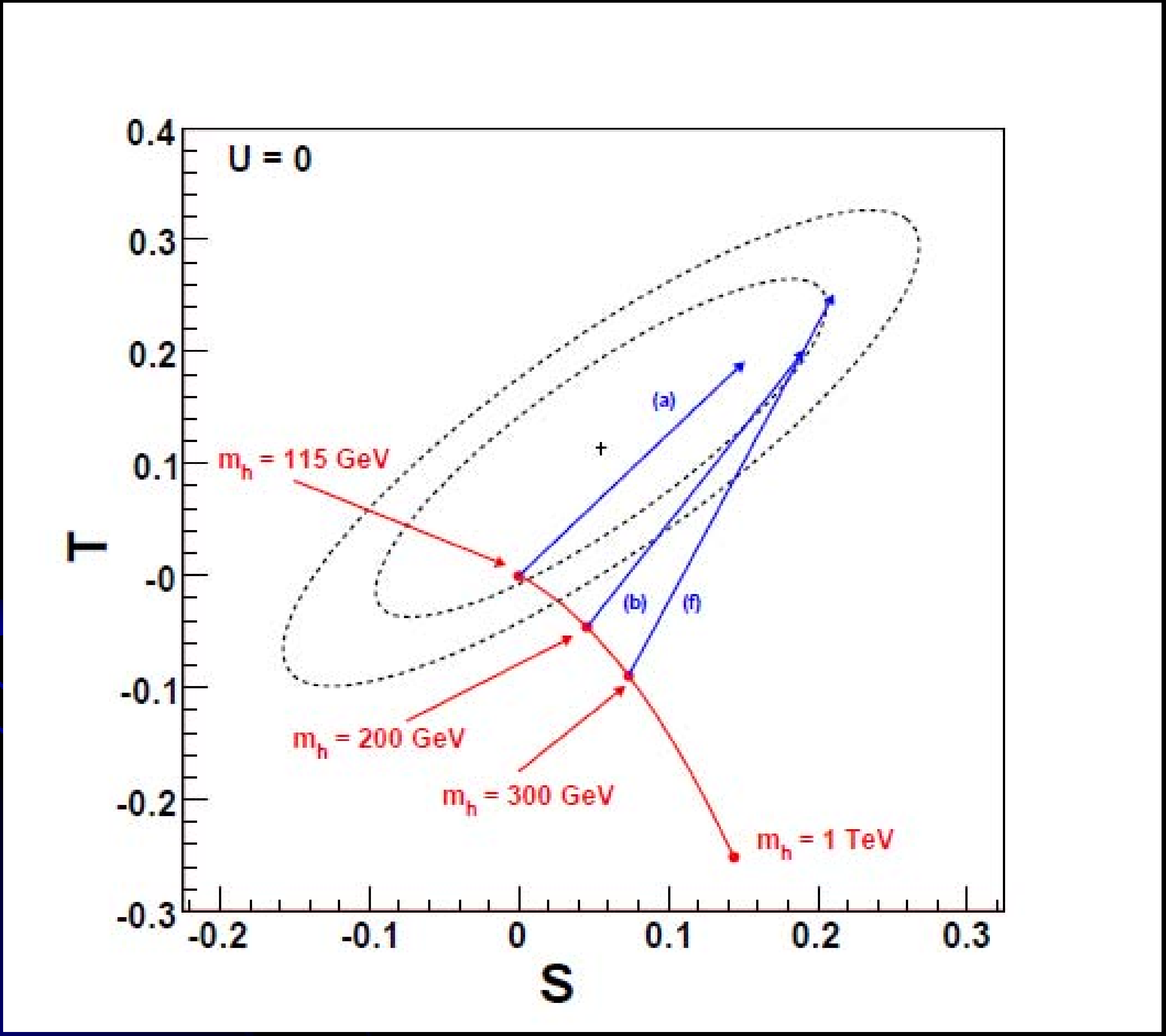


Tevatron Quarks mu>258 GeV
md>268 GeV

LEP neutrinos 101, 102, 90 GeV in e mu tau channel for Dirac neutrinos
90.7, 89.5, 80.5 GeV for Majorana neutrinos

Stable neutrinos 39.5 GeV for Majorana particles, 45 GeV for Dirac

S,T allowed parameter space



From Kribs et al 2007

EW precision constraints not particularly sensitive to lepton sector. For a large space of lepton mass parameters EW is fine if quark masses and splittings are appropriately chosen

parameter set	m_{u_4}	m_{d_4}	m_H	ΔS_{tot}	ΔT_{tot}
(a)	310	260	115	0.15	0.19
(b)	320	260	200	0.19	0.20
(c)	330	260	300	0.21	0.22
(d)	400	350	115	0.15	0.19
(e)	400	340	200	0.19	0.20
(f)	400	325	300	0.21	0.25

From Kribs et al 2007

Mixing constraints

In the quark sector direct measurements of V constrain mixing between fourth generation and first/second generation

$$|V_{ud_4}| \lesssim 0.04$$
$$|V_{u_4d}| \lesssim 0.08$$
$$|V_{cd_4}| \lesssim 0.17$$

Flavor changing measurements constrain generational mixing in the lepton sector mu to e gamma

$$|U_{e4}U_{\mu 4}| \lesssim 4 \times 10^{-4}$$

Neutrino Masses

For the neutrino fields N write mass terms

$$L_m = m_H H^2 + m_D^i \bar{L}_i N_R + M_N N^2 + m_e^{ij} \bar{L}_i E_{Rj}$$

- Which can be diagonalized

$$L_m = m_H H^2 + m_1 \bar{N}_1 N_1 + m_2 \bar{N}_2 N_2 + \sum_{i=1}^{4} m_e^i \bar{L}_i E_{Ri}$$

Define two mass eigen states

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

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

With mixing angle

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

And masses

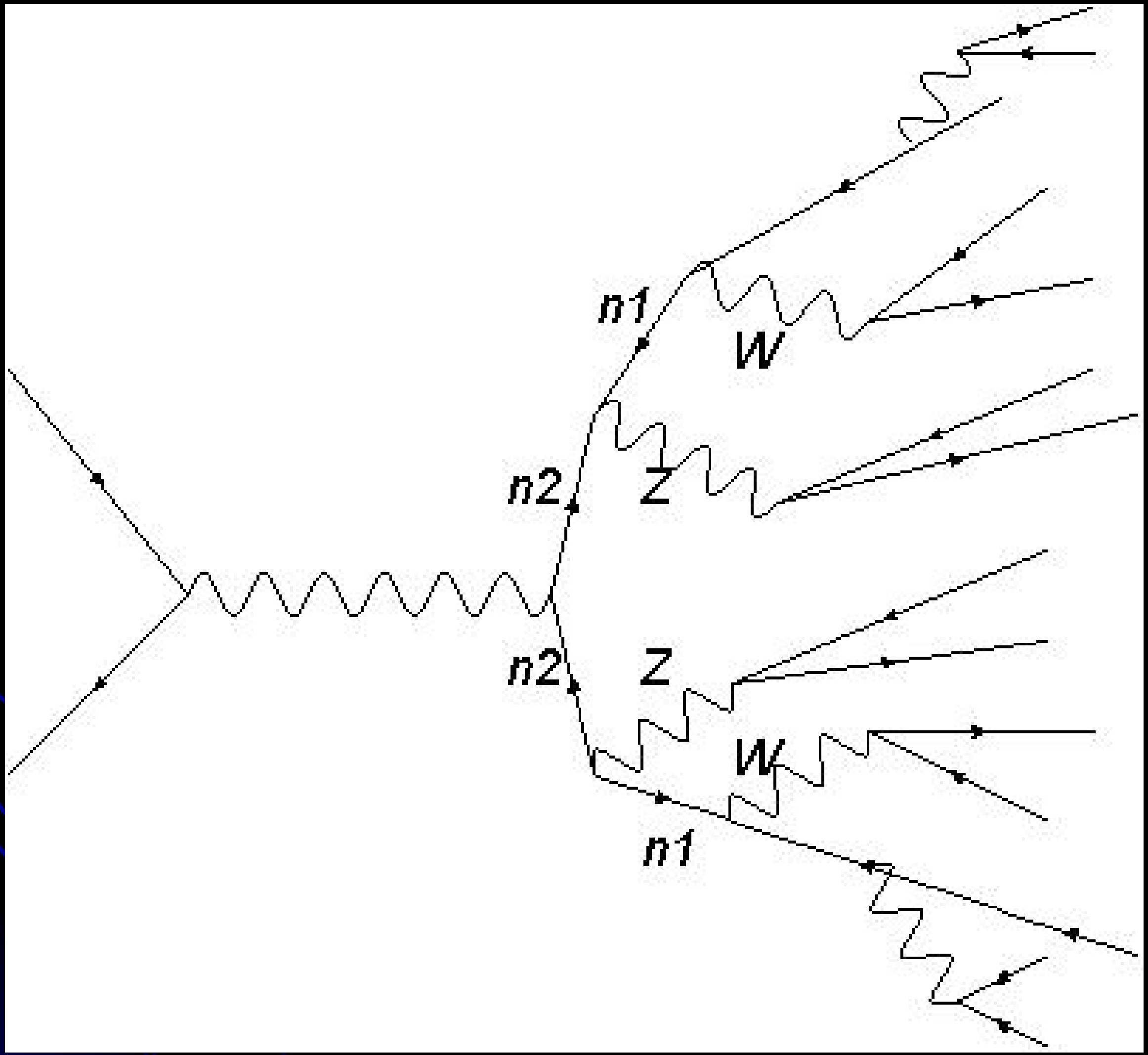
$$m_1 = -(M/2) + \sqrt{m_D^2 + M^2/4}; m_2 = -(M/2) - \sqrt{m_D^2 + M^2/4}$$

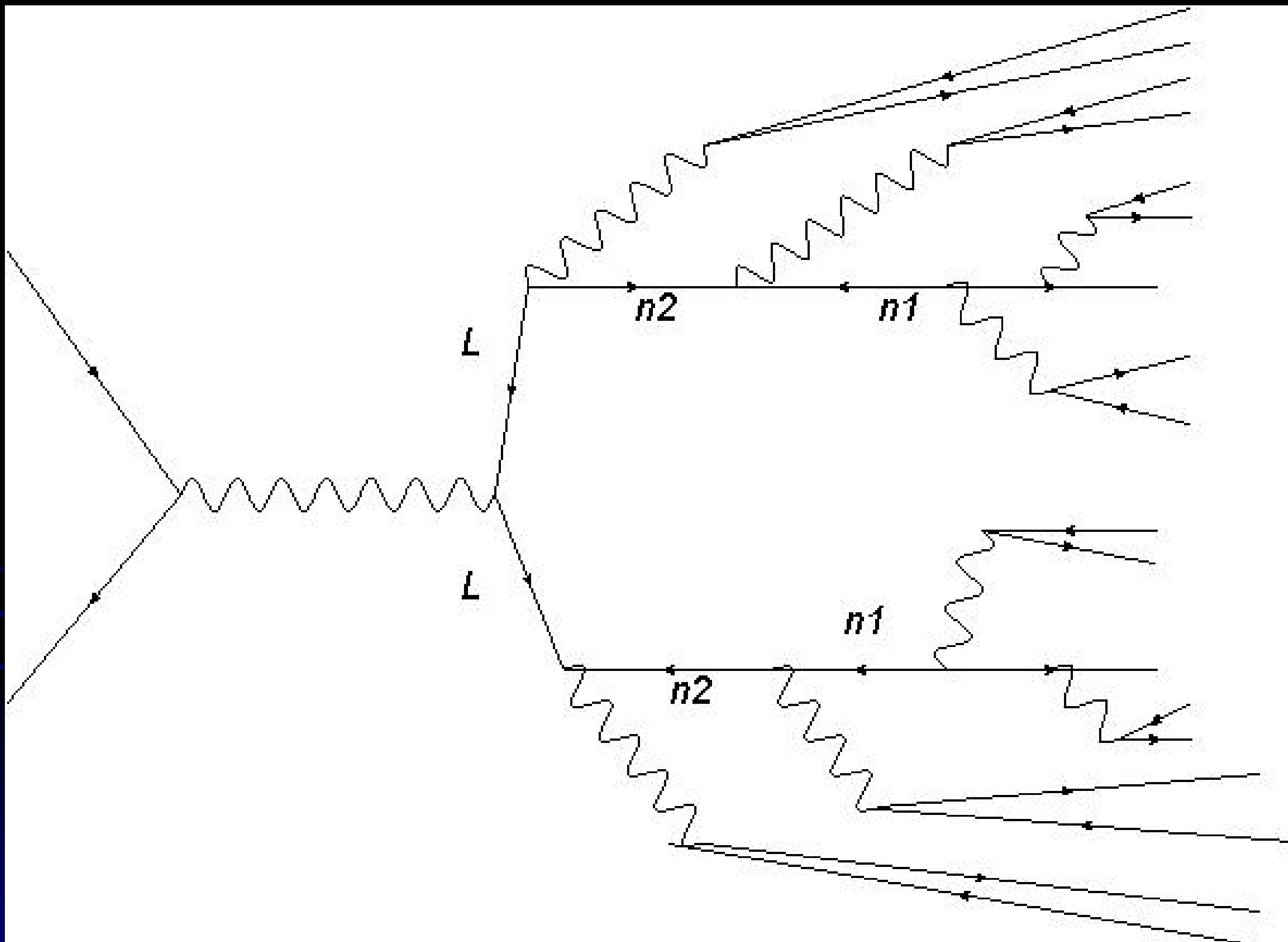
The coupling to gauge bosons is now mixing dependent

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

$$J^{\mu+} = \frac{1}{2}\overline{(c_\theta N_1 - i s_\theta N_2)}\gamma^\mu e_L$$

Possible Neutrino Event





L
n2
n1
L
n1
n2

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

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

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

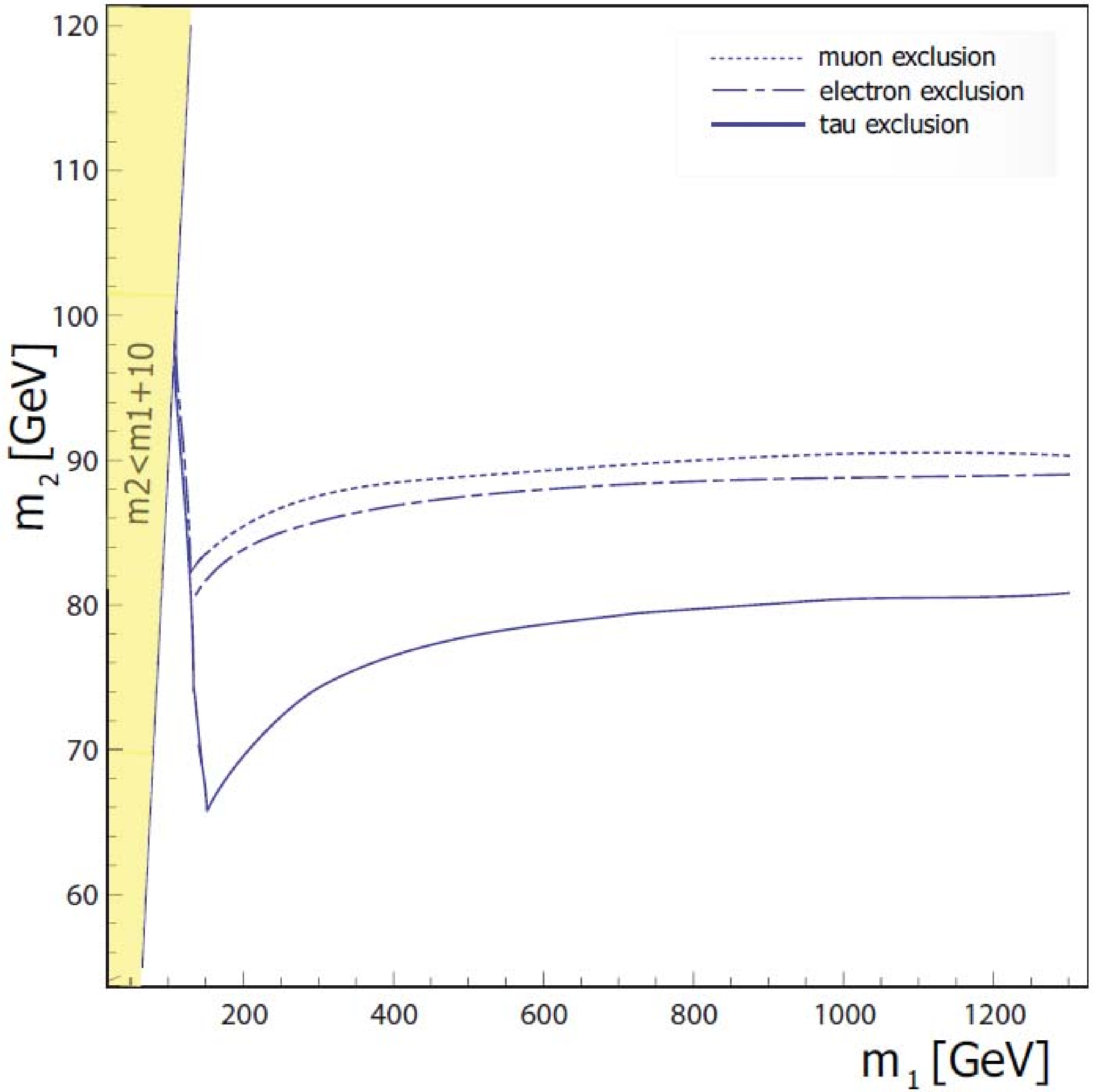
Relied on looking for 2 well isolated leptons of the same flavor.

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
m_2 [GeV]
m_1 [GeV]
120
110
100
90
80
70
60
200
400
600
800
1000
1200

Mass bounds

N_1 Decay Mode	Previous bounds	New bounds
Wτ	80.5	62.1
Wμ	89.5	79.9
W e	90.7	81.8

Stable case

The lightest neutrino may be stable. In this case the light state does not decay, the heavy state decays through an offshell Z boson to the light state plus a quark or lepton pair.

In this case mass bounds are placed by the total Z width and the invisible width of the Z from LEP 1.

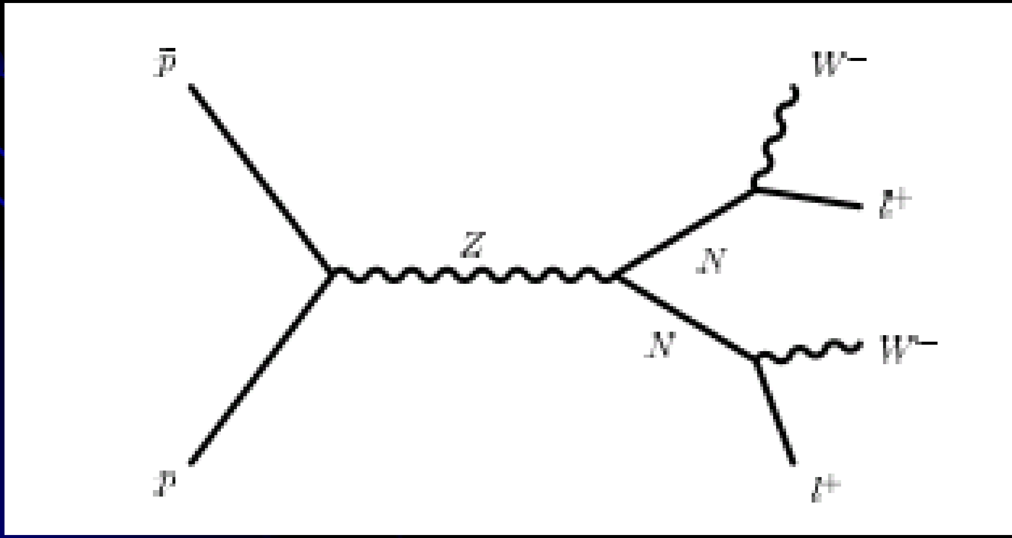
Tentative limits place the absolute lower bound on lightest mixed-state neutrino at 33 GeV from Z pole.

We must check that existing searches do not further constrain the cascade decay n2- n1+Z* to claim this lower limit holds.

Searching for heavy neutrinos, Example with Majorana masses

How to search for heavy neutrinos at Tevatron and LHC?

Like sign di-lepton signal.

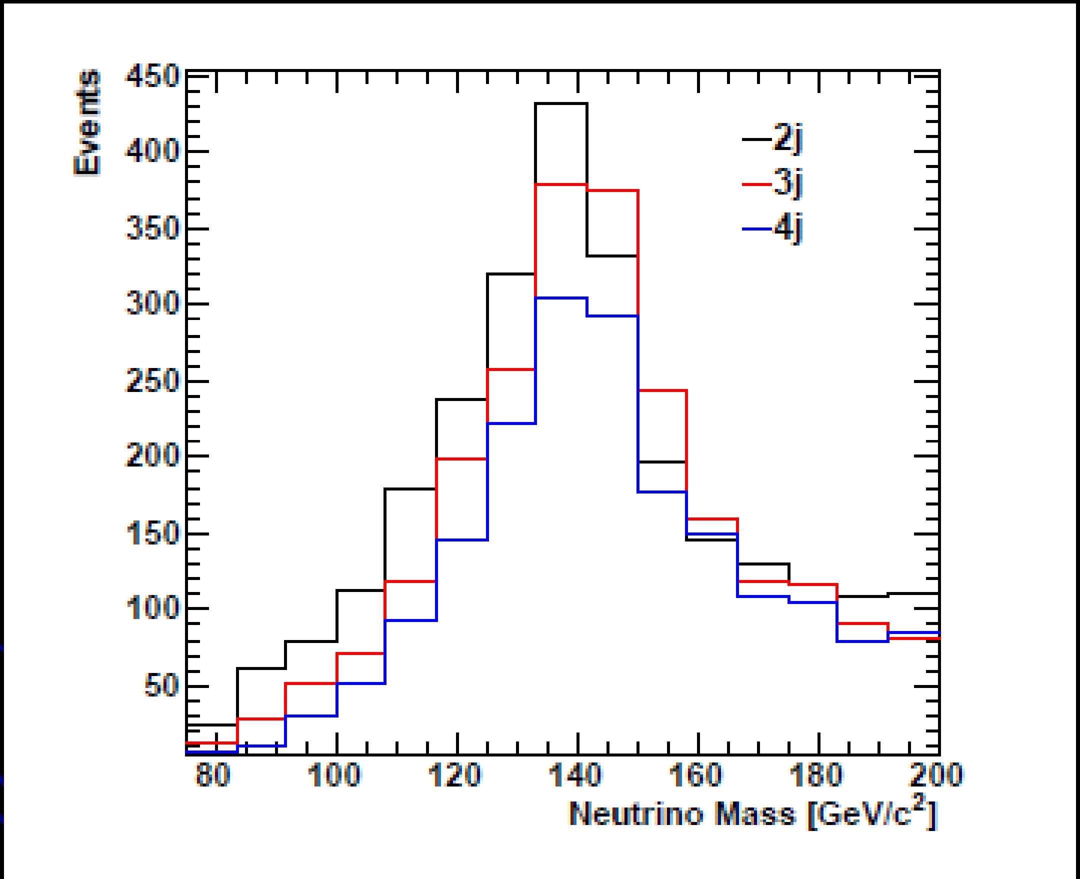


Half of the event will have same sign dileptons and Many event will have the final state

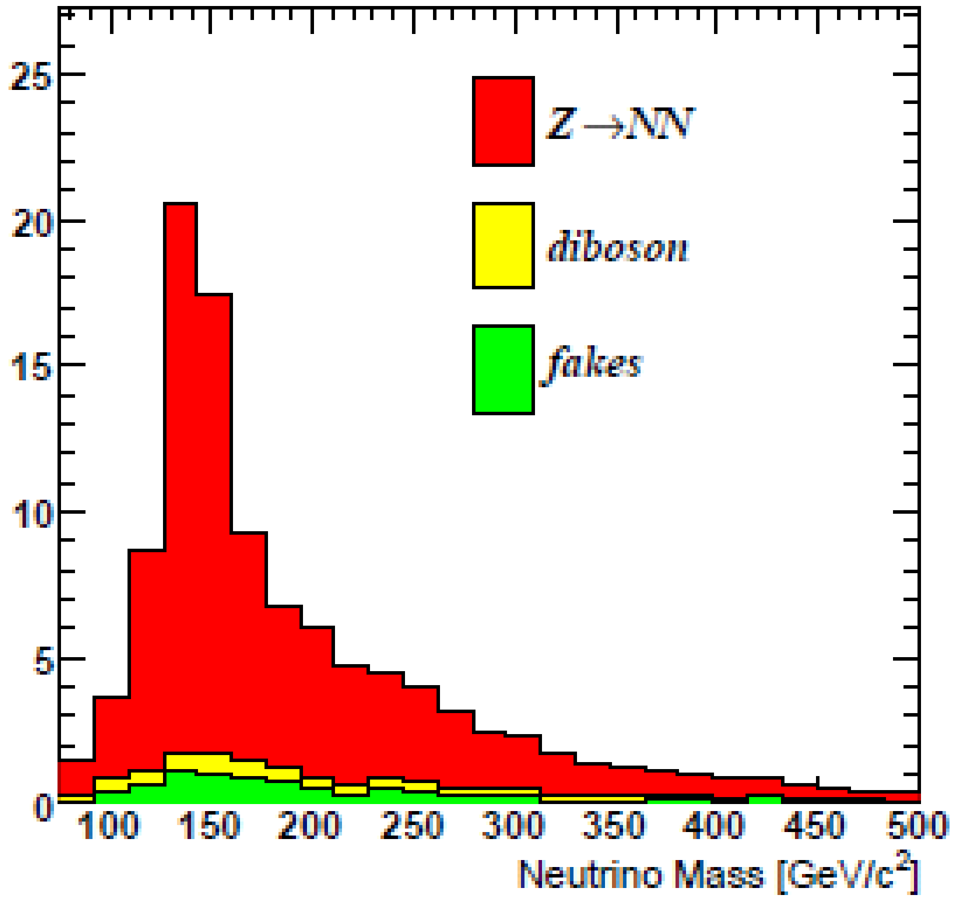
$$\ell^{\pm}\ell^{\pm}jj$$

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 $|\eta| < 2.5$



Events
450
400
350
300
250
200
150
100
50
80
100
120
140
160
180
200
Neutrino Mass [GeV/c^2]
2j
3j
4j



25
20
15
10
5
0
100
150
200
250
300
350
400
450
500
Neutrino Mass [GeV/c^2]
$Z \rightarrow NN$
diboson
fakes

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.

Extending this search with cascade decays for two mass states would in principle follow the same way.

Some production cross section would be lost in the case of heavy mixing. And new efficiencies for the cascade would have to be calculated.

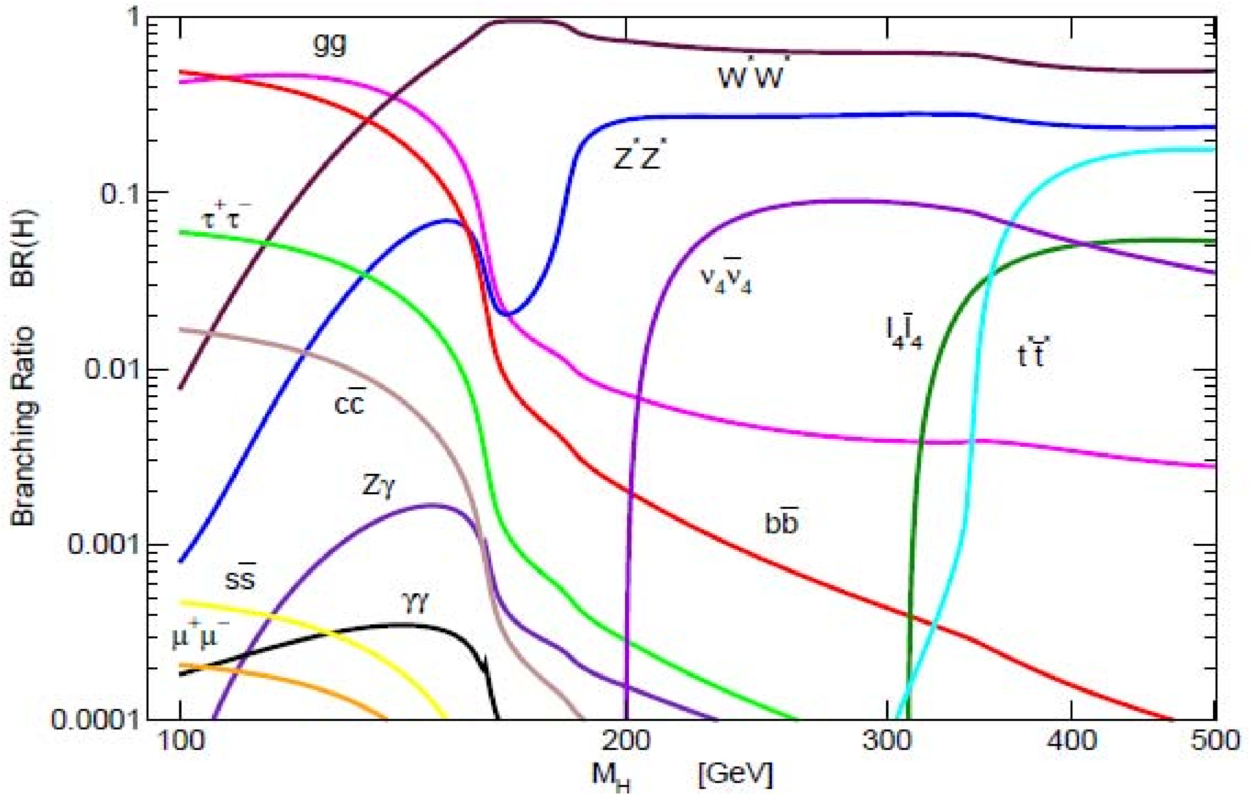
Challenges for light neutrinos

For light neutrinos less than 100 GeV, current searches cannot exclude neutrinos as the efficiency of like sign di-leptons drops dramatically.   Leptons are not well isolated, and pT is small.

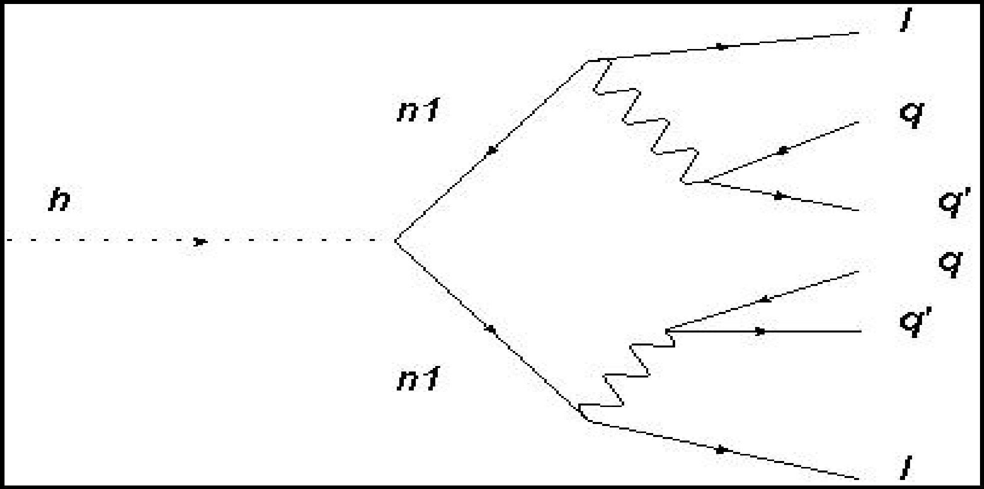
Must develop jets + missing energy search for stable neutrino case.

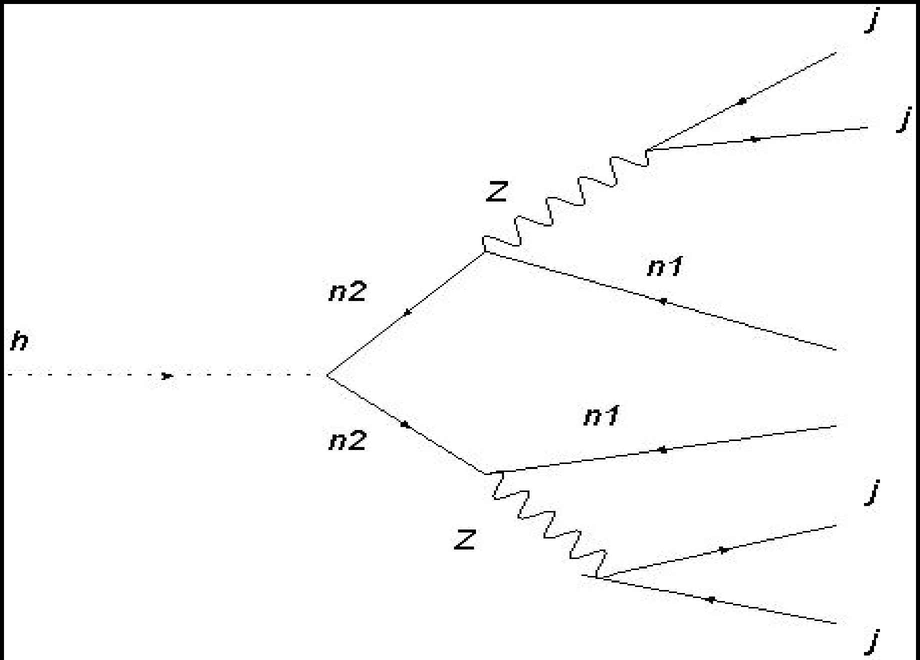
Higgs physics

An example of Higgs branching fractions with a fourth generation



Possible Higgs Decays





In the region of intermediate Higgs, 100-160 GeV gg and bbar are the dominant signals.

For the case of light-heavy neutrinos neutrino pair production is proportional to the square of the Dirac mass component of the neutrino. This will easily beat bbar production by a factor of 50-100 for the case of neutrinos with masses from 35-80 GeV.

At the low end of the allowed mixed mass spectrum, neutrino pair production would overtake other signals as the dominant Higgs decay.

Such a region would be very challenging to find the Higgs in,

-like sign dilepton searches are not sensitive. The Higgs final state contains between 6 and10 particles.

Summary

Fourth generation is a possibility for BSM physics allowed by current constraints

The lightest particle mass bounds may be well under 100 GeV

This may have strong consequences for fourth generation particle searches which include cascade decays as well as for nonstandard Higgs signals.

In the case of heavy particles LHC and Tevatron maybe able to tweak existing searches to rule out or discover these particles.

Ongoing work

Calculate exact mass exclusions for stable light 4^{th} generation neutrinos

Calculate Tevatron and LHC discovery potential for neutrinos with mixed masses

Calculate Higgs decay branching fractions for the case of Higgs<200 GeV and light neutrinos