The Fourth Generation at LEP, Tevatron and the LHC

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based on arXiv:1001.1229, 1005.4407 with Daniel Whiteson,
arXiv:1005.0628, ongoing work with Linda Carpenter
Plan of Talk

1. Why the fourth generation

2. Fourth generation searches: Higgs, quark sectors

3. Fourth generation neutrino searches

4. One neutrino: Current (LEP) bounds, Tevatron and LHC reaches

5. Two neutrinos: New LEP bounds, Tevatron, LHC reaches

6. Fourth generation charged lepton searches

7. Future directions
Why not? We do not have an understanding of why there should be three generations.

Asymptotic freedom allows up to 9 generations.

String model building suggests that four generations may be more common than three.
Why the fourth generation

Fourth generation provides a unique set of signals, different from SUSY, extra dimensions.

Useful model to compare against signals.

Parameter space not too large or complicated, can in principle be completely excluded at LHC.

Signals are interesting in their own right.
Why the fourth generation

Earlier claim (PDG 2006): fourth generation excluded on basis of precision measurements (S parameter)

More recent claim: with appropriate adjustments of masses precision constraints are satisfied.

H. J. He, N. Polonsky, S. f. Su
G. D. Kribs, T. Plehn, M. Spannowsky, T. M. P. Tait
Why the fourth generation

G.D. Kribs, T. Plehn, M. Spannowsky, T.M.P. Tait
Why the fourth generation

B-physics anomalies may be explained by a new generation.

Soni et al. 0807.1971
Why the fourth generation

Mild suggestions of a heavy quark
Fourth Generation searches: the Higgs
Fourth Generation searches: the Higgs

Higgs searches radically modified in presence of 4th generation.

gg-> h enhanced since new quarks can run in loop.

h-> gg, γγ enhanced.

Tevatron has searched for h → WW decays, excluding a Standard Model higgs of mass close to 160 GeV.

Analysis redone for fourth generation.

CDF+D0: arXiv 1005.3216
Fourth Generation searches: the Higgs

Example of modified branching ratios
Fourth Generation searches: the Higgs

131 GeV < $m_H$ < 204 GeV excluded at 95% confidence level.
Fourth Generation searches: the Higgs

The previous analysis ignores possible new light states like fourth generation neutrinos. This could modify signals significantly.

hep-ph 0210153, Belotsky et al.
Fourth Generation searches: Quarks
Fourth Generation searches: Quarks

The simplest signal of the fourth generation comes from fourth generation quark searches.

Quarks cannot be arbitrarily heavy since they get mass from EWSB.

If Yukawa less than 10, quarks less than 3 TeV.

Difficulties with Landau poles unless quarks not too heavy.
Fourth Generation searches: Quarks

Cross sections at LHC very high

From arXiv: 0804.2800v1
Fourth Generation searches: Quarks

Bounds dependent on decay modes.

If $t' \to bW$, then $m(t') > 311 \text{ GeV}$
If $b' \to tW$, then $m(b') > 338 \text{ GeV}$

However, bounds can be changed in various models. In particular, if the decay lifetime is long, the new quarks may decay outside the tracker, and the constraints are weakened.
Fourth Generation searches: Quarks

Bounds as functions of mixing angle (based on old analysis)

Hung and Sher
Fourth Generation searches: Neutrinos
Fourth generation Neutrinos

Why look for neutrinos in particular?

Neutrino search is well motivated.

1) Expect neutrinos to be lightest among the fourth generation particles, in analogy to first three generations

2) New neutrinos decay to leptons, easier to find than new quarks. Charged leptons may decay to $\nu W$, hard to find.

3) Interesting new phenomenology
Fourth generation Neutrinos

The usual neutrino mass term is a dimension 5 operator
\( \nu\nu HH/M \)

where \( M \) is the Majorana mass of the RH neutrino.

To avoid constraints, the neutrino mass is at least of order 45 GeV.

So the RH neutrino mass cannot be too large; less than 1 TeV.

Must consider both LH and RH neutrinos in phenomenological analysis.
Fourth generation Neutrinos

General neutrino mass term

\[(Q_R^c \ N_R^c) \begin{pmatrix} 0 & M_D \\ M_D & M \end{pmatrix} \begin{pmatrix} Q_R \\ N_R \end{pmatrix}\]

Mass eigenvalues

\[M_1 = -M/2 + \sqrt{ (M^2/4 + M_D^2) } \]
\[M_2 = M/2 + \sqrt{ (M^2/4 + M_D^2) } \]

with corresponding eigenstates denoted \(N_1, N_2\).
Fourth generation Neutrinos

We shall begin by performing a simplified analysis, where we restrict ourselves to a single neutrino. This is done by taking the limit $M_D, M$ large keeping $M_D^2/M$ fixed.

The remaining neutrino has couplings to the $Z$ of the form $Z_\mu J^\mu$ where

$$J^\mu = N_1 \gamma^\mu \gamma^5 N_1$$

$N_1$ will decay through a charged current interaction to $lW$, where $l$ is a lepton of the first three generations.

**Majorana fermion:** decays equally to $l^+W^-$ and $l^-W^+$. 

Fourth generation Neutrinos

N can be produced either through a W or a Z at hadron colliders.

The process $pp \rightarrow W \rightarrow lN$ has been studied by several authors. It is enhanced by the larger W cross section, and by the lower required energy.

On the other hand, the process is proportional to the mixing between the fourth generation and the other three generations.

Precision measurements suggest that this mixing is small. We will take this limit. Then the production through charged currents can be ignored.
Fourth generation Neutrinos

We will therefore consider the neutral current process
\[ pp \rightarrow Z \rightarrow NN \]

This rate is suppressed by the smaller Z cross section, but is model independent.

Not studied in much detail for the LHC.

No studies at the Tevatron.

Can the Tevatron find such neutrinos?
Fourth generation Neutrinos: LEP

LEP searched for neutrinos in the process
\[ e e \rightarrow Z \rightarrow N N \rightarrow lW lW \]

Done by L3 in 2001 with 450 \( pb^{-1} \) of data between 192-208 GeV

Search for two isolated leptons plus W decay products.

They obtained the bounds:

For neutrinos decaying as \( N \rightarrow eW \) or \( \mu W \), \( m > 90 \) GeV

For neutrinos decaying as \( N \rightarrow \tau W \), \( m > 85 \) GeV
Fourth generation Neutrinos: Tevatron

At the Tevatron, neutrinos are produced by the process
\[ pp \rightarrow Z \rightarrow NN \rightarrow lWlW \]

We look at hadronic W decays (not enough events to allow for lower leptonic branching fraction)

We only consider the cases \( N \rightarrow (e, \mu ) W \). \( \tau \) signals appear to be impossible to see at the Tevatron.

Half the events are same sign leptons: reduce background.
Fourth generation Neutrinos: Tevatron, LHC

Signal: two central same sign leptons, lepton pT >20 GeV and at least 2 central jets of pT > 15GeV

Background found from old CDF study (PRL 98,221803 (2007))

Signal found in MADGRAPH, processed through PYTHIA and PGS.

AR, Daniel Whiteson
Fourth generation Neutrinos: Tevatron, LHC

Backgrounds, signal to reconstructed mass with 5 fb$^{-1}$ at the Tevatron, LHC for a 150 GeV neutrino.
Fourth generation Neutrinos: Tevatron, LHC

FIG. 4: Theoretical cross-section for $N$ production and decay to $\ell^\pm W \ell^\pm W$ and median expected 95% C.L experimental cross-section upper limits in 5 fb$^{-1}$ of Tevatron data (left) or LHC data (right), assuming BR($N \rightarrow \mu W$) = 100%.
Fourth generation Neutrinos: Tevatron, LHC

For masses between 95 and 175 GeV, Tevatron can exclude (95% CL) a Majorana neutrino decaying to eW or μ W.

Below 100 GeV, the acceptance drops precipitously, because leptons are too soft.

Mass range from 85 to 95 GeV cannot be probed.

Comparison to data is in progress at CDF.

LHC can improve reach up to 225 GeV.

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Fourth generation Neutrinos: Tevatron, LHC

Experimental exclusion (95% CL) as BR to $\tau$ changes
Two Fourth generation Neutrinos

We now turn to the general case of two neutrinos of masses $M_1$, $M_2$. Even more generally, we should include the charged lepton, we will not do so yet (we are implicitly taking it to be heavy.)

The neutrinos interact with $Z$ through the interaction $Z_\mu \ J^\mu$ where

$$J^\mu = \cos^2\theta \ N_1 \gamma^\mu \gamma^5 N_1 + 2i \cos \theta \sin \theta \ N_1 \gamma^\mu N_2$$

$$+ \sin^2\theta \ N_2 \gamma^\mu \gamma^5 N_2$$

where $\cos^2 \theta = \frac{M_2}{(M_1 + M_2)}$
Two Fourth generation Neutrinos

There is also a charged current interaction which couples the fourth generation to the other three generations.

Once again we shall assume that this coupling is small. Explicitly the interaction is taken to be

\[ c_i W_\mu N_i \gamma^\mu (1 - \gamma^5) l \]

and we will take \( c_i < 10^{-4} \).

This interaction is then only important for the decay of the lighter neutrino.
Two Fourth generation Neutrinos

The heavier neutrino can decay either as $N_2 \rightarrow lW$ ($l = e, \mu, \tau$) or as $N_2 \rightarrow N_1 Z$.

The first decay mode is suppressed by the small mixing between the fourth generation and the other three generations. For most masses, the second mode dominates.

However, when the mass difference between the two neutrinos goes to zero (the pseudo-Dirac limit), there is a phase space suppression of the second mode.

We will assume that we do not have this extreme degeneracy and that the mode $N_2 \rightarrow N_1 Z$ dominates.
Two Fourth generation Neutrinos

Note also that in the Dirac limit, only the CKM suppressed decay is allowed to occur, and the interference between the various contributions kills the same sign dilepton decays. This is expected since the Dirac fermion conserves fermion number.

Since we are assuming that the decay $N_2 \rightarrow N_1 Z$ dominates, this interference does not occur. We therefore get same sign dilepton decays for all the parameter space we consider.
Two Fourth generation Neutrinos: LEP

Neutrinos are produced through the Z boson (the W production is suppressed by the small mixing.)

The production processes at LEP are

\[ ee \rightarrow Z \rightarrow N_1 N_1 \]
\[ ee \rightarrow Z \rightarrow N_1 N_2 \]
\[ ee \rightarrow Z \rightarrow N_2 N_2 \]

We want to reinterpret the LEP bounds taking these multiple decays into account.
Two Fourth generation Neutrinos: LEP

Note that the Z coupling to the lighter neutrino is proportional to $M_2 / (M_1 + M_2)$.

As the mass $M_2$ decreases, the coupling decreases. and goes from 1 to $\frac{1}{2}$. This decreases production rate and weakens limits.

On the other hand, when $M_2$ gets small enough, the second neutrino can be produced directly, and the limits get stronger again.

As a function of the heavy mass, the limits should weaken and then tighten.
Two Fourth generation Neutrinos: LEP

AR, Linda Carpenter
Two Fourth generation Neutrinos: LEP

<table>
<thead>
<tr>
<th>$N_1$ Decay Mode</th>
<th>Previous bounds</th>
<th>New bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_\tau$</td>
<td>80.5</td>
<td>62.1</td>
</tr>
<tr>
<td>$W_\mu$</td>
<td>89.5</td>
<td>79.9</td>
</tr>
<tr>
<td>$W_e$</td>
<td>90.7</td>
<td>81.8</td>
</tr>
</tbody>
</table>

Table 3: Bounds on $N_1$ mass in GeV for the various decay channels.
Two Fourth generation Neutrinos: Tevatron

At the Tevatron, the production processes are

\[ pp \rightarrow Z \rightarrow N_1 N_1 \]
\[ pp \rightarrow Z \rightarrow N_1 N_2 \]
\[ pp \rightarrow Z \rightarrow N_2 N_2 \]

At least half the decays produce same sign leptons, along with decay products of the W and Z.

We will not consider the case where \( N_1 \) decays to \( \tau \) W.

Look for same sign leptons (pT> 20 GeV) along with 2 or more jets.
Two Fourth generation Neutrinos: Tevatron

As masses vary, we have the same general features.

We have \[ \cos^2 \theta = \frac{M_2}{M_1 + M_2} \]

As \( M_2 \) decreases, \( \cos^2 \theta \) decreases from 1, the coupling of \( Z \) to the lighter neutrino decreases. This lowers the production rate of \( N_1 \). Eventually \( N_2 \) becomes light and the rate increases again.

For lower masses near 100 GeV, the acceptance drops since the leptons are soft; limits weaken.

We will plot limits as a function of \( M_1, \cos^2 \theta \)
Two Fourth generation Neutrinos: Tevatron

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Two Fourth generation Neutrinos: Tevatron

If no excess is seen, CDF can exclude the existence of $N_1 , N_2$ up to 150-170 GeV, depending on the mixing angle.

A band between 83-97 GeV cannot be probed; the acceptance is very small due to the softness of the produced lepton.
Stable Fourth generation Neutrinos: LEP

If the mixing between the fourth generation and the first three generations is zero, the lightest neutrino can be stable.

The bounds on stable neutrinos can also be weakened.

Current LEP bound: stable neutrinos must have mass $> 40$ GeV to avoid invisible width constraints.

Assumes single Majorana neutrino
Stable Fourth generation Neutrinos: LEP

For large $M_2$, we reproduce the bound that $M_1 > 40$ GeV.

As $M_2$ decreases, the bounds are weakened, because the $Z$ mixing with the light neutrino is reduced.

Eventually $M_2$ gets small enough that the decay $Z \to N_1 N_2$ is allowed, and we run into constraints from the total width.
Stable Fourth generation Neutrinos: LEP

Work in progress with Linda Carpenter
Stable Fourth generation Neutrinos: LEP

Other collider constraints on stable neutrinos not so strong.

\[ pp \rightarrow Z \rightarrow N_1 N_2 \rightarrow N_1 N_1 Z \]

can yield events with dijets/dileptons and missing energy.

\[ pp \rightarrow Z \rightarrow N_2 N_2 \rightarrow N_1 N_1 Z Z \]
can yield events with 4 jets/ 4 leptons/ 2 jets+2 leptons and missing energy.

Low event rates at Tevatron; do not get stronger constraints.
Stable Fourth generation Neutrinos: LEP

Current LEP bound: stable neutrinos must have mass $> 40$ GeV

In 2-neutrino situation, stable neutrinos can be as light as 34 GeV and still be OK if mixing angle chosen appropriately.

Work in progress with Linda Carpenter
Fourth Generation Charged Leptons

Cascades $L \rightarrow N_2 \rightarrow N_1$; events can have up to 16 final state particles.

Signal: high multiplicity events with jets and leptons. Can these be found?
Future directions

Look in data for signals of fourth generation neutrinos. This is in progress.

Redo Higgs bounds. In particular, a light (114-160 GeV) Higgs decaying to neutrinos may have unique signals. e.g. $H \rightarrow N_1 N_1 \rightarrow \tau \tau \, W W$ when the neutrino is about 62 GeV.

What about tau decays?

Charged leptons: can we find these in multijet events?

Can we close the gap for light neutrinos? Maybe one can redo Tevatron analysis with lower pT cut. One can also perhaps look at LEP data imposing same sign lepton requirement.
Backup Slides
Why the fourth generation

LHC reach: about TeV.

Lepton sector unexplored.

In particular, Tevatron has not performed searches for fourth generation neutrinos.
Two Fourth generation Neutrinos: Tevatron

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Fourth Generation searches: Charged Leptons