Fourth Generation Neutrinos at the Tevatron and LHC

Arvind Rajaraman

UC Irvine

based on arXiv:1001.1229 with Daniel Whiteson,
ongoing work with Daniel Whiteson,
ongoing work with Linda Carpenter

Plan of Talk

1. Motivation for fourth generation neutrino studies

2. Phenomenology of fourth generation neutrinos
   in particular, we should have both a left handed
   and a right handed neutrino

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

4. Two neutrinos: Revised LEP bounds

5. Two neutrinos: Tevatron, LHC reaches

6. Future directions

Why the fourth generation

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

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.

(G.D. Kribs, T. Plehn, M. Spannowsky, T.M.P. Tait, Phys. Rev. D 76 (2007) 075016)

Why the fourth generation

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

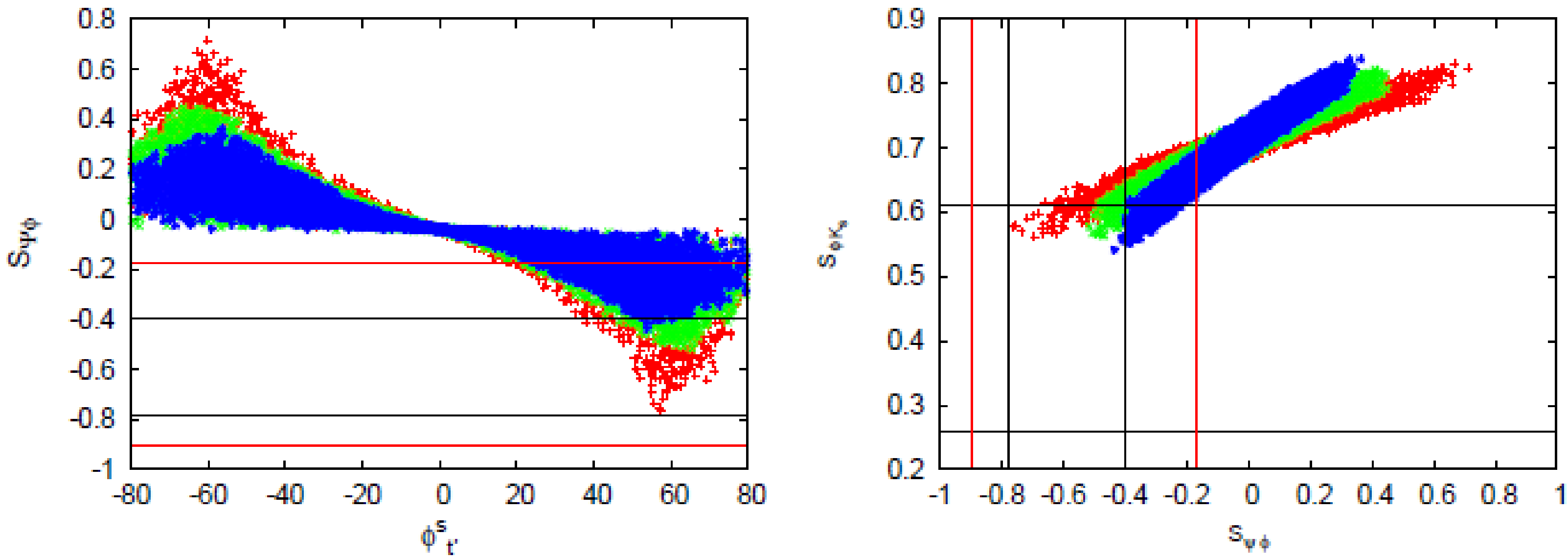
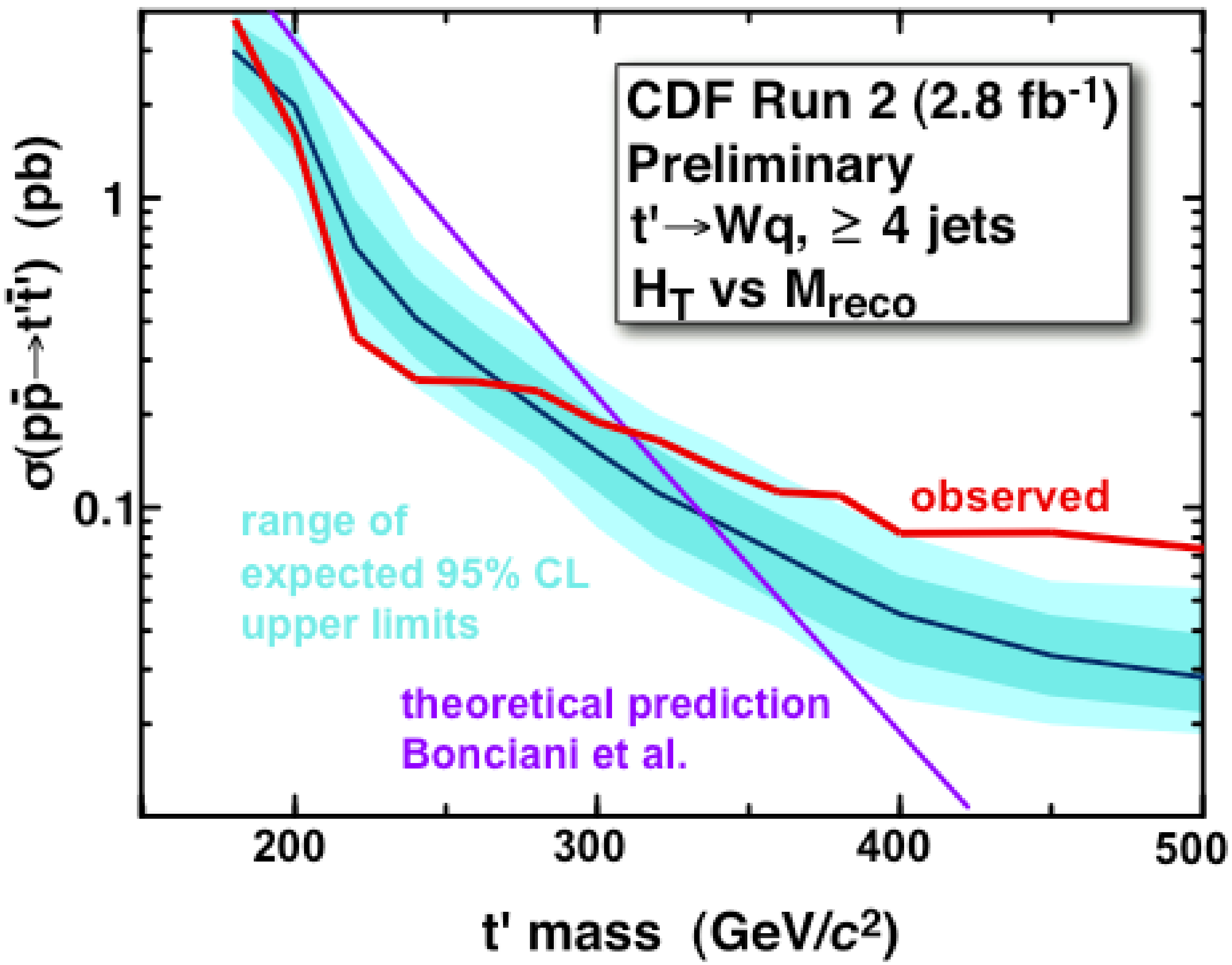


FIG. 1: The left panel shows the allowed range for $S_{\psi\phi}$ in the $(S_{\psi\phi} - \phi^s_{t'})$ plane for $m_{t'} = 400$ (red), 500 (green) and 600 (blue) GeV respectively. Black and red horizontal lines in the figure indicate 1-σ and 2-σ experimental ranges for $S_{\psi\phi}$ respectively. The right panel shows the correlation between $S_{\phi K_s}$ and $S_{\psi\phi}$ for $m_{t'} = 400$ (red), 500 (green) and 600 (blue) GeV respectively. The horizontal lines represent the experimental 1σ range for $S_{\phi K_s}$ whereas the vertical lines (Black 1-σ and red 2-σ) represent that for $S_{\psi\phi}$.

Soni et al. 0807.1971

Why the fourth generation

Mild suggestions of a heavy quark



Why the fourth generation

Tevatron has searched for heavy t', b'

Current bounds: m(t') > 311 GeV
m(b') > 338 GeV (if b' decays to tW)

LHC reach: about TeV.

Lepton sector unexplored.

In particular, Tevatron has not performed searches for fourth generation neutrinos.

Why the fourth generation

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 νW, 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

$$\left(Q_R^{\,c} \quad N_R^{\,c}\right)\begin{pmatrix} 0 & M_D \\ M_D & M \end{pmatrix}\begin{pmatrix} Q_R \\ N_R \end{pmatrix}$$

Mass eigenvalues

$$M_1 = -M/2 + \sqrt{\left(M^2/4 + M_D^2 \right)}$$

$$M_2 = M/2 + \sqrt{\left(M^2/4 + M_D^2 \right)}$$

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
$e\ e \to Z \to N\ N \to lW\ lW$

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 $N \to eW$, $m > 90$ GeV

For neutrinos decaying as $N \to \tau W$, $m > 85$ GeV

Fourth generation Neutrinos:Tevatron, LHC

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 $N \rightarrow (e, \mu)\ W$. τ 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

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

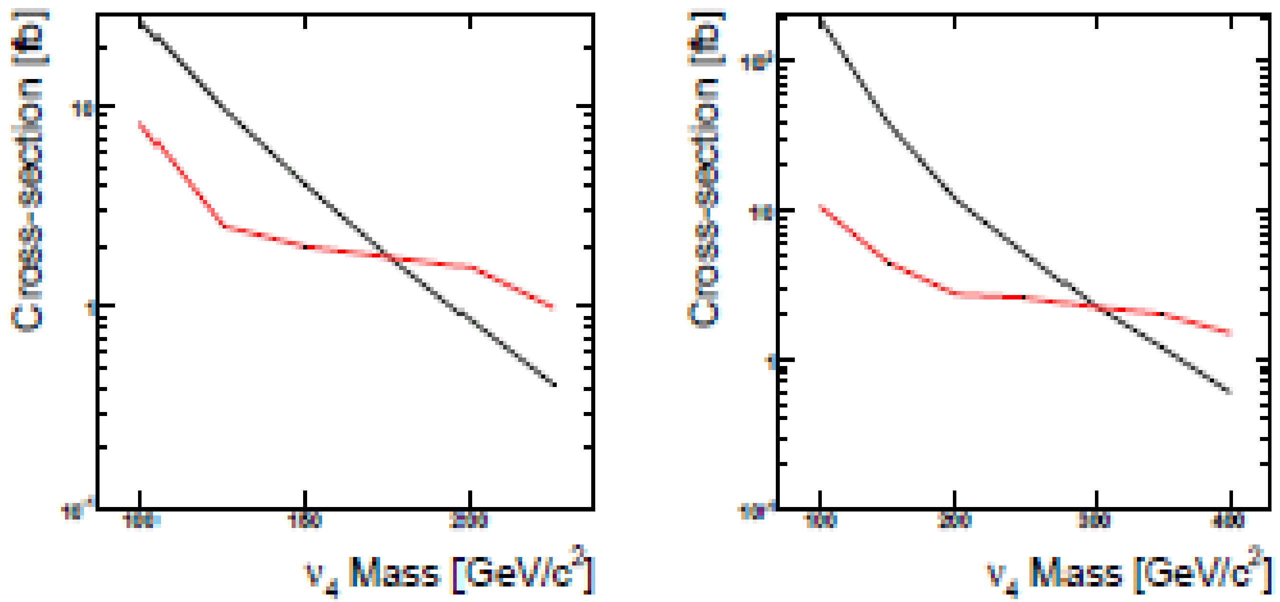
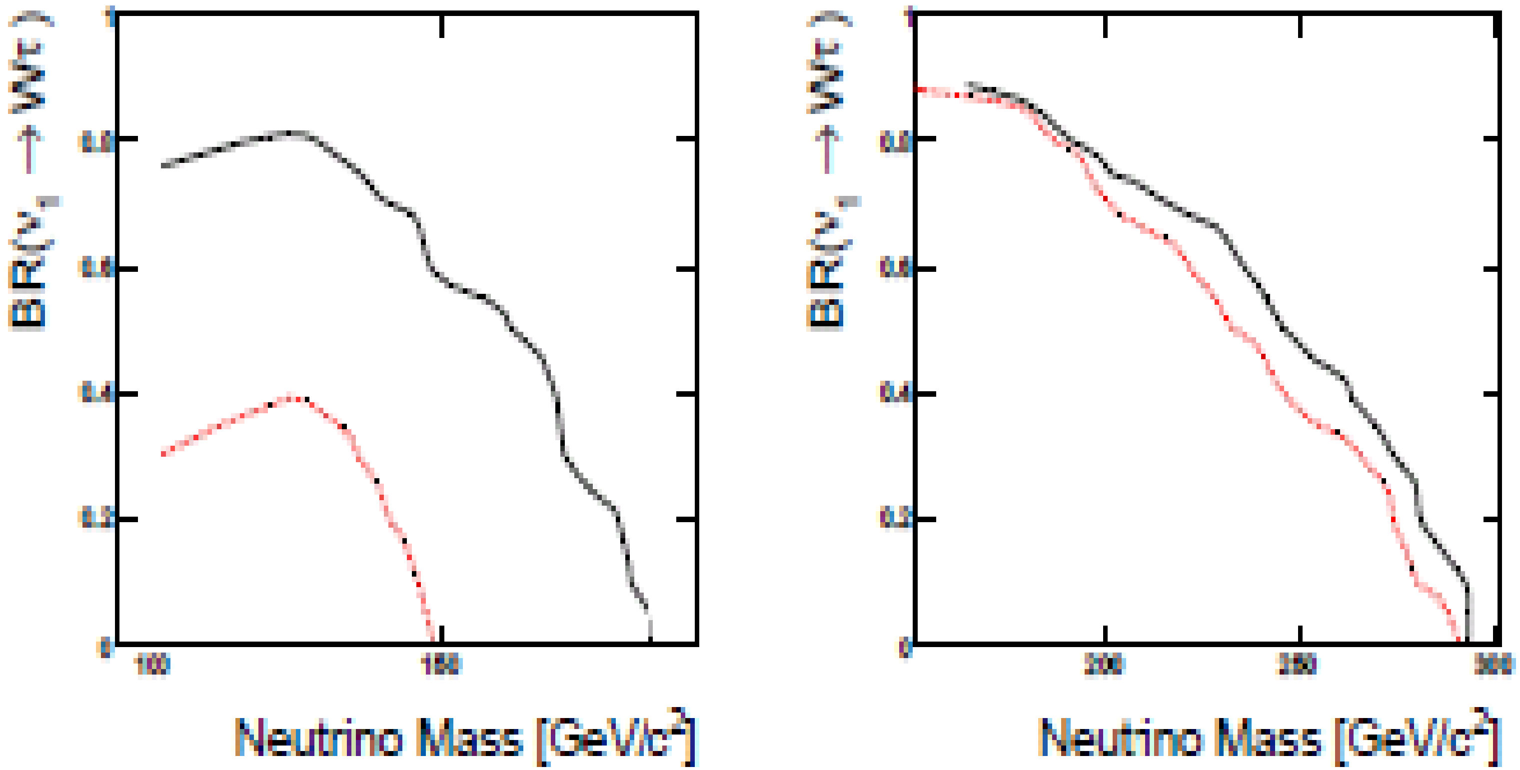


FIG. 4: Theoretical cross-section for N production and decay to $\ell^{\pm}W\ell^{\pm}W$ and median expected 95% C.L experimental cross-section upper limits in 5 fb^{-1} of Tevatron data (left) or LHC data (right), assuming $\text{BR}(N \to \mu W) = 100\%$.

Fourth generation Neutrinos:Tevatron, LHC



Experimental exclusion (95% CL) as BR to τ 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

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

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

where $\cos^2\theta = M_2 / (M_1 + M_2)$

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

$ee \to Z \to N_1 N_1$
$ee \to Z \to N_1 N_2$
$ee \to Z \to N_2 N_2$

We want to reinterpret the LEP bounds taking these multiple decays into account.

Two Fourth generation Neutrinos: LEP

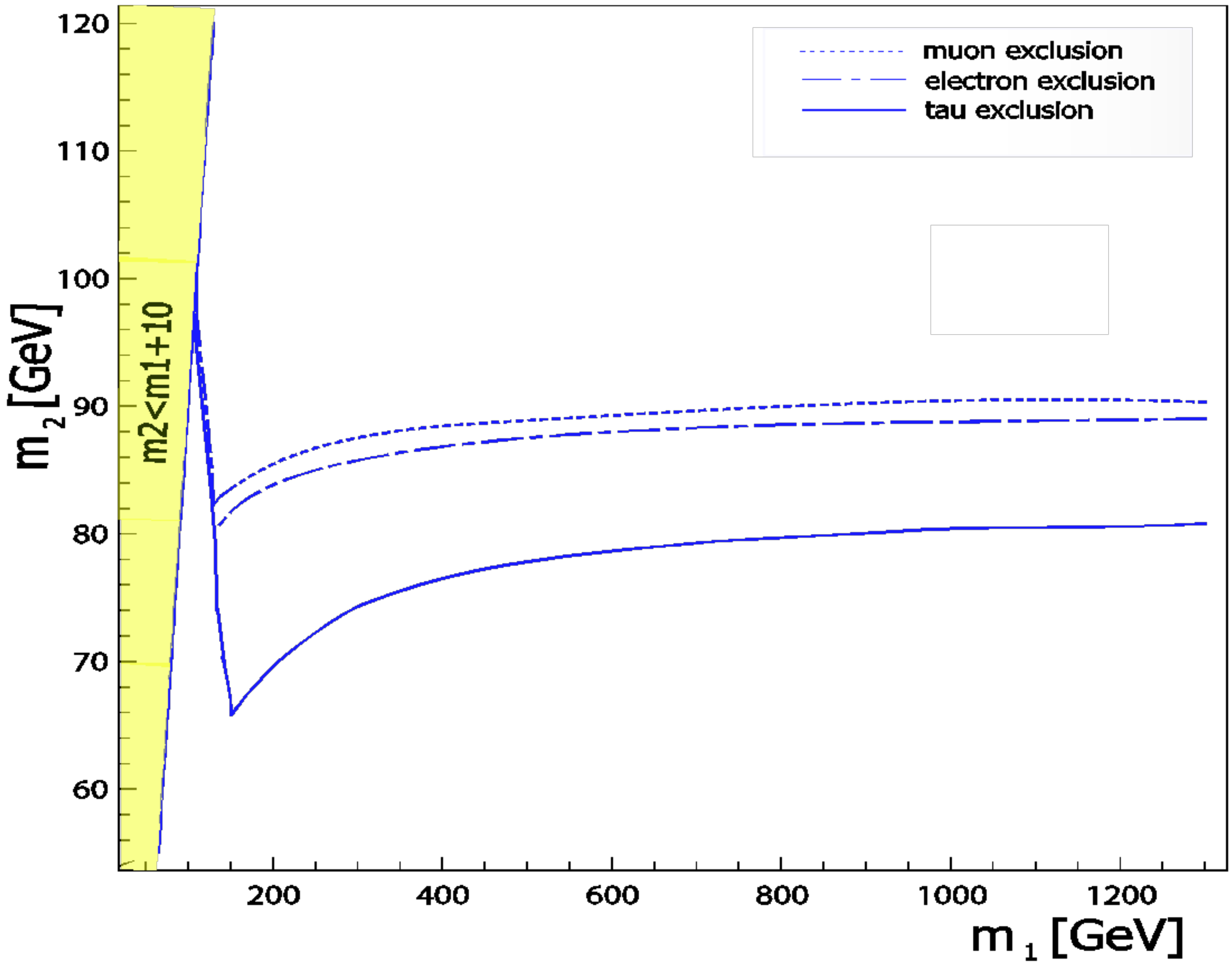
Note that the Z coupling to the lighter neutrino is proportional to $M_2 / (M_1 + M_2)$

As the mass M_2 decreases, the coupling decreases. and goes from 1 to ½. 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



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Two Fourth generation Neutrinos: LEP

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

Table 3: Bounds on N_1 mass in GeV for the various decay channels.

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Two 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

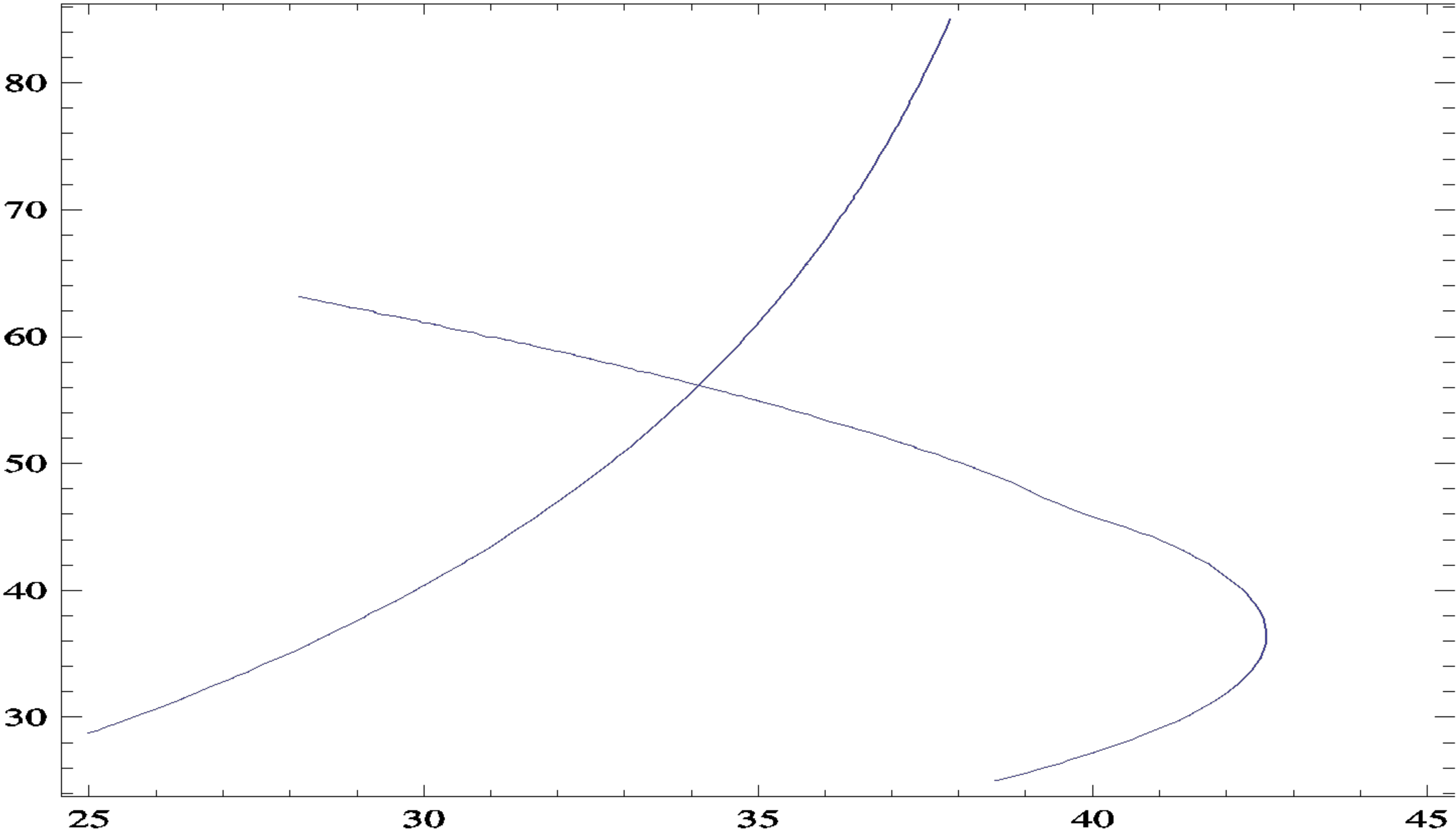
Two Fourth generation Neutrinos: LEP

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 $Z \rightarrow N_1\ N_2$ is allowed, and we run into constraints from the total width.

Two Fourth generation Neutrinos: LEP



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Two 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.

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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 τ 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.

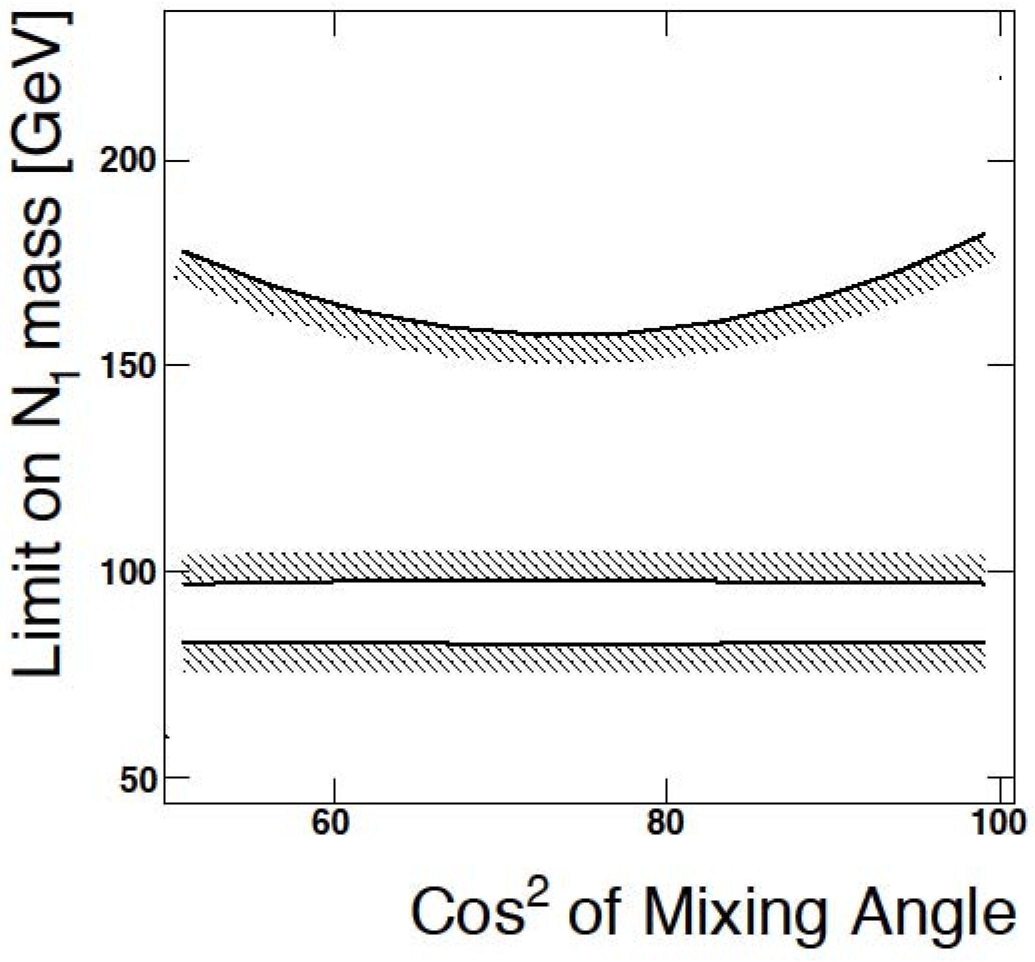
We have $\cos^2\theta = M_2 / (M_1 + M_2)$

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, $100\cos^2\theta$

Two Fourth generation Neutrinos: Tevatron



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Future directions

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

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

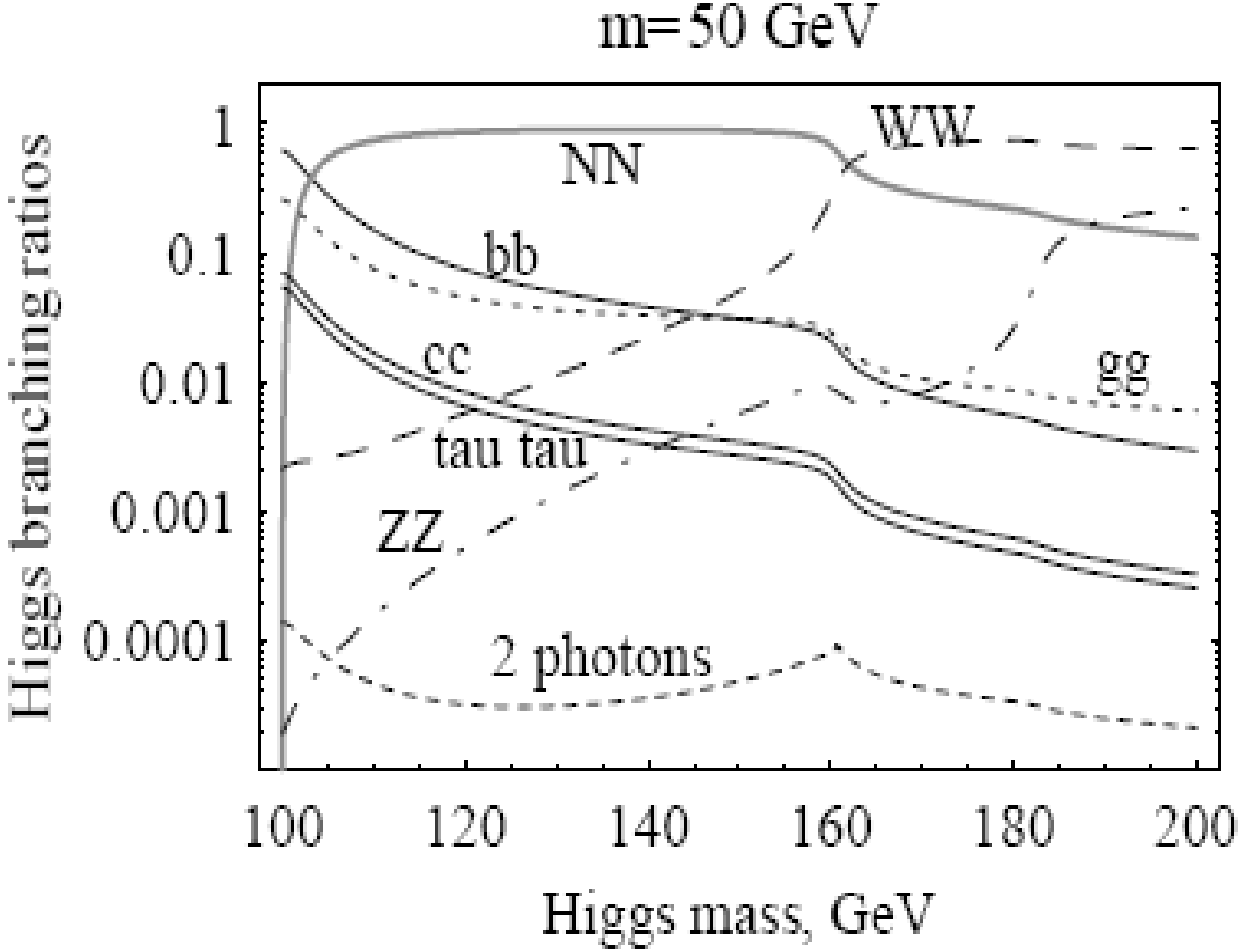
Include charged lepton into analysis. Extra gauge bosons in event. Events can have up to 14 final state particles.

What about tau decays?

Future directions

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



hep-ph 0210153, Belotsky et al.