Searching For Majorana Neutrinos In The Like Sign Muon Final State at $\sqrt{s} = 10$ TeV at the LHC

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Introduction

- We know that neutrinos must be massive particles.
  - $1.9 \times 10{-}3\ eV^2 < \Delta m^2_{atm} < 3.0 \times 10{-}3\ eV^2$
  - $7 \times 10{-}5\ eV^2 < \Delta m^2_{sol} < 9 \times 10{-}5\ eV^2$
- The simplest method of adding a Dirac mass term in the SM requires right handed neutrinos, which haven't been observed.
- With the addition of Majorana mass terms the left handed nature of the 3 known neutrinos can be preserved. They would have a mass scale given so called "seesaw" relationship: $m_M m_\nu \sim m_D^2$ where the Majorana mass and neutrino mass must balance each other and the dirac mass is on the order of a standard quark or lepton mass.
- There would be an addition of new heavy Majorana mass neutrinos with a mass $m_N \sim m_M$
- We are investigating the discovery potential of such a massive neutrino at the LHC.
- There have been two recent papers which discuss the potential of finding a heavy Neutrino between the masses of 100 and 200 GeV at the LHC
  – *The Search for Heavy Majorana Neutrinos*[1]
  – *The Little Review on Leptongenesis*[2]

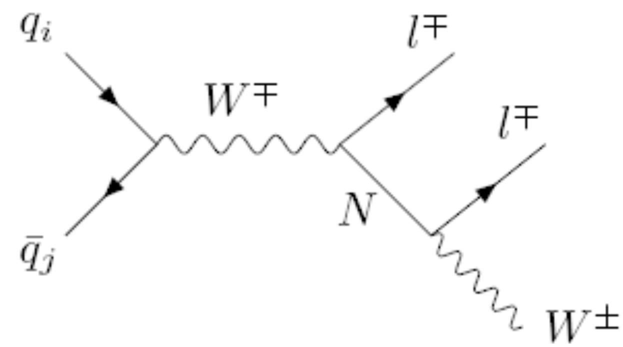
1) A. Atre, T. Han, S. Pascoli, B. Shang, 0901.3589 [hep-ph]
2) A. Pilaftsis, 0904.1182 [hep-ph]

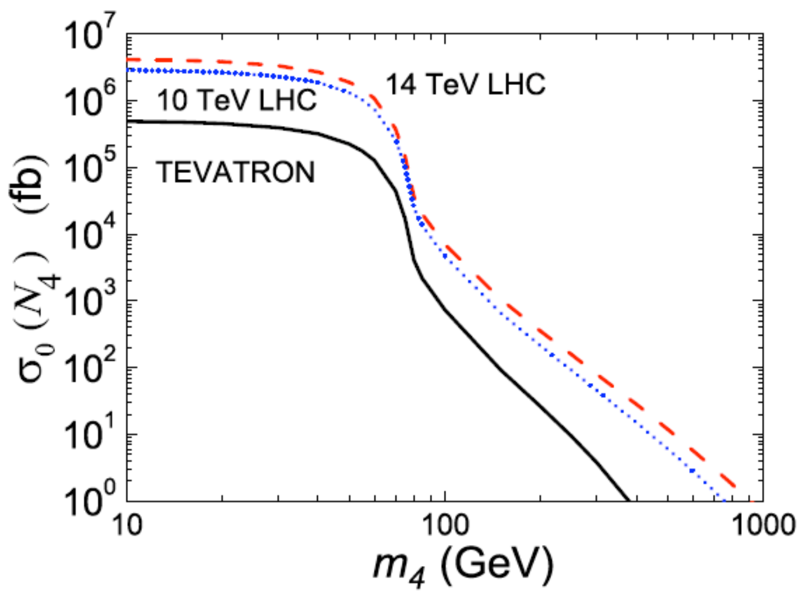
Signature

- The Majorana nature of the heavy neutrino allows for lepton # violating final states.
  - In order to still be within the SM, we only look at decays with SM gauge bosons.
  - Our primary signature is chosen to be two same sign muons with no E_T^{miss} and 2 jets from a W.
- We choose to look for decay into muons as the non-observation of neutrinoless double-β decay puts a very low bound on the Majorana mass and mixing element for electrons:

$$\sum_N \frac{|V_{eN}|^2}{m_N} < 5 \times 10^{-8}\ \mathrm{GeV}^{-1}$$

- Also this takes advantage of the excellent muon detection of CMS.





Signal Generation

- A program based upon matrix element calculation is used to generate weighted Majorana neutrino events with pp collision properties. (T. Han)
- The output from the first step is is in unweighted Les Houches format.
- These events are interfaced with CMSSW 2_1_17 to include parton showering with pythia. Simulation, digitization and reconstruction are performed, also with CMSSW 2_1_17.

M_N (GeV)	# MC Events	Cross-section (pb)	Number Events at 100 pb^{-1}
100	50k	3.17	317
120	5k	1.24	124
140	5k	0.632	63
160	5k	0.363	36
180	5k	0.227	23
200	50k	0.152	15

Backgrounds

- We Consider SM backgrounds that can produce 2 same sign muons
- Our primary backgrounds are therefore
  - pp → $W^{\pm}W^{\pm}$
  - pp → ZZ
  - pp → WZ
  - pp → triple W/Z combinations
  - pp → ttbar
  - pp → $W^{\pm}t$
  - Vqq (V=W/Z q=c/b)
  - Drell Yan (depends on sign misidentification)
- The simulation of sufficient statistics for the study of the QCD background is impractical.
- We instead consider a factorized approach

Background	# MC Events	Cross-section (pb)	Event Rate (100 pb^{-1})
WW	200k	44.8	4480
ZZ	200k	7.1	710
tW	170k	27.3	2730
WZ	250k	20.7	2070
Triple W/Z	200k	0.071	7.1
DY/ Z−>μμ	10k/900k	1.5/657	150/65700
TTbar	2M	317	31700
Vqq (V=W/Z)	1M	289	28900

Event Selection

- Our Majorana Neutrino signature is two same sign isolated muons, 2 jets and no E_T^{miss}.
- We look for global isolated muons with a P_T above 15 GeV
  - We use the track quality cuts suggested by the Muon POG group in CMS-AN2008/098
    1) Nb. of tracker hits > 8 2) Fit Chi^2 / fit NDOF < 10
  - We currently require that the tracker track and global tracks have matching charges.
- We use the suggested isolation cuts from CMS-AN2008/098
  - Sum track P_T within a dR of 0.3 of the muon must be less than 3 GeV
  - Sum Calo E_T within the same dR cone must be less than 5 GeV
- The Majorana mass reconstruction includes 2 jets from the W decay.
  - We select events with at least 2 jets with a corrected P_T above 30 GeV
  - The jets are corrected using the Summer 08 L2L3 jet corrections.
- An b-tag veto is used, only events without any jets tagged as b quarks are kept.
  - We use the track counting high efficiency algorithm and veto on any jet tagged with a value greater than 5

Muon Selection Criteria Efficiencies

DataSet	# Events	2 SS Quality	P_T	Isolation	All Muon
tt	1933780	4.7%	2.5%	1.5%	0.012%
tW	169048	3.1%	2.0%	1.7%	$5.3x10^{-5}$
WW	203591	0.28%	0.74%	0.94%	$4.9x10^{-6}$
ZZ	200564	0.89%	4.0%	4.2%	0.020%
WZ	249100	0.81%	2.0%	2.0%	0.061%
Triple W/Z	190000	2.0%	36%	44%	0.24%
DY/ ZmumuJ	890324	1.8%	0.15%	1.5%	$1.9x10^{-5}$
Vqq	1006772	13.0%	74.5%	80.9%	$2.2x10^{-5}$
100GeV Neutrino	49400	72.7%	38.2%	60.0%	30.0%
200GeV Neutrino	49899	74.2%	70.9%	63.8%	60.9%

Selection Cut Efficiencies

DataSet	# Events	Muon	Jet	b Tag	All Cuts	# Events (100 pb^{-1})
tt	1983780	0.012%	99.1%	25.6%	$3.5x10^{-5}$	1.5
tW	169048	$5.3x10^{-5}$	96.6%	42.1%	$2.4x10^{-5}$	0.076
WW	203591	$4.9x10^{-6}$	78.7%	94.4%	$< 4.9x10^{-6}$	< 0.036
ZZ	200564	0.020%	76.6%	81.2%	$4.0x10^{-5}$	0.042
WZ	249100	0.061%	76.9%	88.1%	$8.0x10^{-5}$	0.26
Triple W/ Z	190000	0.24%	94.2%	80.9%	0.10%	0.011
DY/ ZmumuJ	890324	$1.9x10^{-5}$	22.2%	97.4%	$3.1x10^{-6}$	0.14
Vqq	1006772	$2.2x10^{-5}$	26.0%	91.1%	$9.9x10^{-7}$	0.029
100GeV Neutrino	49400	30.0%	60.0%	96.2%	14.7%	46
200GeV Neutrino	49899	60.9%	78.6%	94.2%	39.2%	6.0

Trigger

- For this analysis we used the HLT DoubleMu3 path which is available in the both of the initial startup trigger tables
- It uses the L1 DoubleMu3 seed
- We have a trigger efficiency of ~89% for those events which pass our selection cuts.
- We are currently unsure why the efficiency is this low, the untriggered events are uniform in muon eta and p_T
- We can increase our trigger efficiency by including the single muon triggers HLT Mu9 and HLT Mu11 which are available in the 1E31 trigger table.
- With the inclusion of these triggers the efficiency increases to ~98%

QCD Background

QCD p_T Bin (GeV)	# MC Events	Cross-section	Event Rate (100 pb^{-1})
15−>30	1.9M	1.35 mb	135000000000
30−>50	2.2M	94.7 μb	9470000000
50−>80	726k	12.2 μb	1220000000
80−>120	49k	1.62 μb	162000000
120−>170	54k	256 nb	25600000
170−>230	49k	48.3 nb	4830000

- We have used two of the Summer08 QCD datasets to attempt to characterize the QCD background
- We used the binned QCD dijet samples for the range above 80 GeV
- We used the larger statistics from the unbinned QCD data sets for the lower range from 15−>50 and imposed our own upper p_T hat cut.
- To maximize statistics we used events from both datasets for the 50−>80 GeV bin

QCD Background Factorization

- Based upon factorized efficiencies we've calculated the expected yield for these datasets, there are 3 factorizations that may be used
  - The efficiencies are calculated with respect to the total number of events

QCD p_T Bin (GeV)	Method 1	Method 2	Method 3
15->30	0.026	0.038	< 0.022
30->50	0.75	0.78	0.73
50->80	2.0	1.8	1.8
80->120	0.19	0.21	0.21
120->170	0.066	0.076	0.063
170->230	0.00045	0.00048	0.00048
Total	3.0	2.9	< 2.8

1. $N_{expected}(1Mu^2 + 2Jets + 0\text{ b jets}) = \sigma \times \mathcal{L} \times \varepsilon_{1Mu}^2 \times \varepsilon_{2Jets} \times \varepsilon_{nob} \times BF_{2ss\mu}$
2. $N_{expected}((1Mu + 1Jets)^2 + 0\text{ b jets}) = \sigma \times \mathcal{L} \times \varepsilon_{1Mu+1Jet}^2 \times \varepsilon_{nob} \times BF_{2ss\mu}$
3. $N_{expected}(1Mu + (1Mu+1Jets) + 0\text{ b jets}) = \sigma \times \mathcal{L} \times \varepsilon_{1Mu} \times \varepsilon_{1Mu+1Jets} \times \varepsilon_{nob} \times BF_{2ss\mu}$

QCD Factorization Check

- We checked for any correlation between the efficiencies used in the factorization calculations
- Four potential correlations
  1) Between muon and jet selection
  2) Between efficiency of one muon and two muons
  3) Between efficiency of two muons and two like sign muons
  4) Between muon efficiency and b-tag efficiency
- Only saw correlation in the fourth case, as the b-tag veto has an efficiency over 90% for the low p_T hat region this is a small affect.

Efficiencies compared	**Average across the QCD range**
Eff. 1μ + 2jets to Eff. 1μ × Eff. 2jets	0.98
Eff. $1\mu^2$ to Eff. 2μ (Global μ)	0.87
Frac. 2μ are SS to Number SS ÷ $1\mu^2$ (Standalone μ)	1.0
Eff. 1μ+nob to Eff. 1μ × Eff nob	0.59

Control Sample

Data Set	Number Observed eμ Events (100 pb^{-1})	Number Expected μμ Events (100 pb^{-1}) (A)	Number Observed μμ Events (100 pb^{-1})
T Tbar	2.89	1.71 (1.18)	1.50
tW	0.23	0.086 (0.76)	0.076
WZ (no Jet Cuts)	1.23	1.65 (2.69)	1.66
WZ (w/ Jet Cuts)	0.95	1.28 (2.69)	0.23

- We would like to introduce a control region for use in a data driven method for background estimation.
- Outside of the QCD background our largest Standard Model background is ttbar.
  - We can estimate the number of like-sign same lepton flavor events from the number of like-sign different flavor lepton events.
  - $N(exp)_{\mu\mu} = A/2 * N(obs)_{e\mu}$
  - A is the ratio of the acceptance times efficiencies for 2 SS isolated muons to 2 SS isolated different flavor leptons (found from 1 half of MC)
- All the selection criteria have remained the same in the ttbar and tW data sets
- We use electron selection cuts developed for by the electroweak groups WW analysis.
- This works well for the top quark data sets. Using 2nd half of MC as "data."
- It doesn't work as well for the WZ dataset. To obtain two lepton flavors both boson's must decay leptonically however the dominant production of 2μ+2jets is from only the Z decaying leptonically
  - We expect the method to improve with the relaxation of the jet cuts, and it does
  - The value for A is from a low efficiency on the lepton isolation requirement.

Error

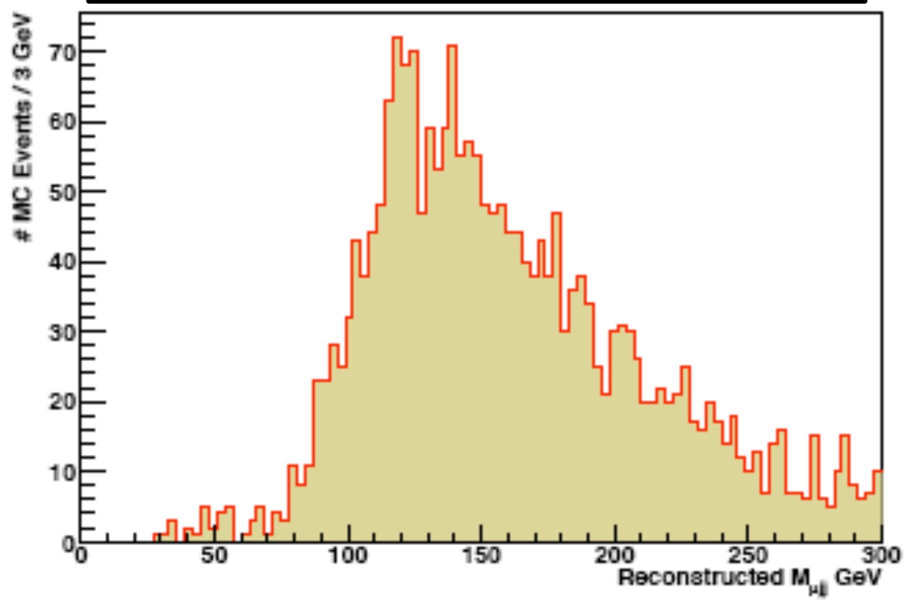
Error	ttbar	WZ, ZZ	tW	DY	VQQ	QCD	JES	B tagging	Stat	Totals
Input	50%	20%	20%	20%	20%	100 %	10% per jet	8.5%	20%	
N_B (100 pb^{-1})	1.5	0.34	0.076	0.14	0.03	2.9	-	-	-	5.01
$\pm N_B$ (100 pb^{-1})	0.75	0.068	0.015	0.028	0.006	2.9	0.24	0.23	0.66	3.1

- Cross-section
  - We Use 20% error on the Standard Model backgrounds except for the QCD where we use 100% and the ttbar where we used 50% based upon the e-mu control sample results
- b-tagging
  - 8.5 % uncertainty on tagging efficiencies.
- Muon Reconstruction
  - No significant contribution for muons in the P_T range of interest
- Jet energy scale (JES)
  - Detailed description of Jet Corrections in CMS AN-2007/055
  - The initial JES is expected to have an uncertainty of +/- 10%
  - We have run our analysis while smearing the jet momentum by 10%.

Discovery or Exclusion

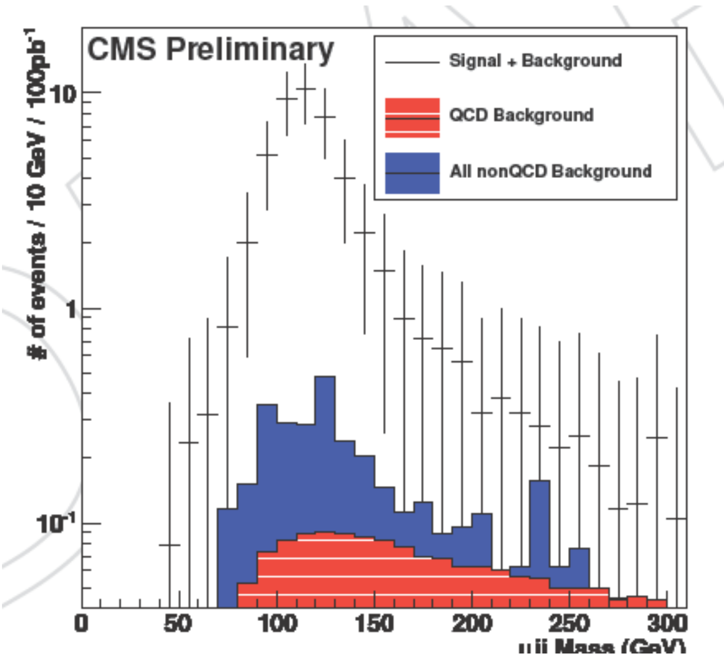
- We have looked at the possibility of discovery through excess events or baring discovery setting a lower limit.
- The expected number of Standard Model events is near to the number of signal events in the upper mass range.
- The events are not uniformly distributed across the mass range.
- We can look for excess events within mass bins

The reconstructed mass for the QCD 30-80 bins shown for a range of 0-300 GeV. The peak is at 120 GeV.



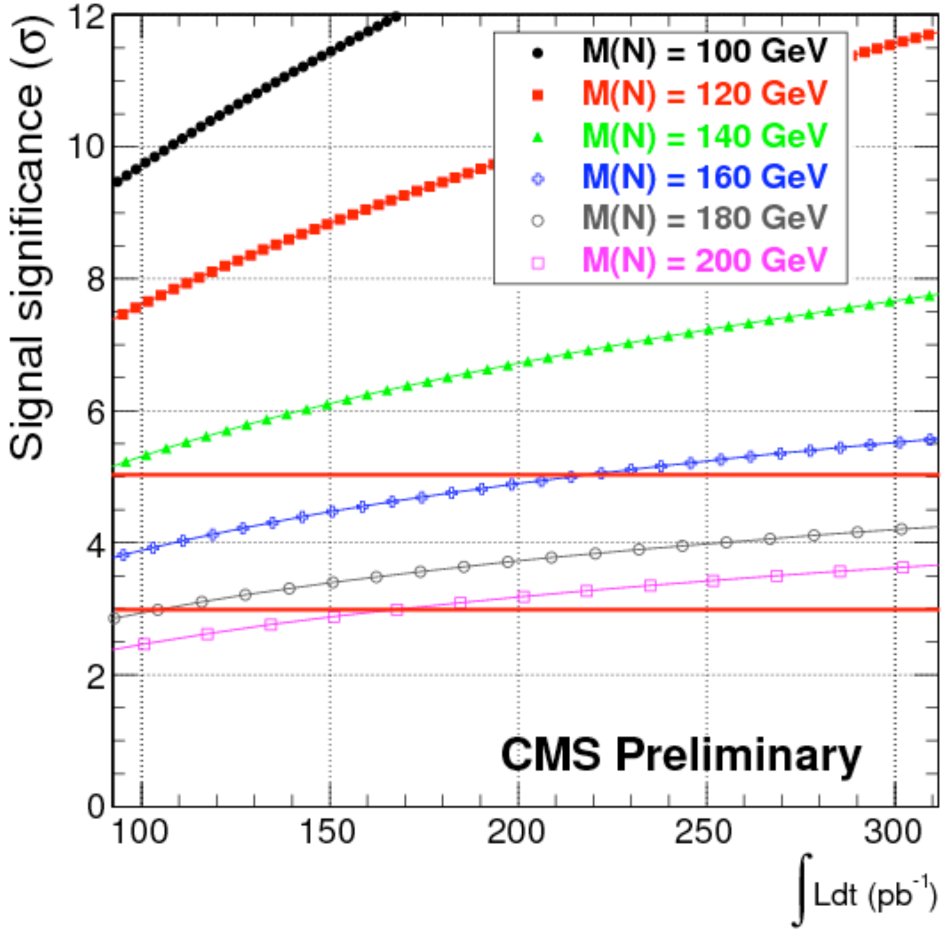
Number of Events in Mass Bins

- We chose the bin limits based upon the mass reconstruction results
- In the lower mass range we use $\pm 1.5\sigma$
- As the mass increases we allow the lower bin edge to widen to allow for masses reconstructed from the choice of the wrong muon.



M_N (GeV)	Lower Bin	Upper Bin	QCD BG	Total BG	Signal
100	90	130	1.03	1.88	38.3
120	100	150	1.09	1.93	27.3
140	110	170	1.11	1.93	16.8
160	120	190	1.06	1.83	10.8
180	130	210	0.828	1.59	7.03
200	140	230	0.676	1.16	4.79

Discovery & Exclusion Results



- The discovery plot is found by calculating the probability of the background to fluctuate up to the expected number of S+B events.
- We also calculated that we can exclude the entire mass range at 95% confidence level across the entire mass range.
  - Exclusion was calculated through the use of Bayesian confidence limits with a flat prior.
- Both methods take into account the systematic and statistical uncertainties.

Conclusions

- We have presented the possibility for the CMS detector to discover a Majorana mass neutrino.
- Discovery of a M_N less than ~150 GeV in the first year of running should be possible.
  – Exclusion is possible across the entire mass range studied with 100 pb^{-1}
- A method for controlling the largest background of ttbar has been outlined
- An estimation of the QCD background has been discussed.

Thanks

- Any Questions?

Backup Slides

Kinematic Figures