Latest Results on Heavy Neutrino Searches with CMS

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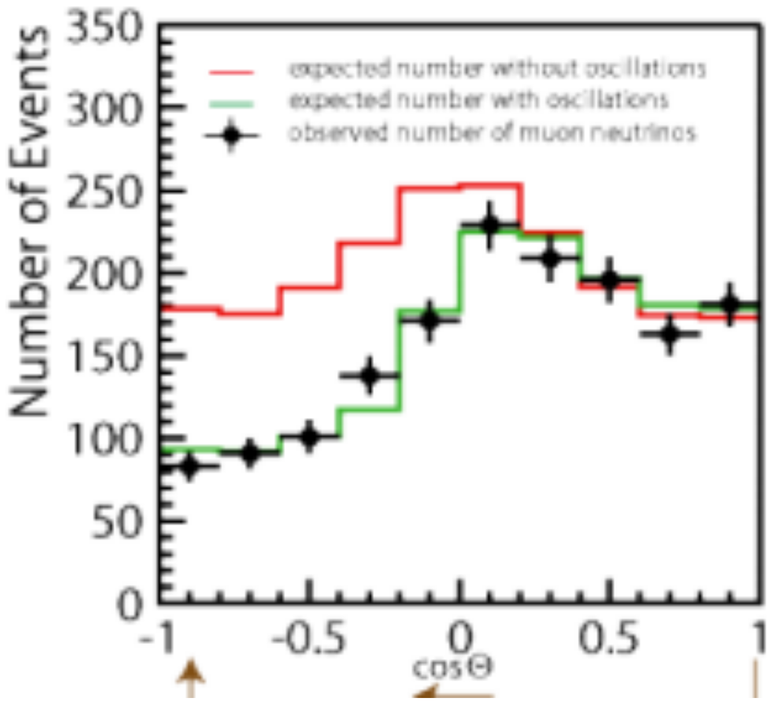
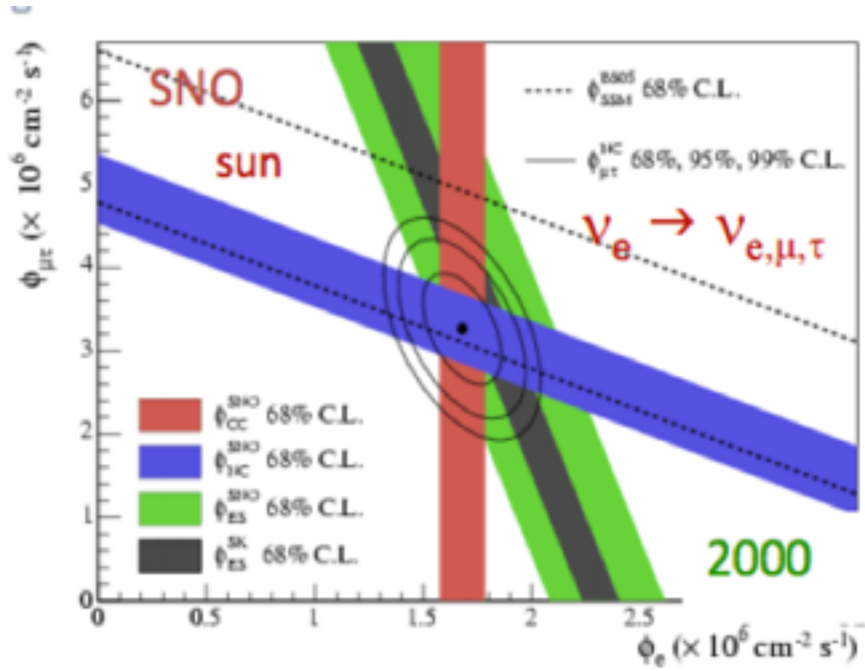
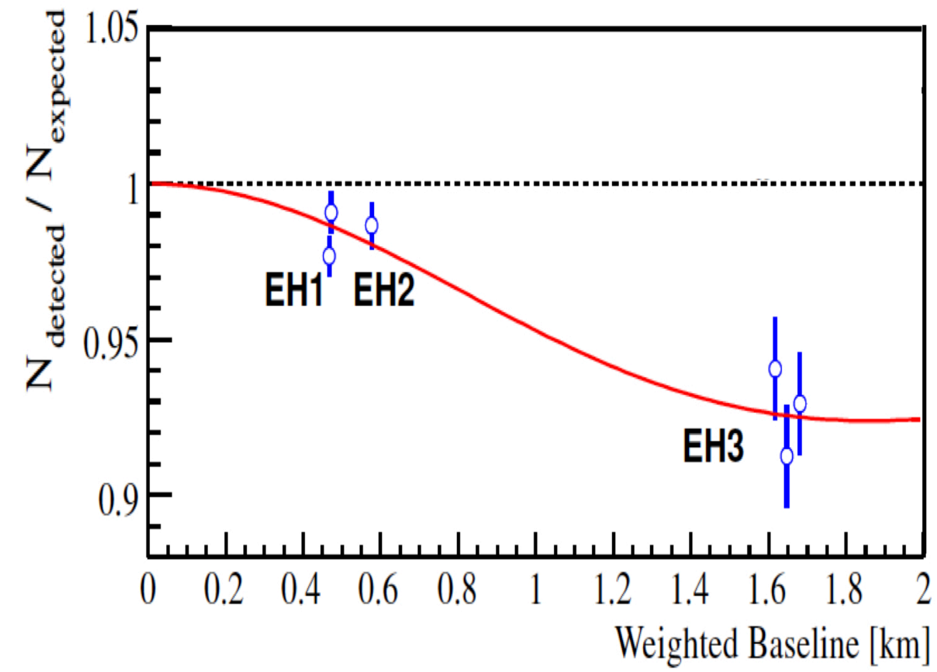
On behalf of the CMS collaboration

SUSY15 @ Lake Tahoe , August 23-29, 2015

Why Look For Heavy Neutrinos?







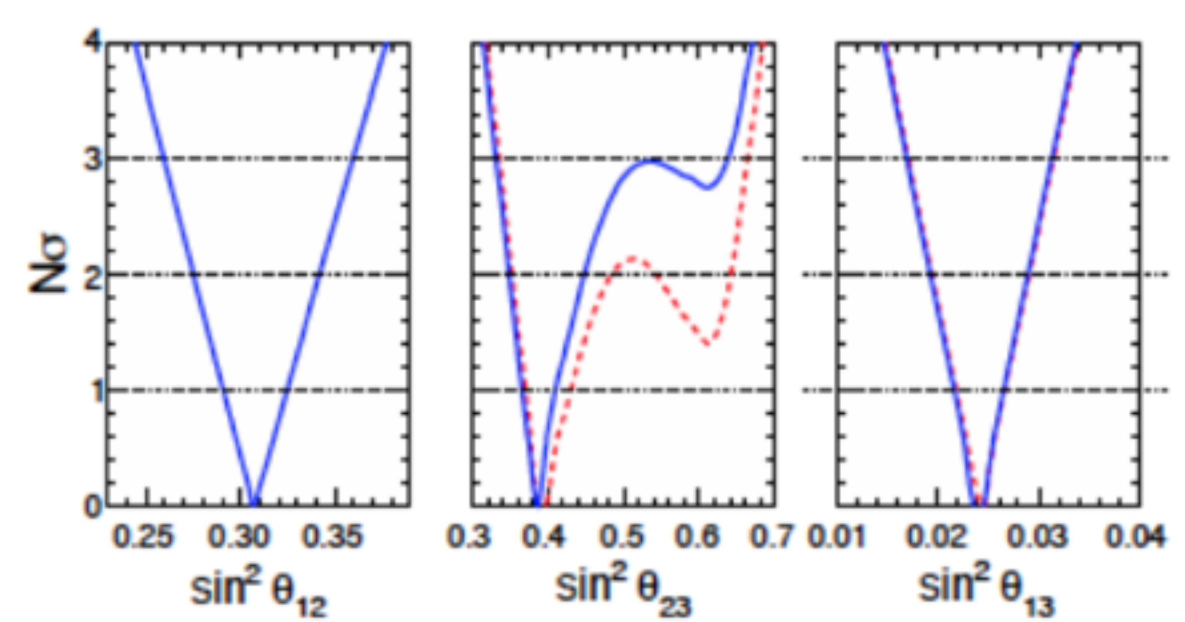
- Neutrinos oscillate between all three flavours.
  - At least two massive neutrinos

- First conclusive experimental evidence for BSM physics.

- Sum of light neutrino masses < 0.23 eV from cosmology.

- Small neutrino mass can be naturally explained by the SeeSaw mechanism with heavy Majorana neutrinos.

- Some theories with heavy neutrinos can also provide a Dark Matter candidate.



Searches For Heavy Neutrinos at CMS

- Small neutrino mass -> heavy neutrino (N_R) by "SeeSaw"
- Several models predict TeV scale heavy neutrinos.

- If heavy neutrinos exist at TeV scale we should be able to see them at the LHC.
- CMS and ATLAS have performed searches for heavy neutrinos in a number of models.

- Type 1: weak-singlet fermion (N)
  EXO-12-057 EXO-14-014
- Left-Right Symmetric Model (LRSM): $SU(2)_R$ symmetry to the SM: N, W_R, Z'
  EXO-13-008
- Type 3 : weak-triplet fermion ($\Sigma^0\Sigma^{+/-}$)
  EXO-14-001

Type 3 In Back Up slides

Heavy Neutrino production at the LHC
Type-1 Seesaw

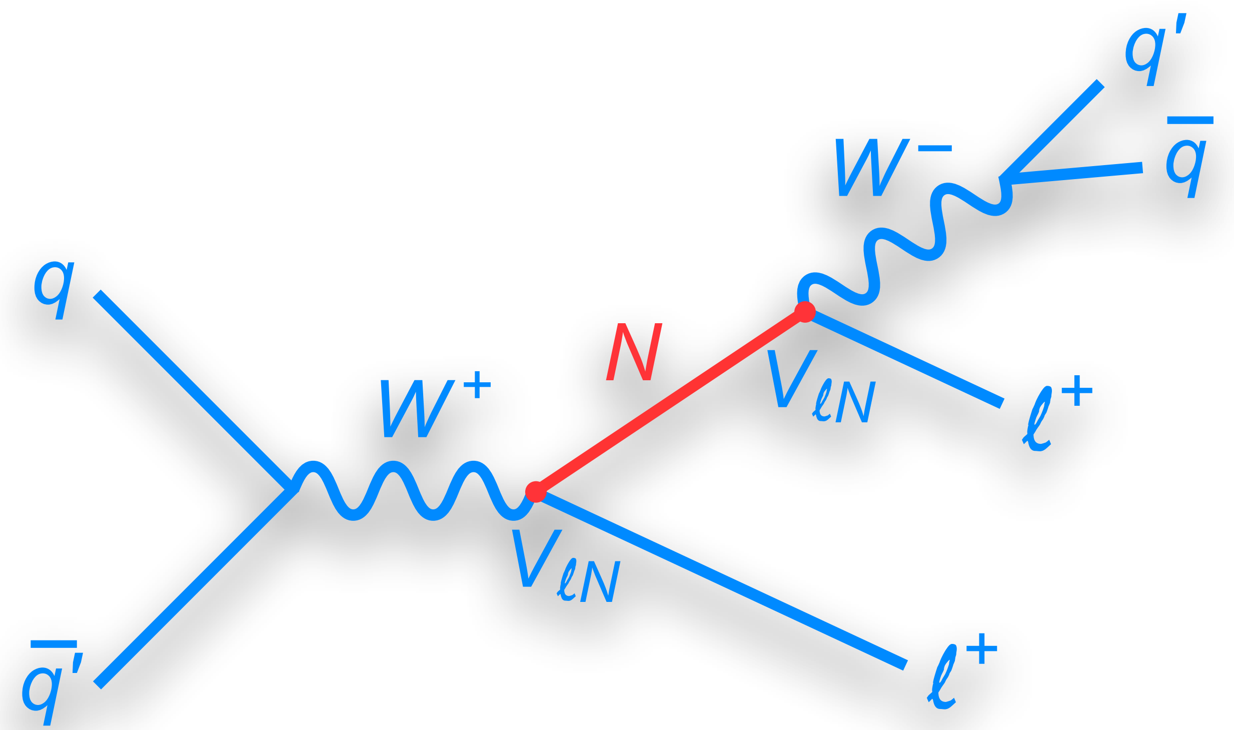
EXO-12-057 EXO-14-014

- This is the simplest model that allows for heavy neutrinos **N**.

- Assume N has no new interactions.

- **N** mixes with SM leptons via mixing angle V_{lN}.

- Best channel to search for this is s-channel using di-lepton final state:
    - Majorana neutrino can decay into positive or negative lepton.
    - cross section depends on $|V_{lN}|^2$

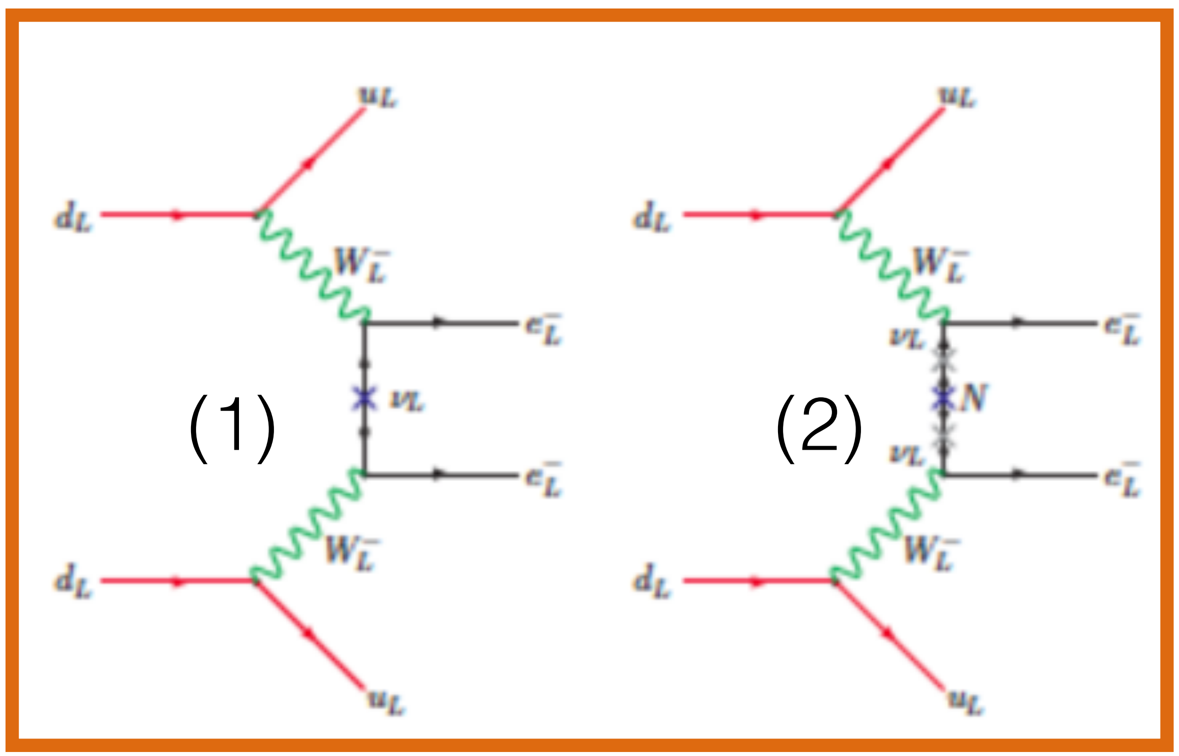


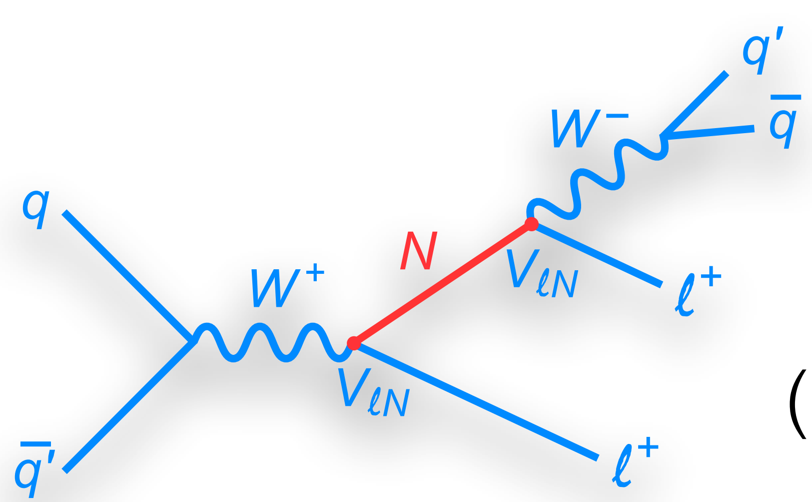
Analysis sets limit on cross section and mixing angles $|V_{lN}|^2$

Previous Constraints on Mixing

- Strong limits on $|V_{eN}|^2$ from neutrino-less double beta decay experiments (arXiv:hep-ph/0412300):

$$\left| \sum_{j=1}^{n} V_{eN_j}^2 \frac{1}{m_{N_j}} \right| < 5 \times 10^{-8}\ \mathrm{GeV}^{-1},$$





(3)

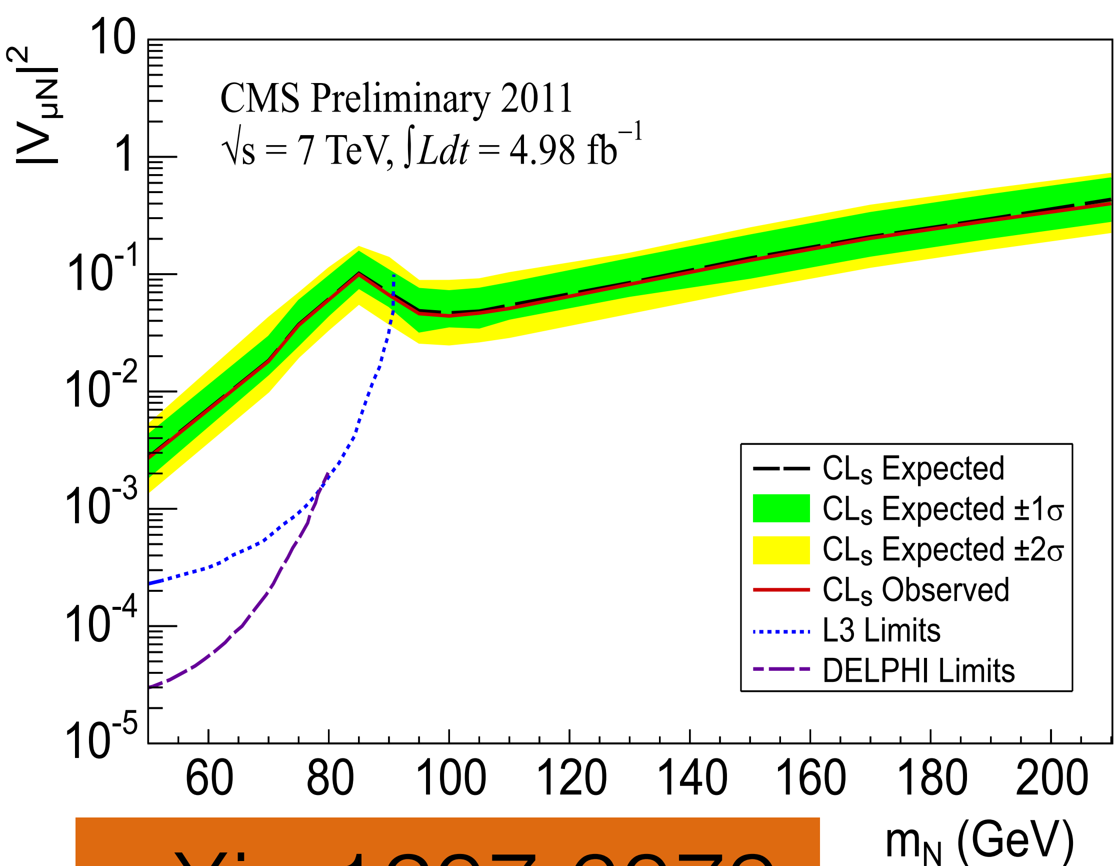
- The neutrino-less double beta decay:
  - (1) a long-range interaction
  - (2) a short-range interaction
- But the limits were extracted assuming (2) is dominant.

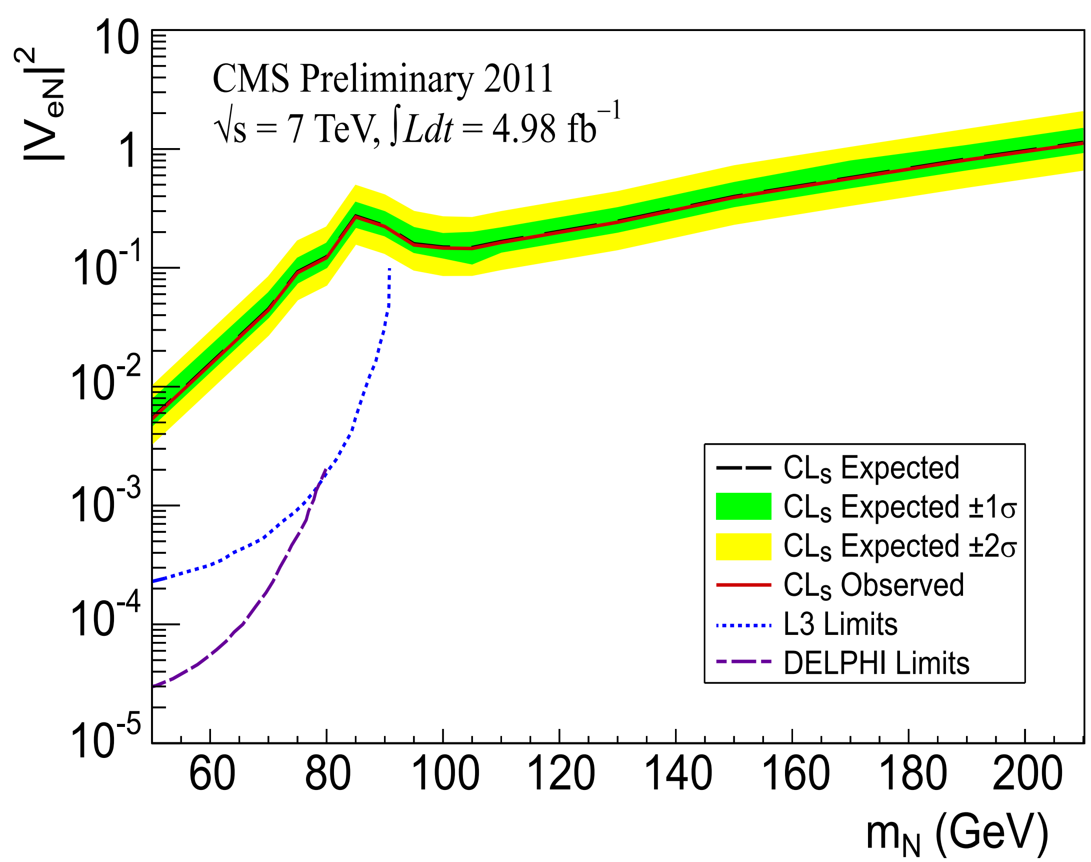
- At LHC, heavy N production (3) is short-range only.

Previous Constraints on Mixing

- Strong limits on $|V_{eN}|^2$ from neutrino-less double beta decay experiments (arXiv:hep-ph/0412300):
- Strong limits for ee (and μμ) for $M_N < 90$ GeV by LEP
- CMS and ATLAS set limits with 7 TeV:

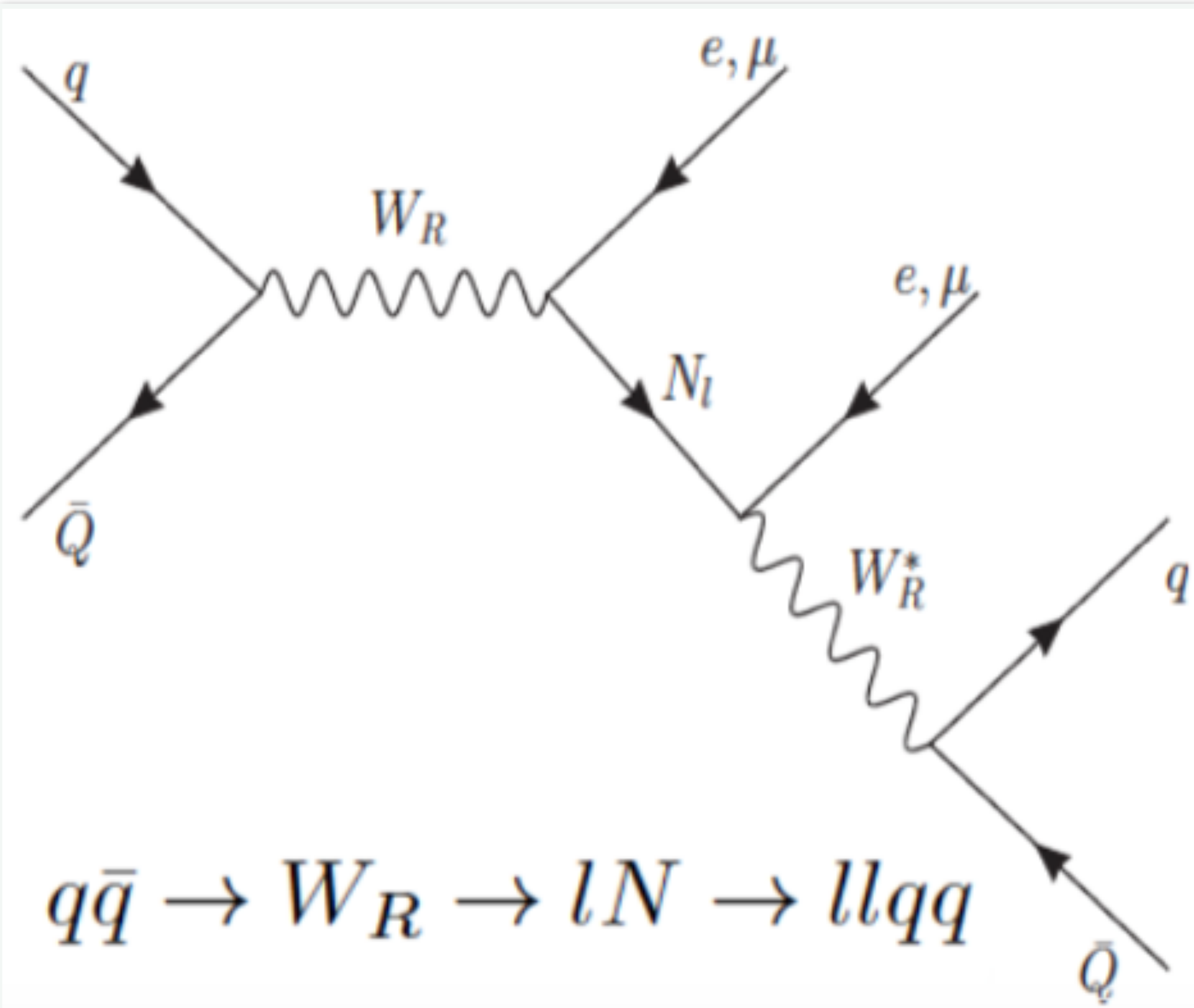
$$\left|\sum_{j=1}^{n} V_{eN_j}^2 \frac{1}{m_{N_j}}\right| < 5 \times 10^{-8}\ \mathrm{GeV}^{-1},$$





arXiv:1207.6079

Heavy Neutrinos in the Left-Right Symmetric Model at LHC EXO-13-008



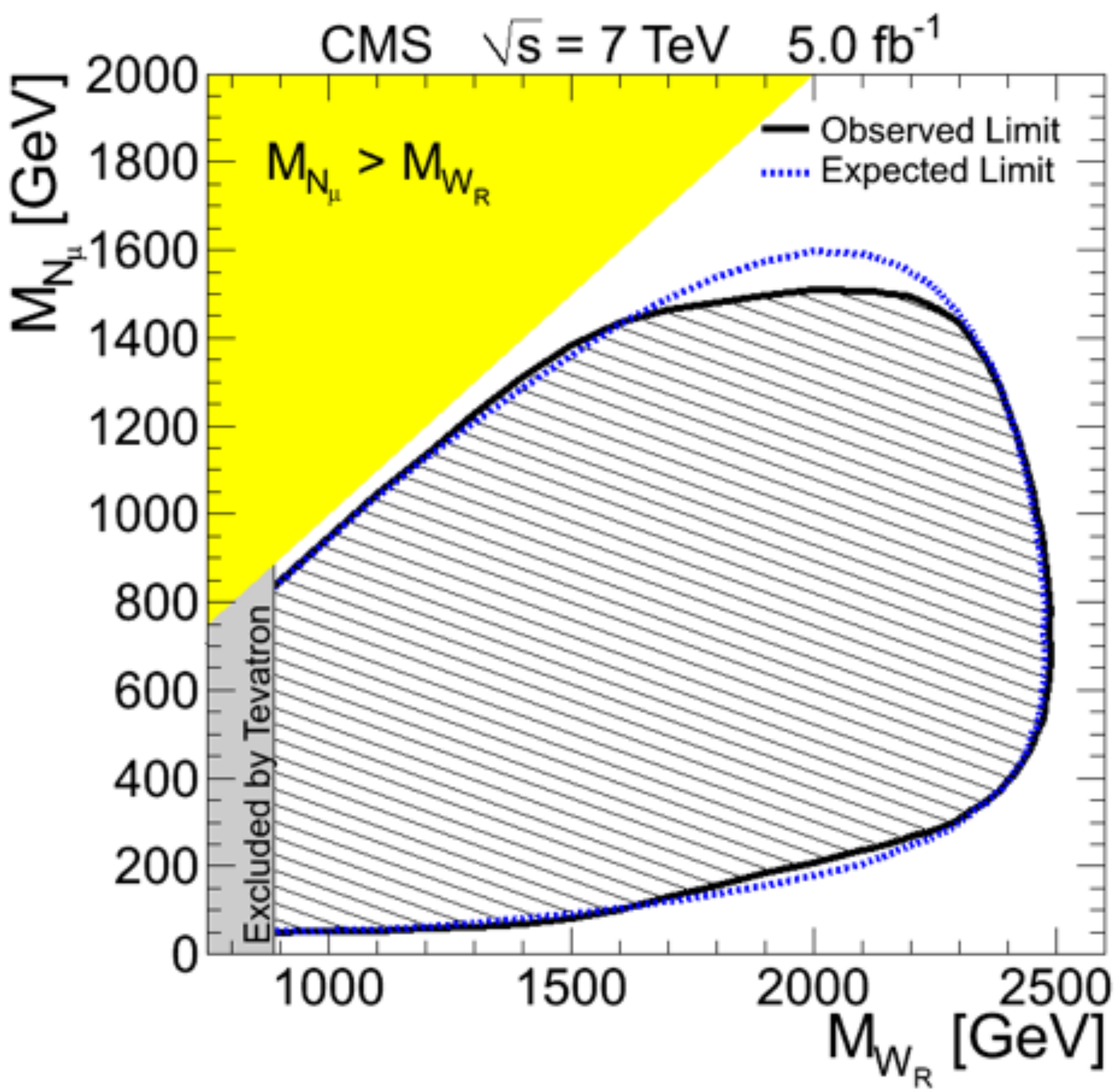
$$q\bar{q} \rightarrow W_R \rightarrow lN \rightarrow llqq$$

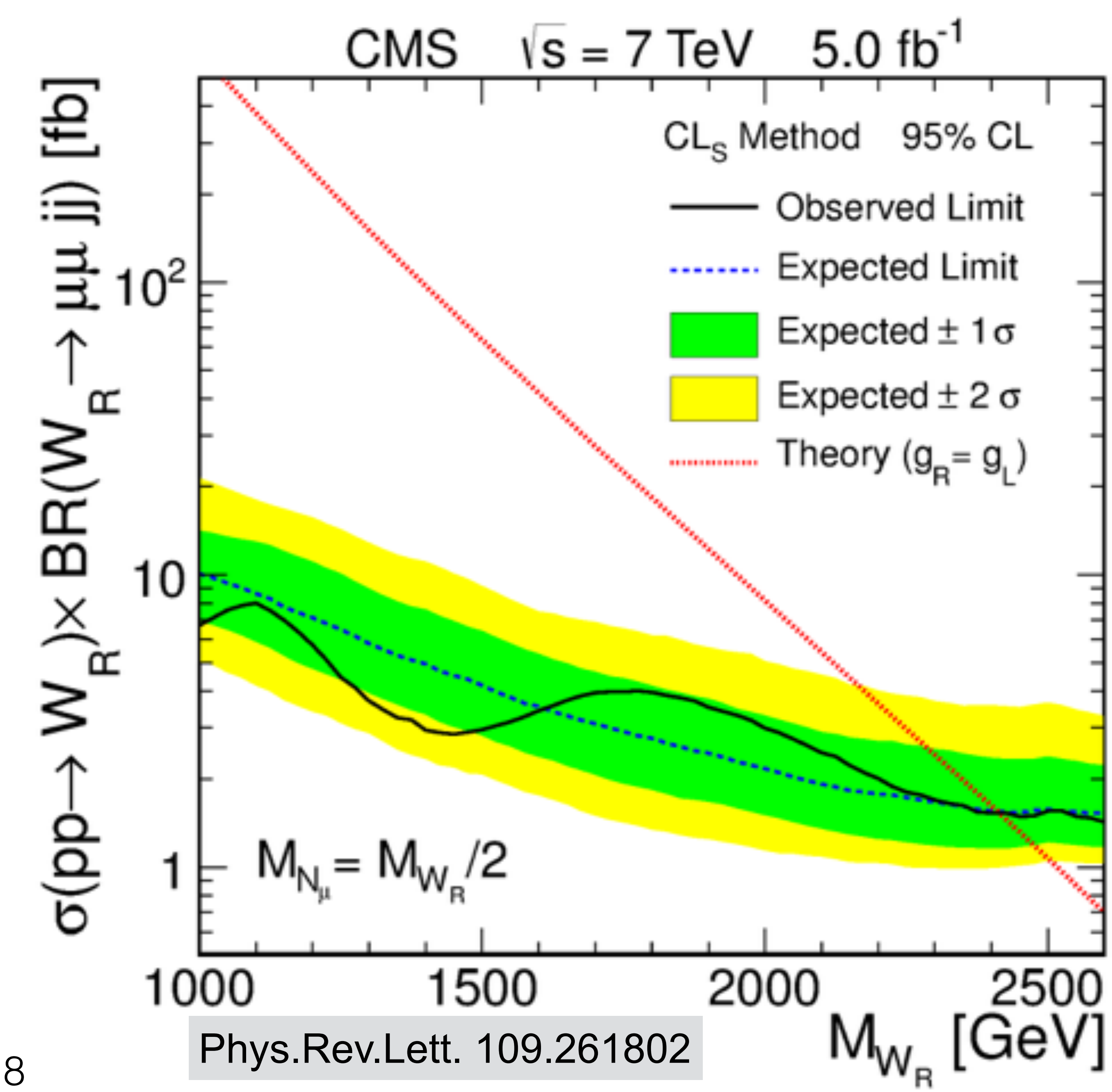
- A high energy gauge theory that can explain parity violation in the weak sector.
- Included 3 TeV scale gauge bosons (2W_R and Z')
- Naturally introduces right-handed heavy neutrinos N.
- Promising signal at the LHC.

Analysis sets limit on Mass of W_R and N.

Previous Constraints on M_N and M_{WR}

- ATLAS and CMS set limits with 7 TeV.
- CMS excluded masses up to 2.5 TeV for M_{WR}
- and 1.4 TeV for M_N for certain values of M_{WR}



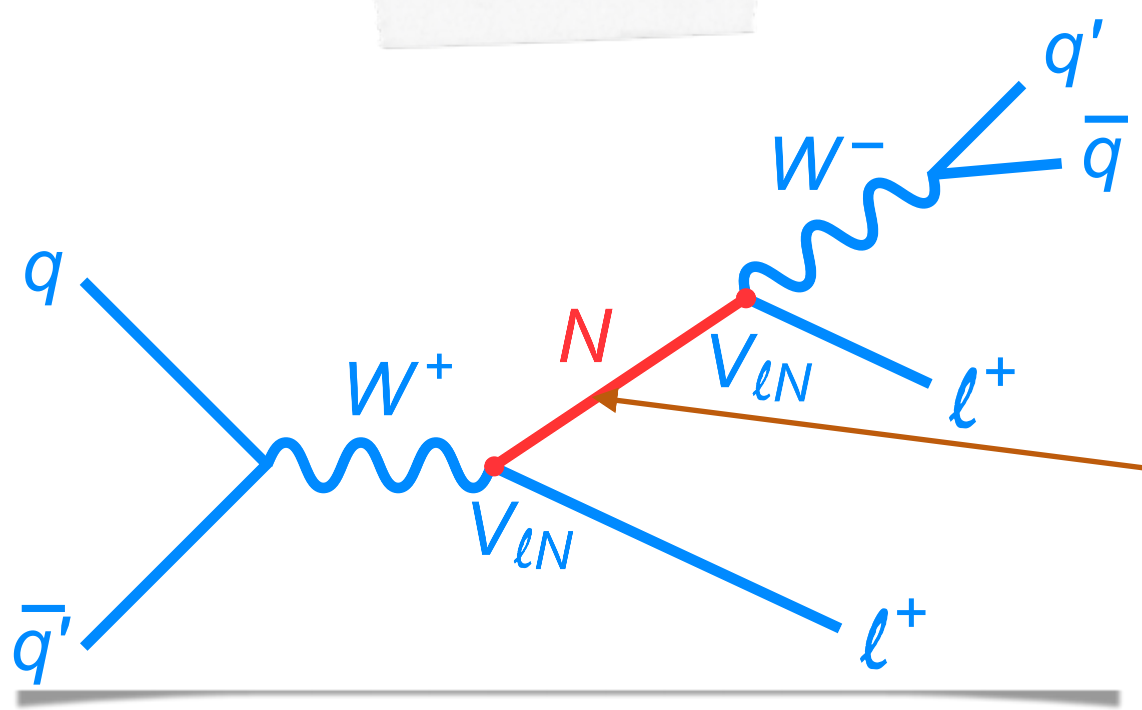


Phys.Rev.Lett. 109.261802

8 TeV Analyses
At
CMS

Searches in Minimal Type-1 Seesaw at 8 TeV

- Search for resonant s-channel production of a heavy Majorana neutrino.



Rare signature characterised by:
- two same-sign isolated leptons,
- two jets,
- no significant missing energy.

Majorana Neutrino
Same-sign in 50% of events

Remarks:
- Use same-sign events due to Z+jet background.

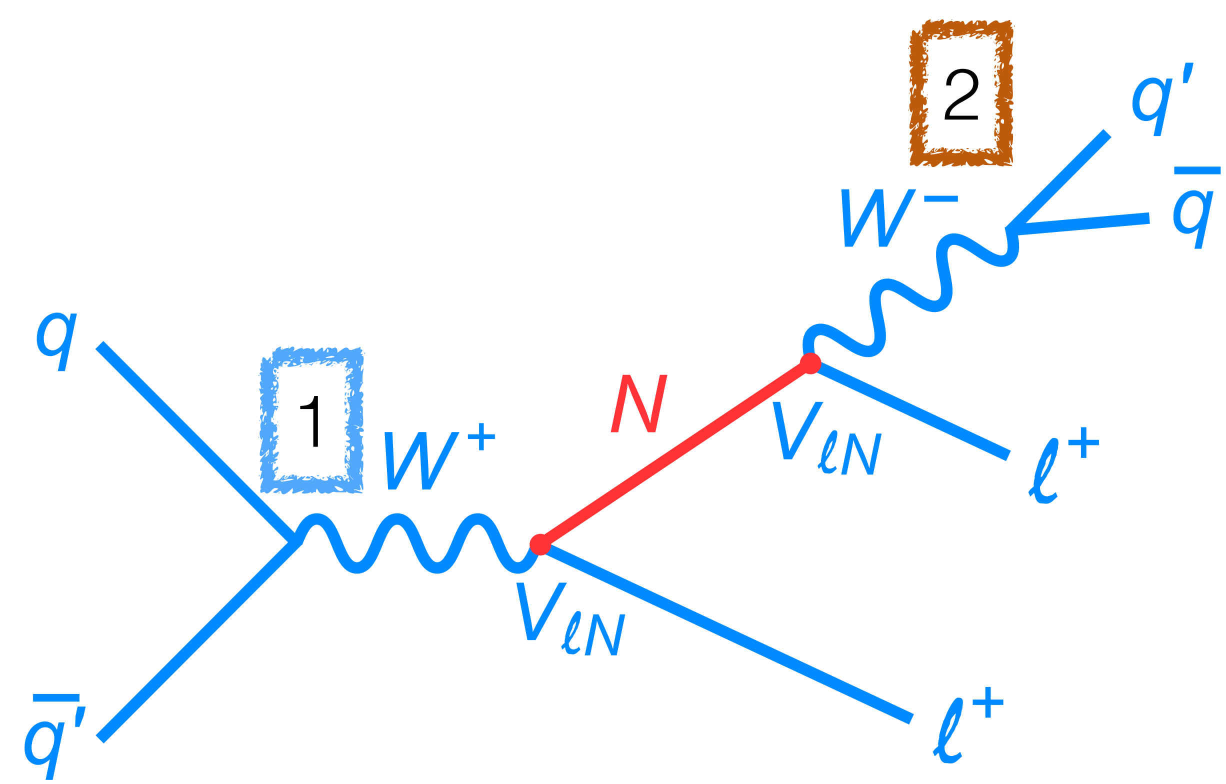
Challenges:
- Daughter particles can be very soft: Main issue is understanding background from misidentified leptons from multi-jet QCD events.
- Understand charge mis-measurement rate for electron: Z+jet bkgd

Analysis Strategy for 8 TeV

Two main regions can be distinguished across the neutrino mass scan for all three channels:

1) $M_N < M_W$ GeV. Low-Mass Signal Region
2) $M_N > M_W$ GeV. High-Mass Signal Region

- In case 1 the first W [1] is real and the second W [2] is virtual.
  - $M(lljj) = M_W$
- In case 2 the first W [1] is virtual and the second W [2] is real.
  - $M(jj) = M_W$



Event Selection

Preselection

- Dilepton trigger (17/8 GeV)
- 2 same-sign leptons**
- njet >= 2
- veto third looser lepton

**Very Tight cuts on lepton:
Isolation
Impact parameter

Low-Mass and High-Mass selection (on top of preselection) :

Region	$\not\!\!E_T$ (GeV)	$m(\ell^\pm\ell^\pm jj)$ (GeV/c^2)	$m(\ell^\pm\ell^\pm)$ (GeV/c^2)	$m(jj)$ (GeV/c^2)	$p_T^{j_1}$ (GeV/c)
Low-Mass	< 30	< 200	> 10	< 120	> 20
High-Mass	< 35	> 80	> 15	$50 - 110$	> 30

+ bjet veto

- Low-mass has soft final state particles.
- Two jets chosen such that:
    - Low-Mass : M(lljj) closest to M_W
    - High-Mass : M(jj) closest to M_W

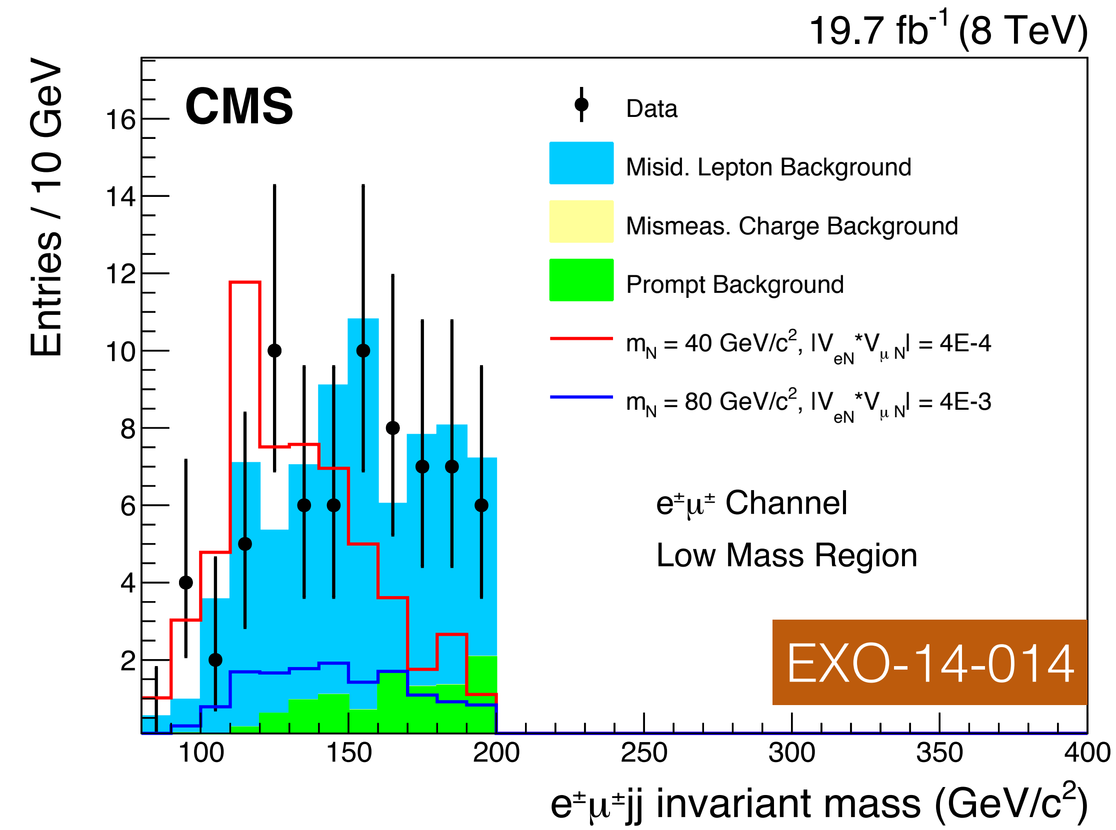
control regions

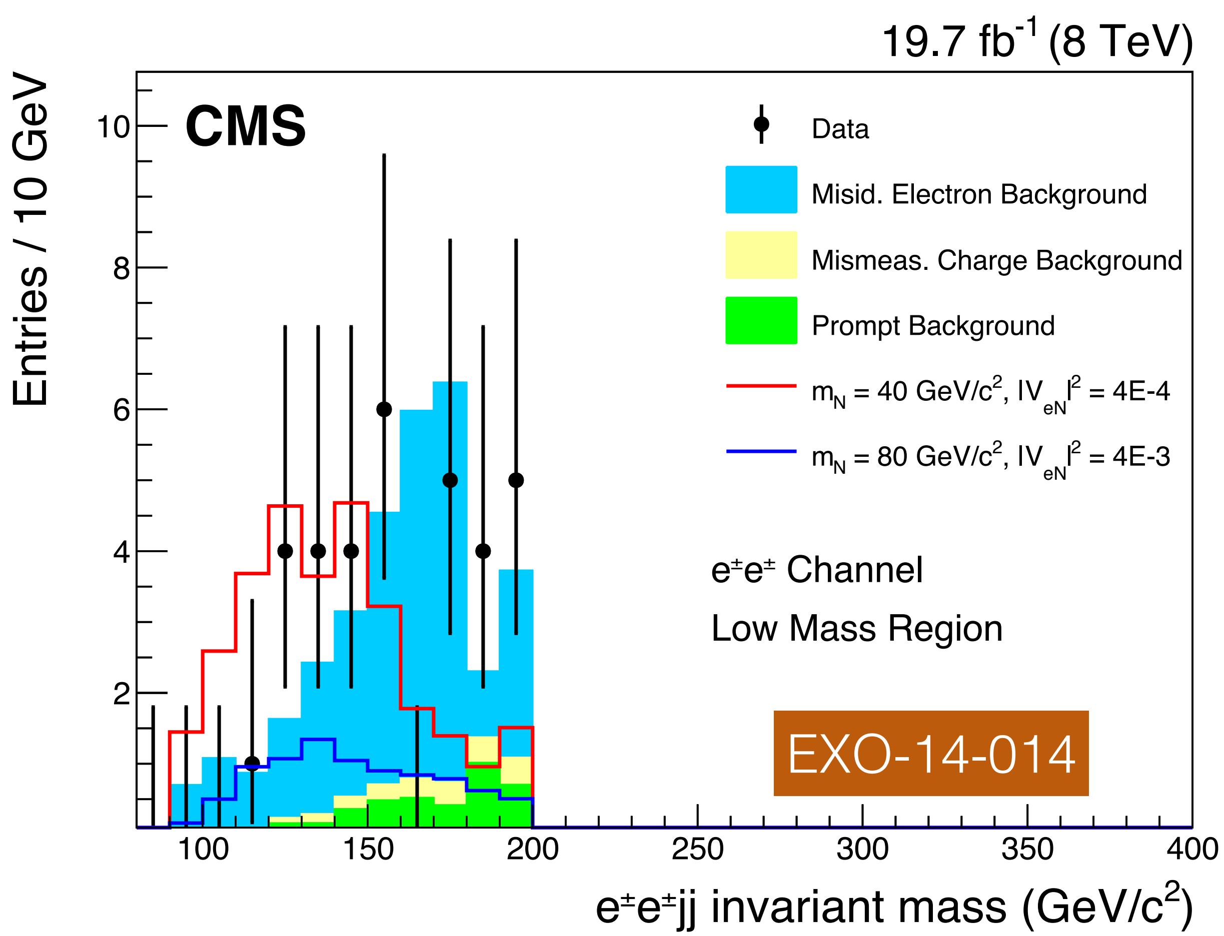
- reverse the b-jet veto
- place a MET > 50 GeV.
- Events with 1 jet (m(ll) > 100 GeV)

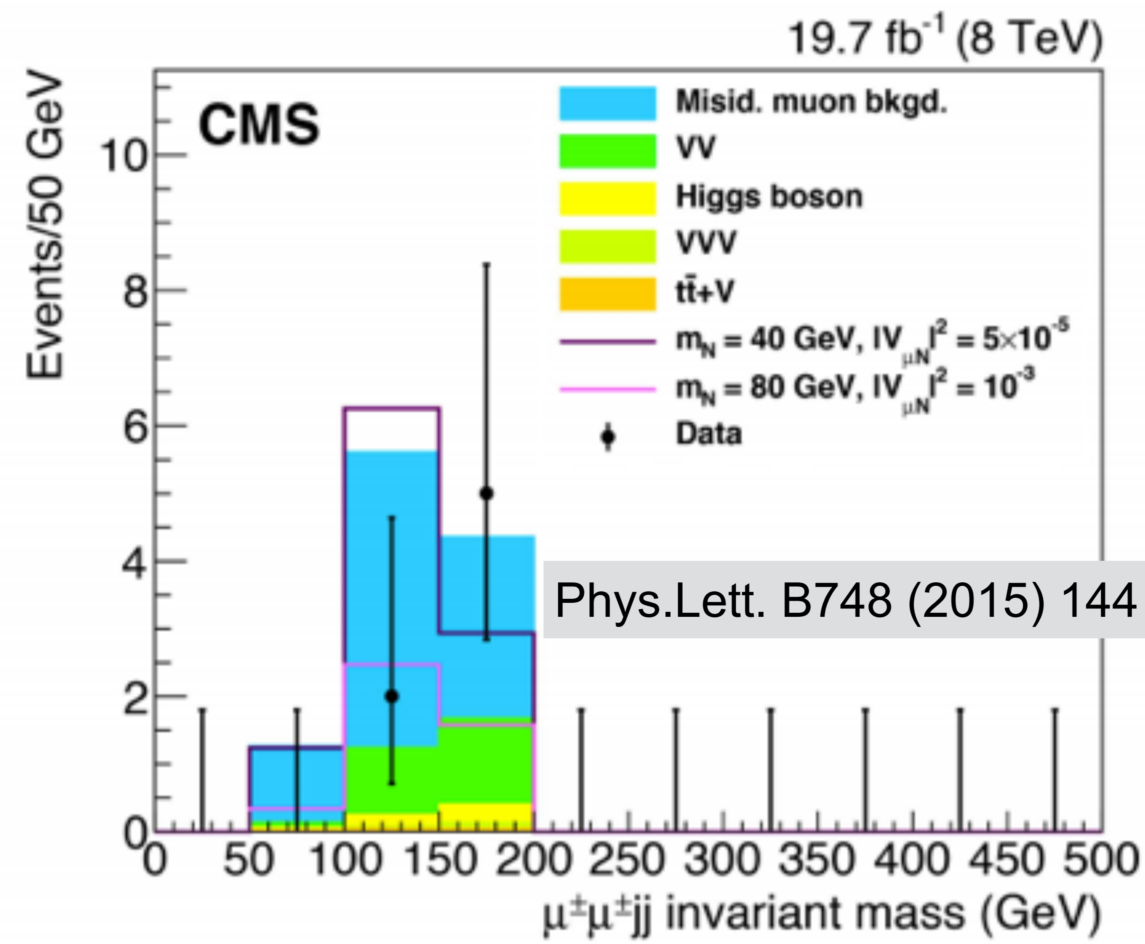
Backgrounds

Background	Estimation Method
Charge-flip	Data + MC
SM irreducible	MC
Misidentified leptons	Data

- Muon charge-flip bkg. is considered negligible
- Misidentified lepton background the largest







Systematics

Main systematic is from misidentified leptons bkd.

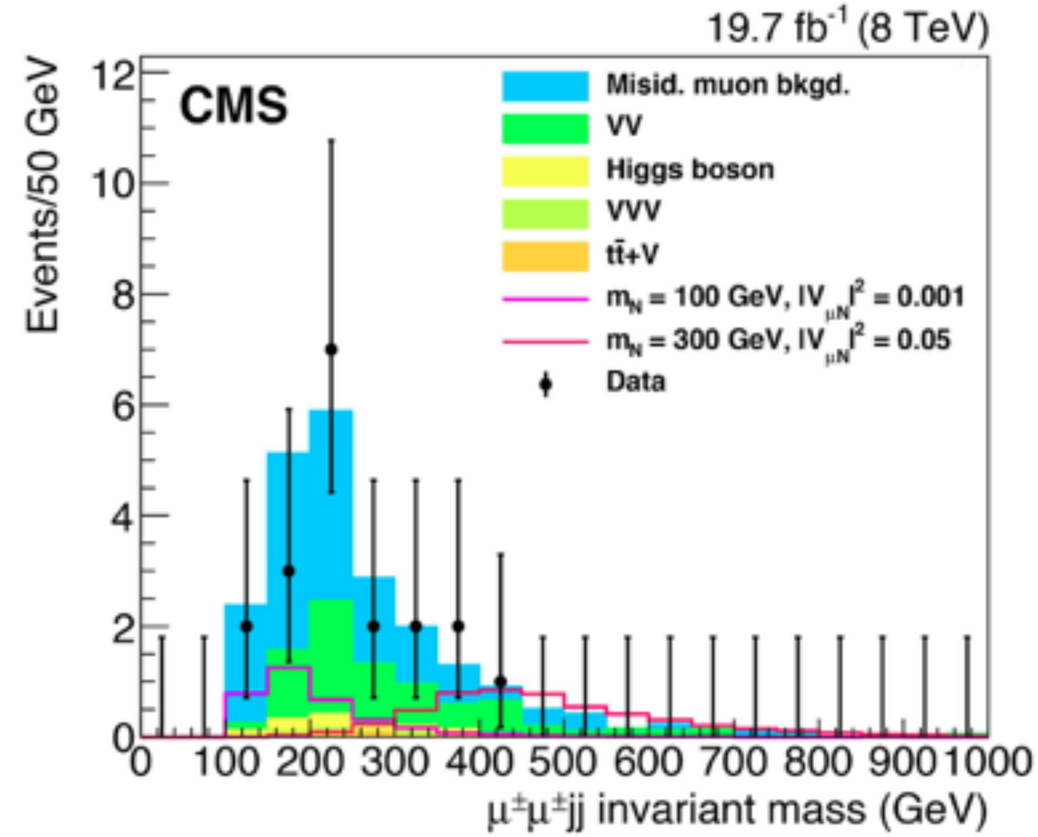
- μμ = 28%, eμ= 35%, ee= 40%

MC (Prompt) Systematic:
Determined for low and high-mass:

- Low Mass = ~20 % High Mass = ~18 %
- Main systematic is from cross section: ~15%

Signal Systematic:

- Low Mass = 15-18% High Mass = 7-19 %
- JET uncertainty and Q^2 is dominant



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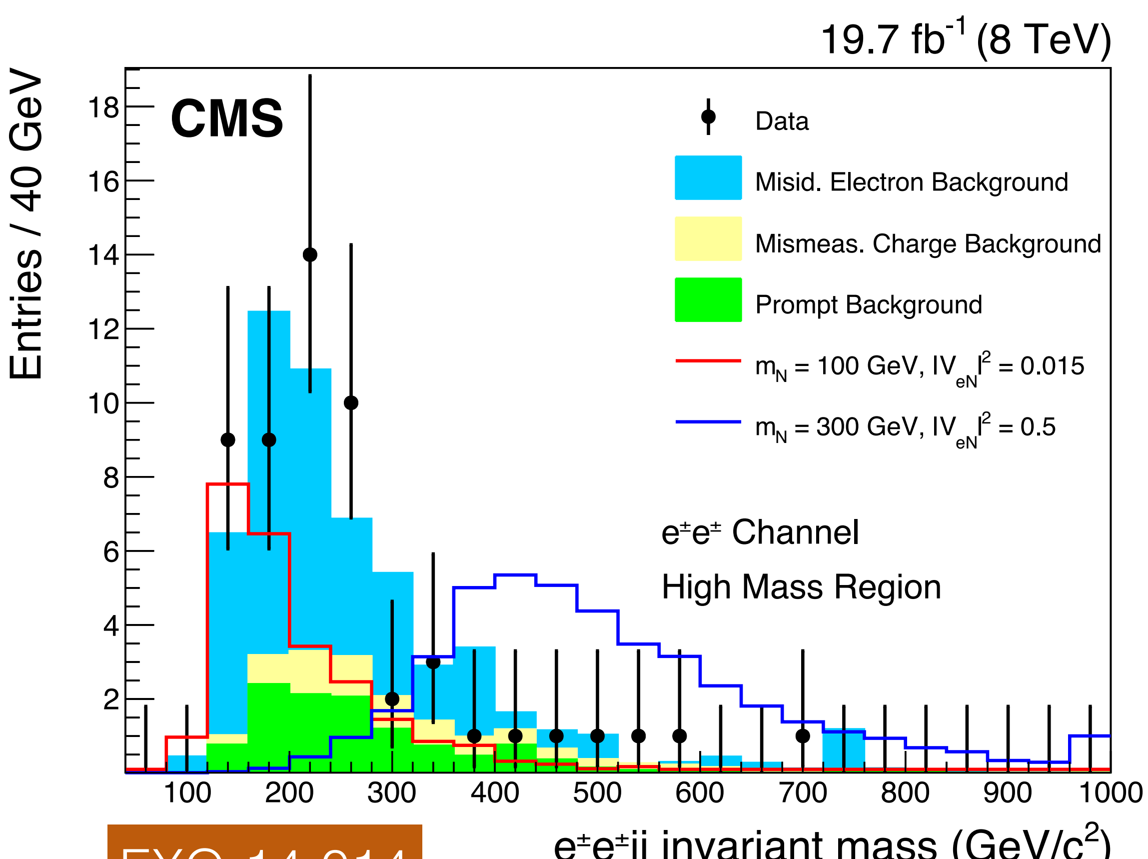
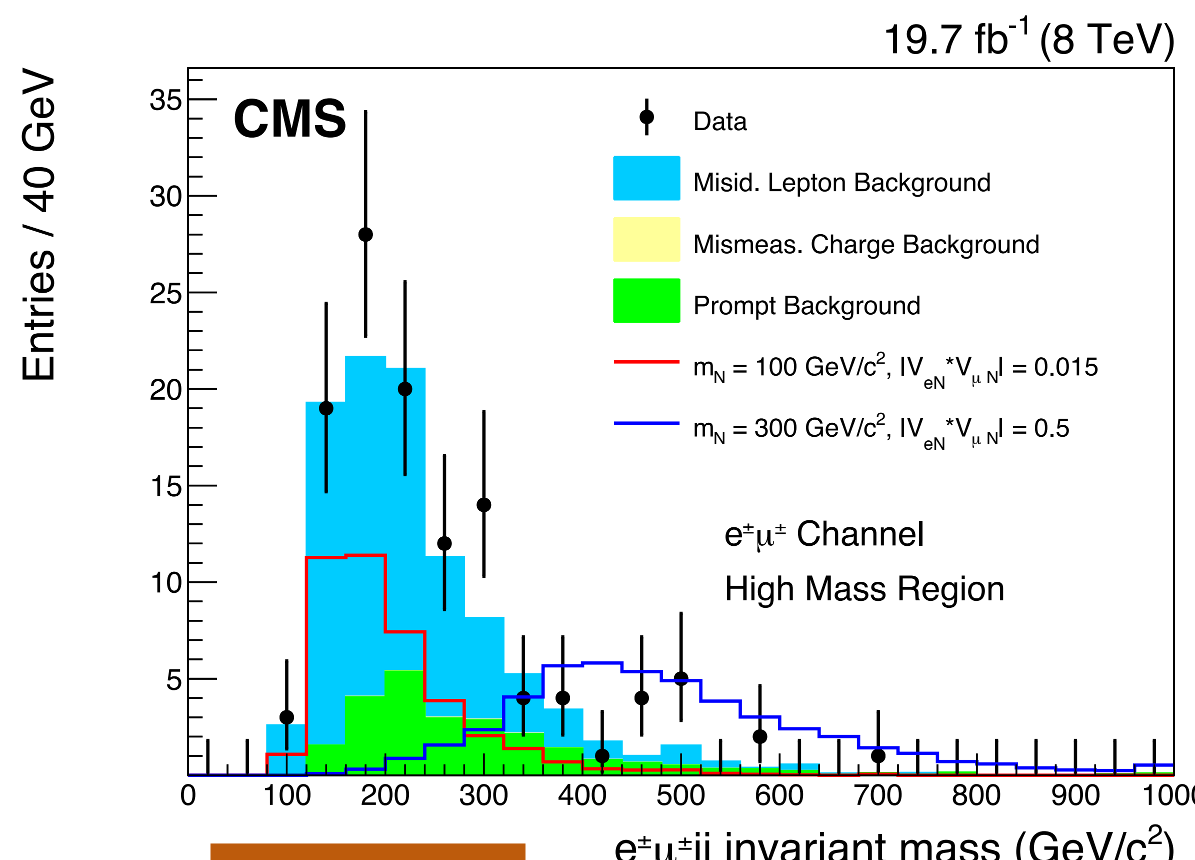


EXO-14-014



EXO-14-014

Signal Optimisation and Results

- Further optimisation done per mass point using punzi** figure of merit using (**new for 8 TeV**):
  - pt leptons
  - m(lljj)
  - $m(l_2jj)$ (for ee and eμ channels)
- Table for μμ channel shown:

$$** \quad \frac{\epsilon(s)}{1+\sqrt{B_{tot}+(0.35B_{fake})^2}}$$

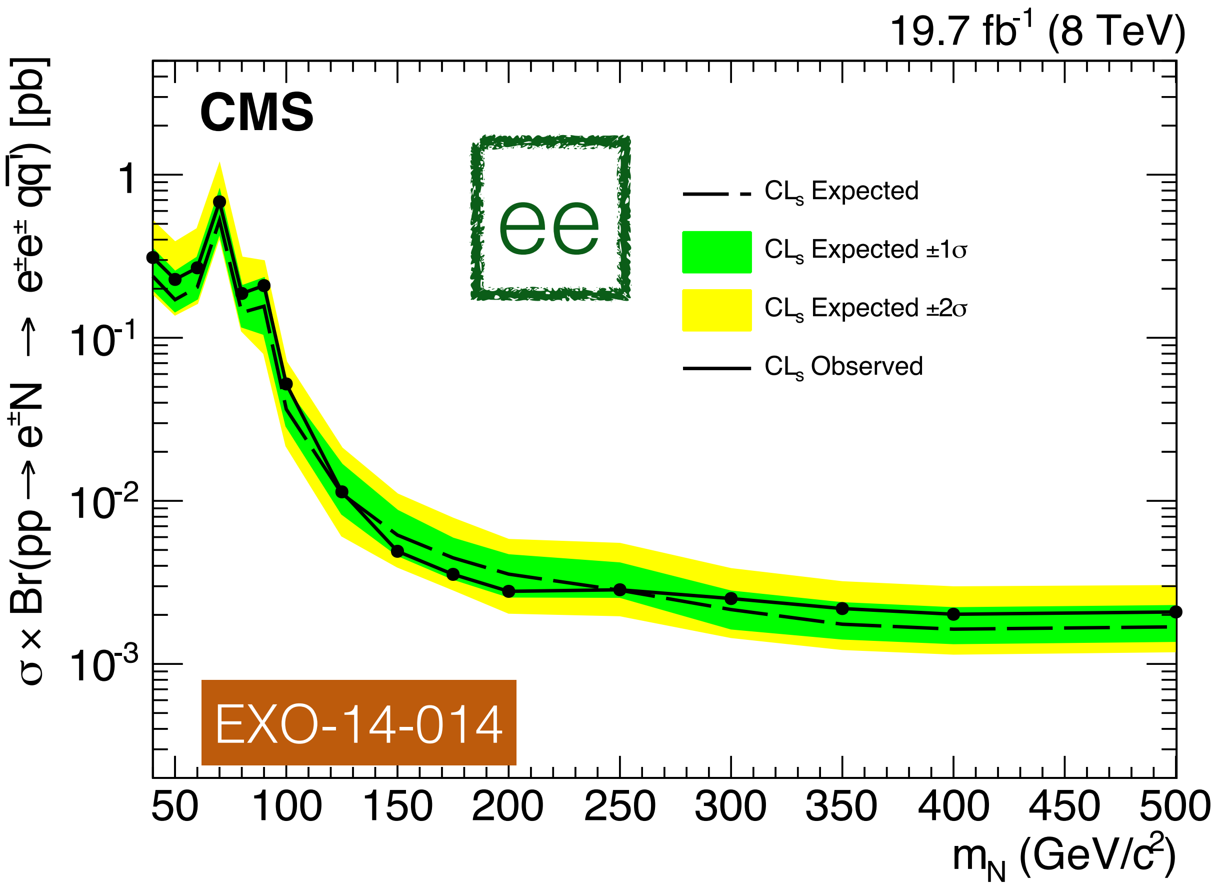
m_N (GeV)	$m(\mu^\pm\mu^\pm jj)$ (GeV)	p_{T1} (GeV)	p_{T2} (GeV)	Acceptance (%)
40	80	20	15	0.69
50	80	20	15	0.80
60	80	20	15	0.64
70	80	20	15	0.26
80	80	20	15	1.2
90	110	20	15	1.2
100	120	20	15	4.7
125	140	25	20	11
150	160	35	25	13
175	200	45	30	15
200	220	50	35	16
250	270	75	35	17
300	290	100	45	15
350	290	100	45	16
400	290	100	45	15
500	290	100	45	12

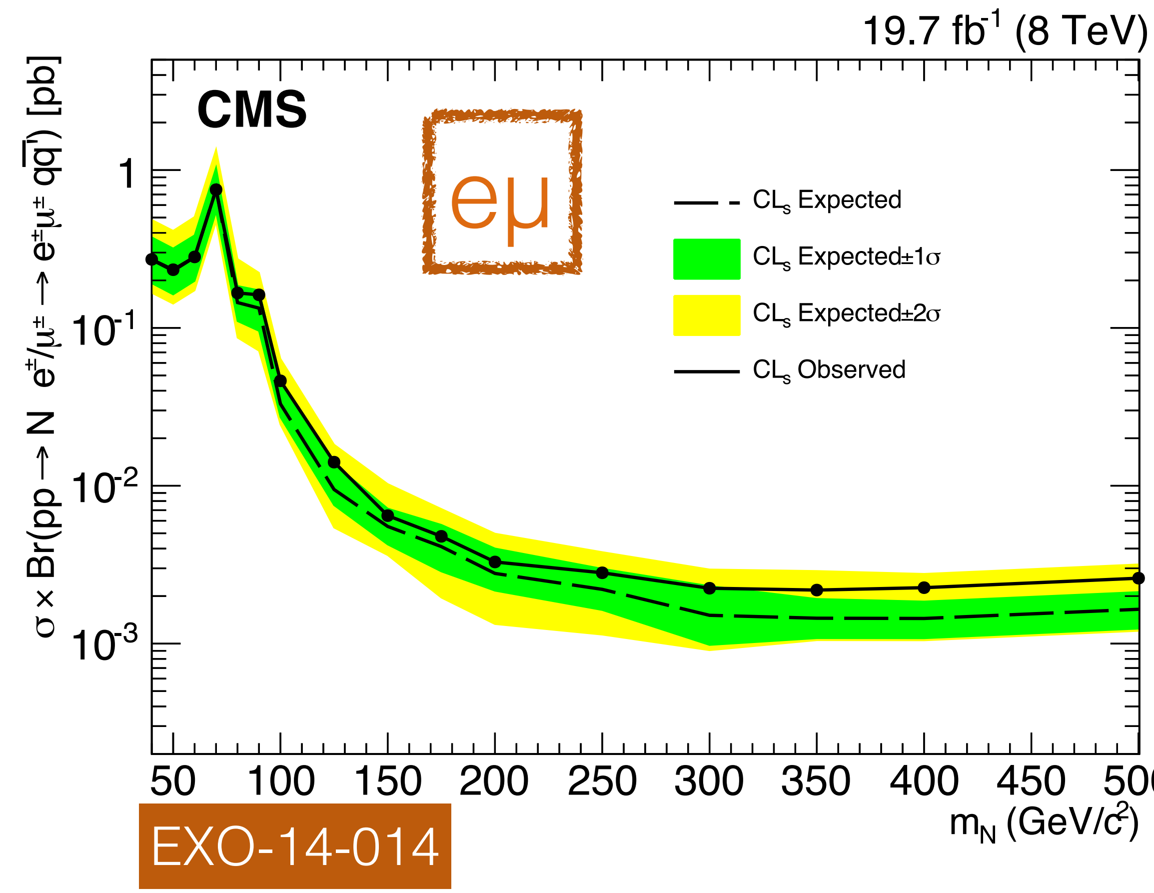
Low Mass

High Mass

m_N (GeV)	SM Bkgd.	Misid. Bkgd.	Total Bkgd.	N_{obs}
40	$3.0 \pm 0.4 \pm 0.6$	$6.7 \pm 0.9 \pm 1.9$	$9.8 \pm 1.0 \pm 2.0$	7
50	$3.0 \pm 0.4 \pm 0.6$	$6.7 \pm 0.9 \pm 1.9$	$9.8 \pm 1.0 \pm 2.0$	7
60	$3.0 \pm 0.4 \pm 0.6$	$6.7 \pm 0.9 \pm 1.9$	$9.8 \pm 1.0 \pm 2.0$	7
70	$3.0 \pm 0.4 \pm 0.6$	$6.7 \pm 0.9 \pm 1.9$	$9.8 \pm 1.0 \pm 2.0$	7
80	$3.0 \pm 0.4 \pm 0.6$	$6.7 \pm 0.9 \pm 1.9$	$9.8 \pm 1.0 \pm 2.0$	7
90	$8.7 \pm 0.7 \pm 1.7$	$12.6 \pm 1.1 \pm 3.5$	$21.3 \pm 1.3 \pm 3.9$	19
100	$8.7 \pm 0.7 \pm 1.7$	$11.7 \pm 1.0 \pm 3.3$	$20.4 \pm 1.2 \pm 3.7$	19
125	$7.9 \pm 0.6 \pm 1.5$	$5.9 \pm 0.7 \pm 1.6$	$13.8 \pm 0.9 \pm 2.2$	8
150	$6.4 \pm 0.5 \pm 1.2$	$3.6 \pm 0.6 \pm 1.0$	$9.9 \pm 0.8 \pm 1.6$	7
175	$4.4 \pm 0.4 \pm 0.8$	$1.6 \pm 0.4 \pm 0.5$	$6.0 \pm 0.6 \pm 1.0$	7
200	$3.4 \pm 0.4 \pm 0.7$	$0.8 \pm 0.3 \pm 0.2$	$4.2 \pm 0.5 \pm 0.7$	5
250	$1.9 \pm 0.3 \pm 0.3$	$0.6 \pm 0.2 \pm 0.2$	$2.5 \pm 0.3 \pm 0.4$	3
300	$0.9 \pm 0.2 \pm 0.2$	$0.1 \pm 0.2 \pm 0.0$	$1.0 \pm 0.3 \pm 0.2$	1
350	$0.9 \pm 0.2 \pm 0.2$	$0.1 \pm 0.2 \pm 0.0$	$1.0 \pm 0.3 \pm 0.2$	1
400	$0.9 \pm 0.2 \pm 0.2$	$0.1 \pm 0.2 \pm 0.0$	$1.0 \pm 0.3 \pm 0.2$	1
500	$0.9 \pm 0.2 \pm 0.2$	$0.1 \pm 0.2 \pm 0.0$	$1.0 \pm 0.3 \pm 0.2$	1

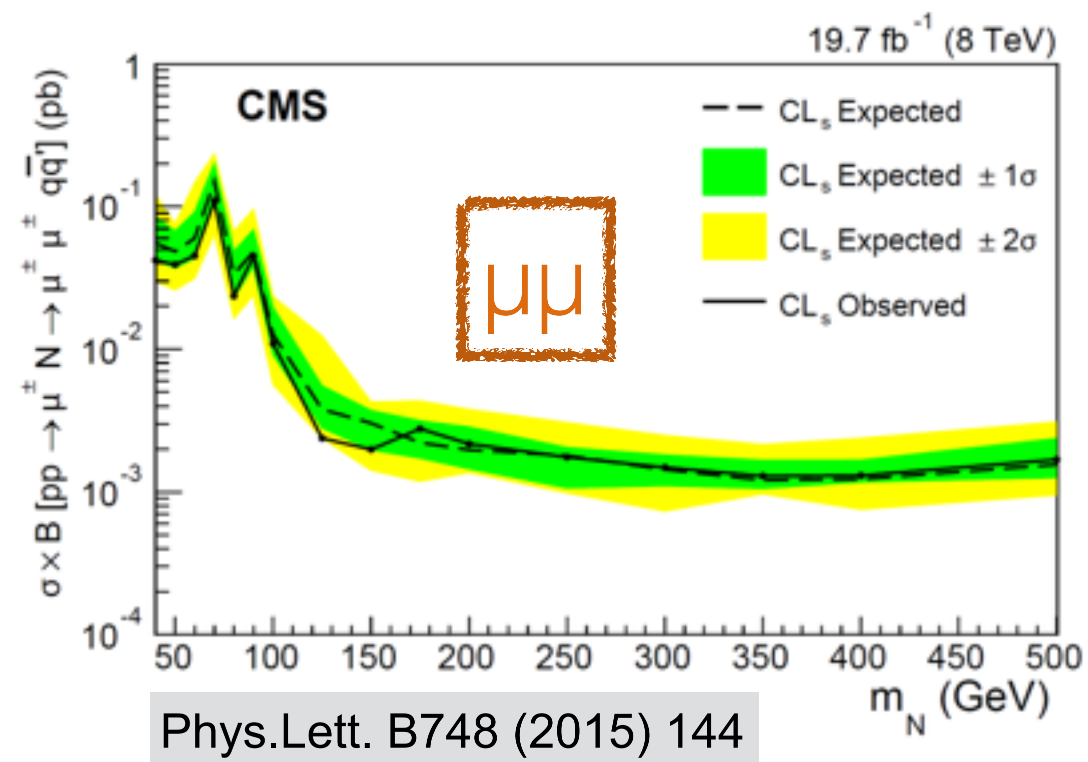
NEW Limits on cross section (approved this week)





- No excess is seen beyond expected background.
- 95% CL limits on the cross section are set.
- Limits are obtained by counting number of events passing signal selection.
- Limits calculated using CLs method.

- **First** direct limits on eμ cross section.



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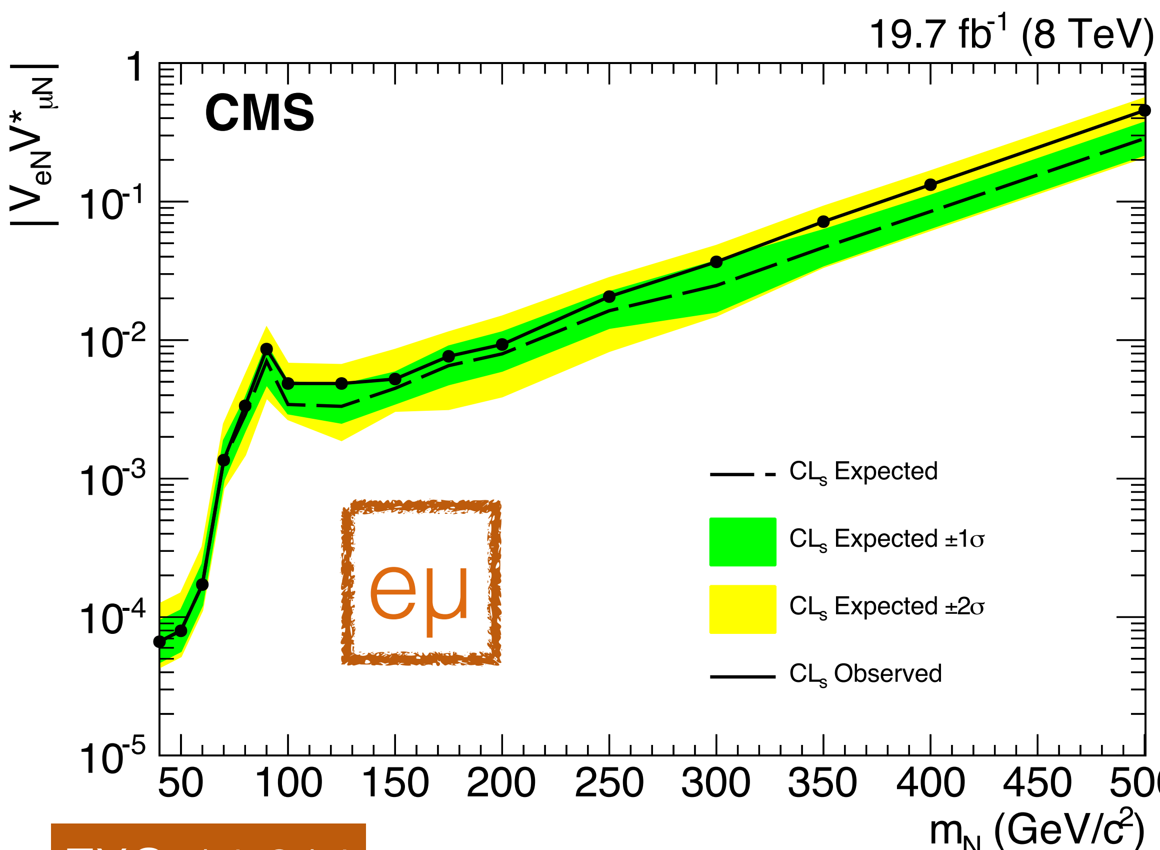
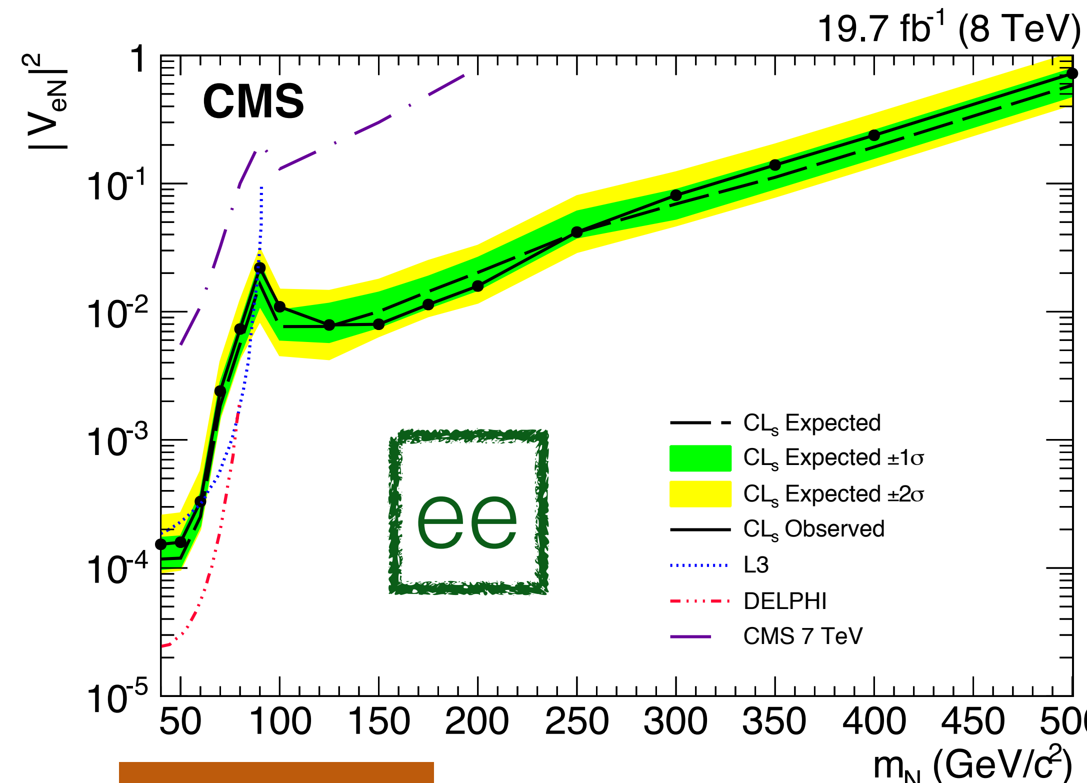
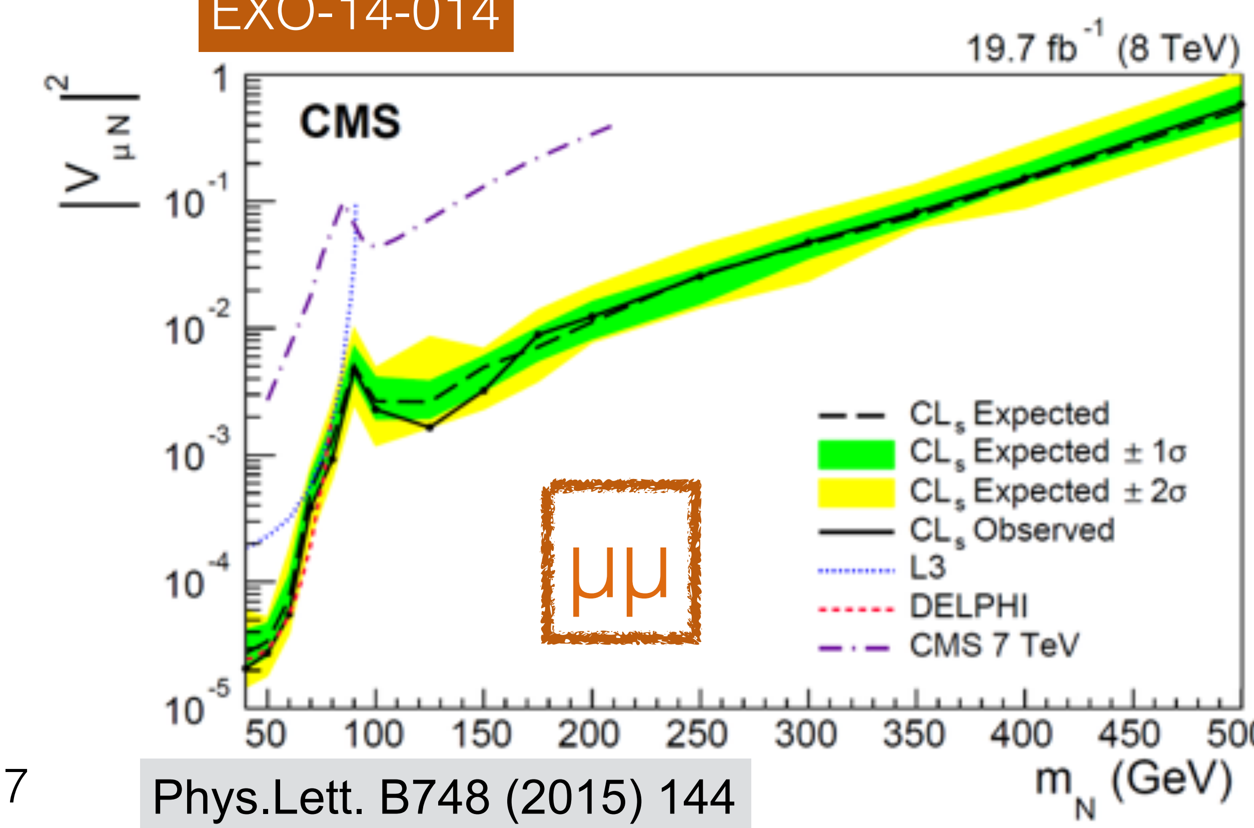
Limit on coupling $|V_{lN}V^*_{l'N}|$



EXO-14-014



EXO-14-014



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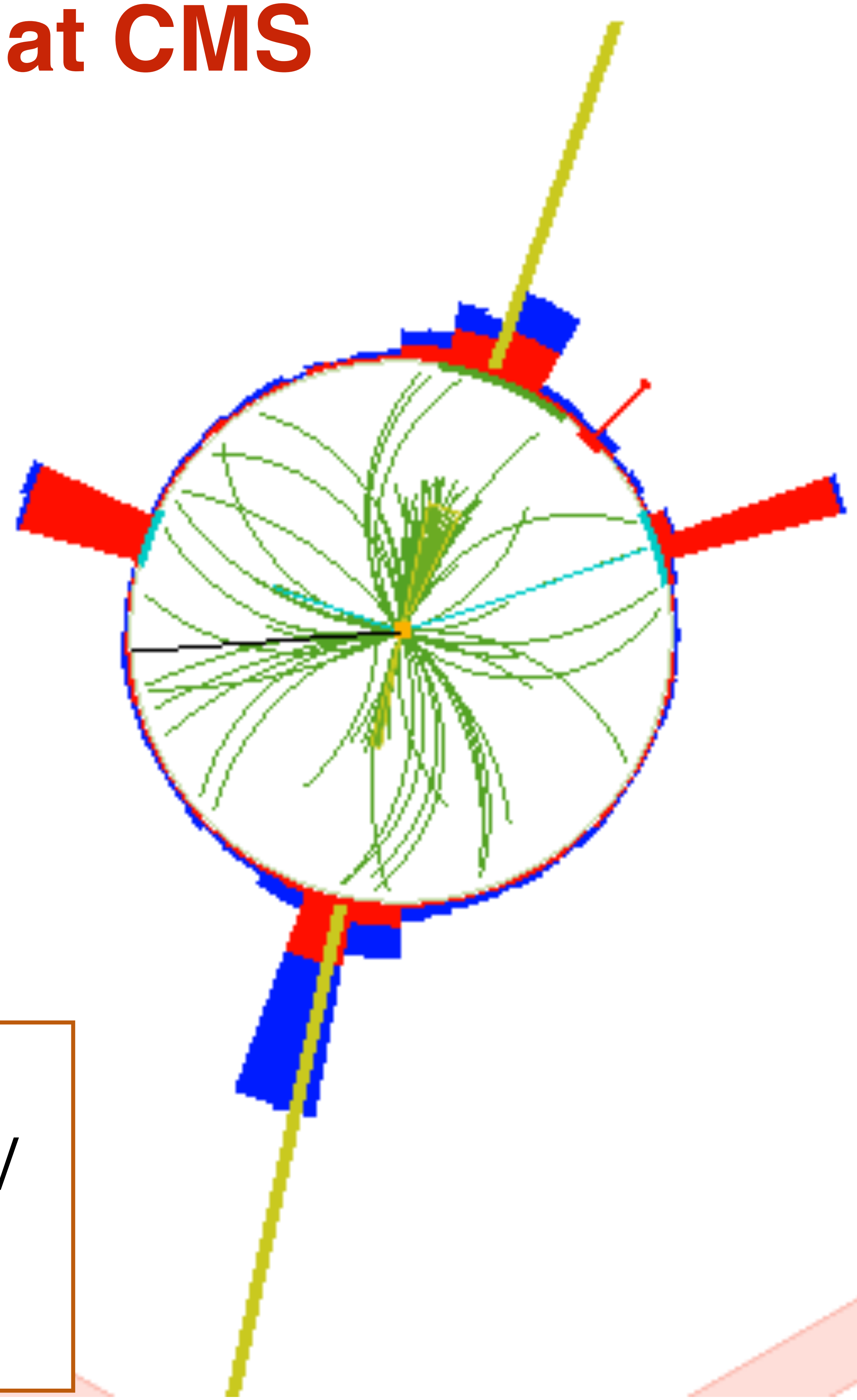
- Limits significantly improve previous direct searches for $m_N > 90$ GeV.
- Muon channel comparable with LEP.
- More than an order of magnitude better than 7 TeV for lowest masses.

Searches in Left Right Symmetric Model at CMS



eejj candidate:

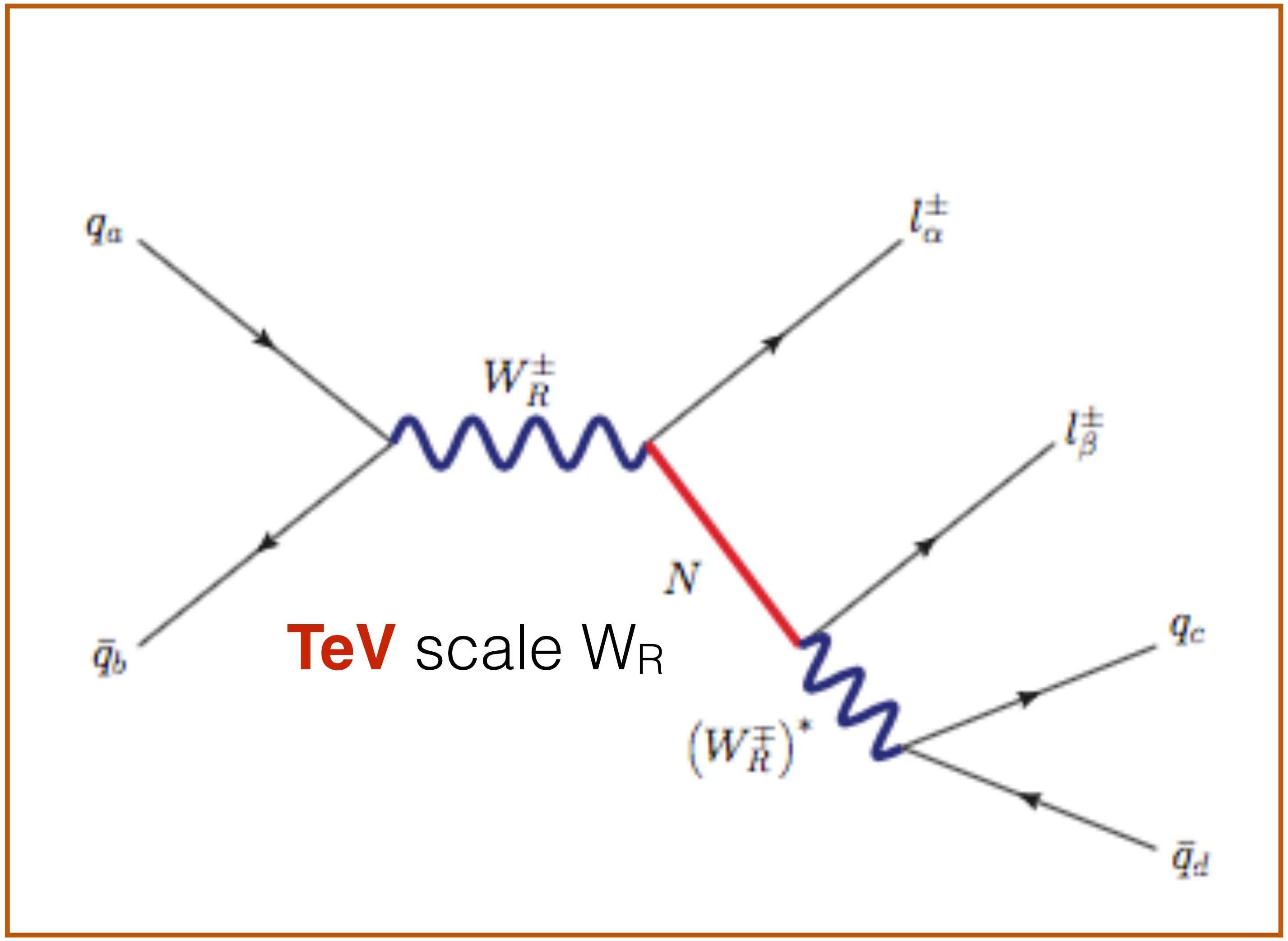
M(eejj) = 3228 GeV

M(ee) =639 GeV

M(jj) = 2553 GeV

EXO-13-008

Searches in Left Right Symmetric Model at CMS at 8 TeV



Final State
2 leptons
2 Jets
No Missing Energy

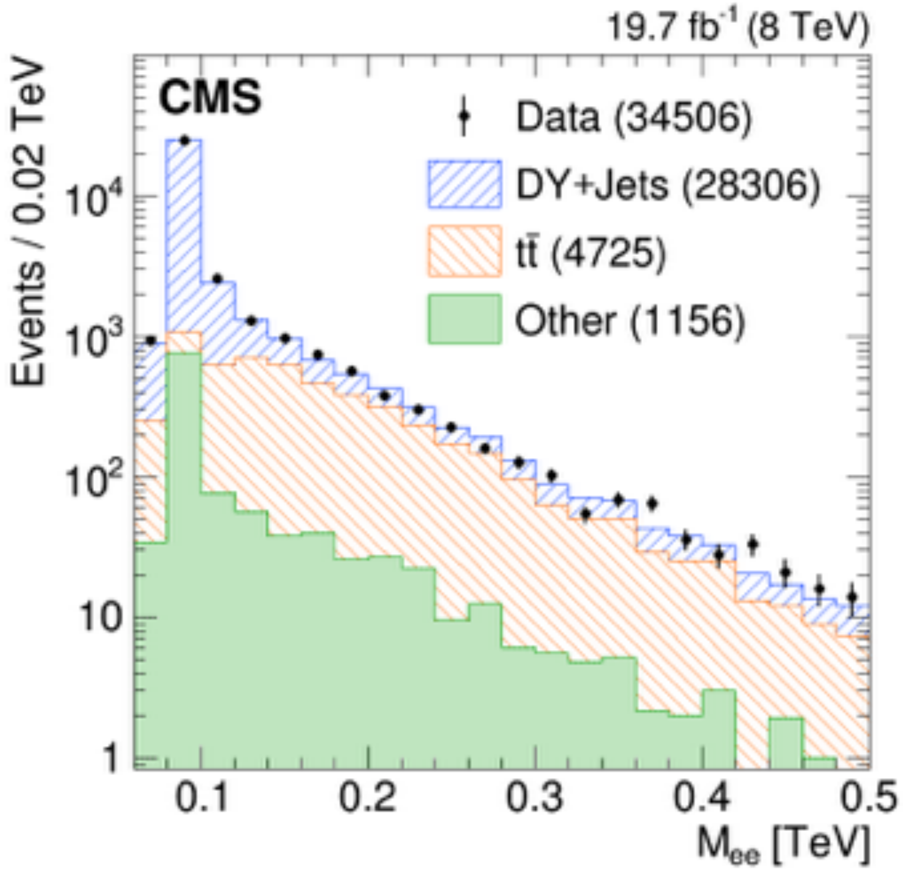
Resonant Production
$M(lljj) = M_{WR}$
$M(l_2jj) = M_N$

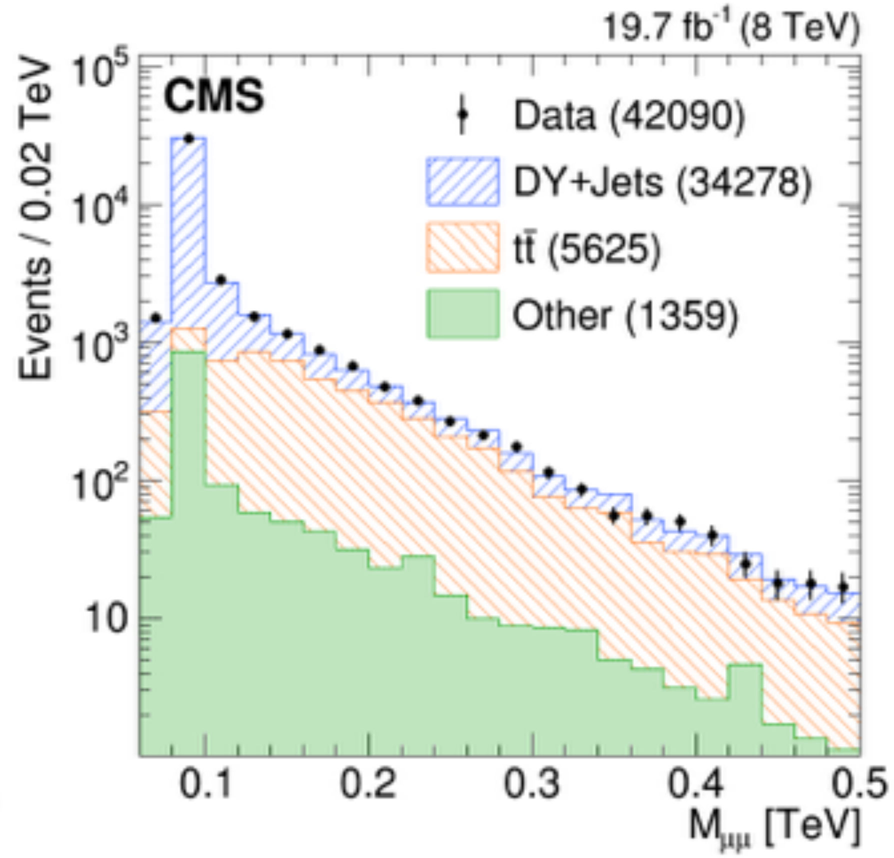
- Included electron channel for 8 TeV.
- Same final state as Seesaw type-1 BUT very different kinematics.
- For $M_N << M_{WR}$ jets and leptons from N overlap in detector since N is boosted. Standard isolation kills signal.

Event Selection

2 *isolated leptons of same flavour: e or μ.
No charge requirement on leptons (OS +SS)
Leading(trailing) lepton P_T > 60(40) GeV
Njets >= 2 : Jet P_T > 40 GeV

1





* signal efficiency drops as M_N/M_{WR} decreases since N becomes boosted

Plots use selection [1]

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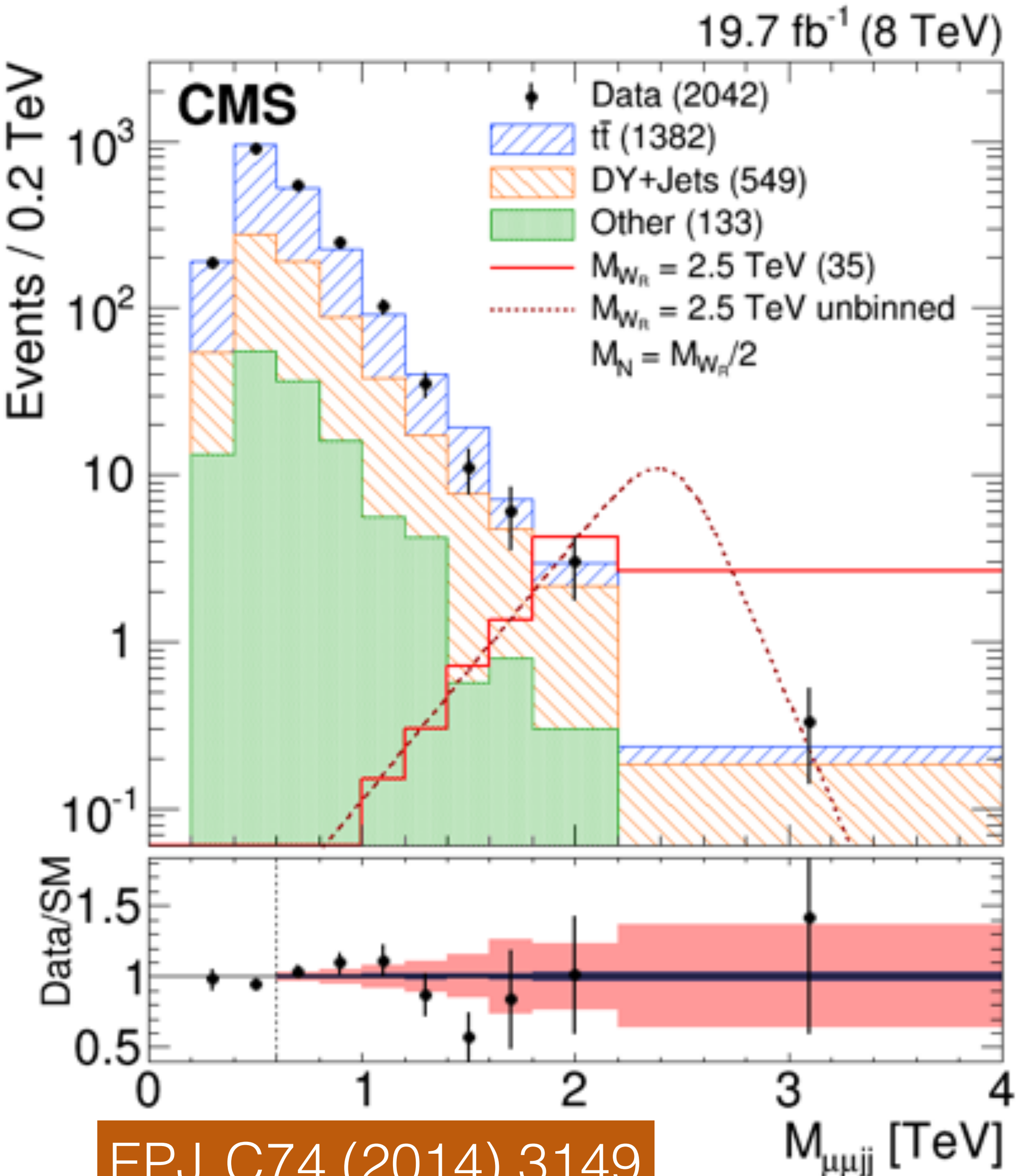
M(ll) > 200 GeV (remove Z bkg)
M(lljj) (i.e. M_{WR})) > 600 GeV

2

Backgrounds and Systematics



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Dominant Backgrounds

Background	Shape	Norm.
tt	Data	MC
DY+jets	MC	Data
VV + singletop	MC	NLO/NNLO

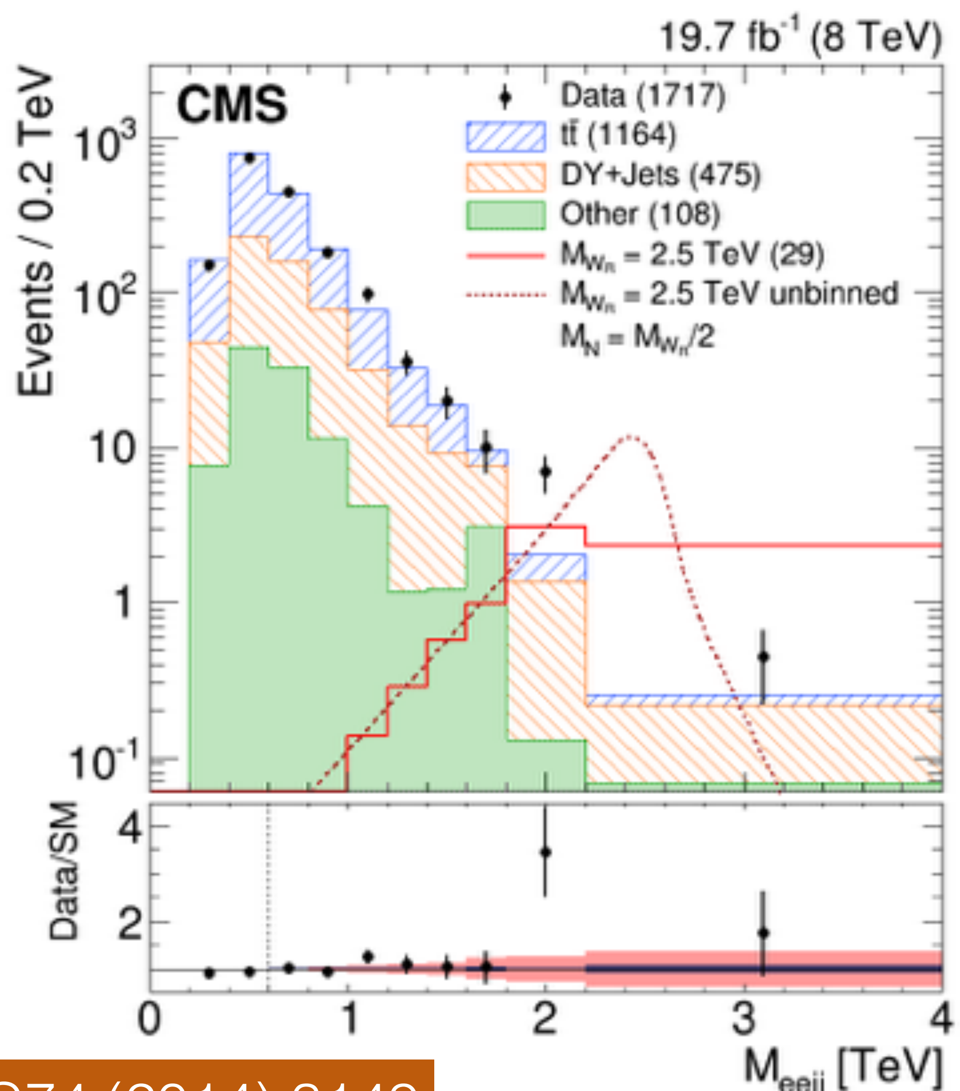
- tt: use eμ events to get shape.
- DY MC norm. to data in 60 <M(ll) < 120 GeV
- Background from misidentified leptons found to be negligible.

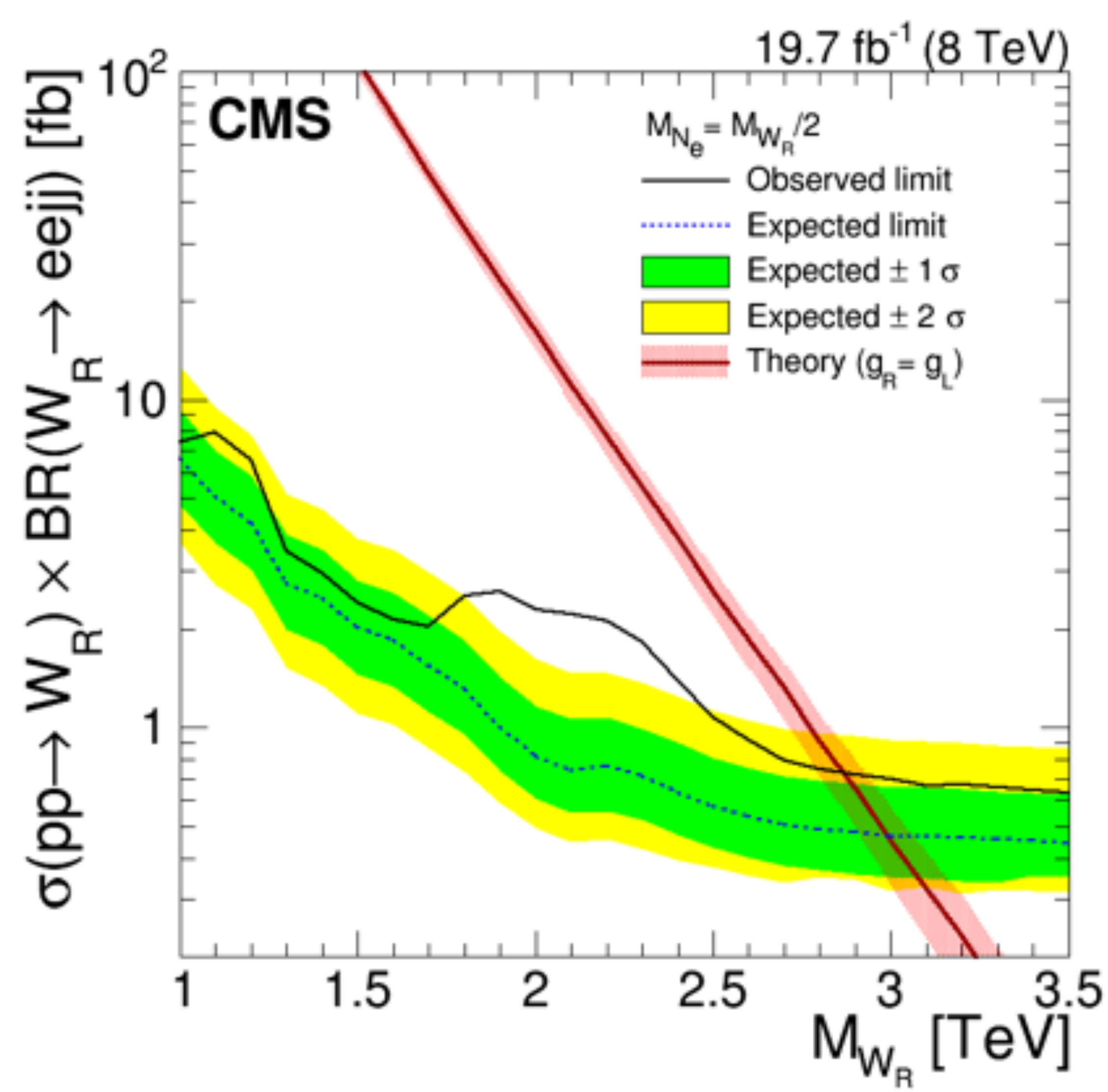
Systematic:
- Leading systematic is from background shape
- PDF uncertainty largest for signal

Limits in the LRSM

An interesting excess in electron channel:

- Local significance, 2.8σ effect at M(eejj) ~2.1 TeV.
- Not consistent with LRSM model
- Excess in OS events: ATLAS looked at SS only.





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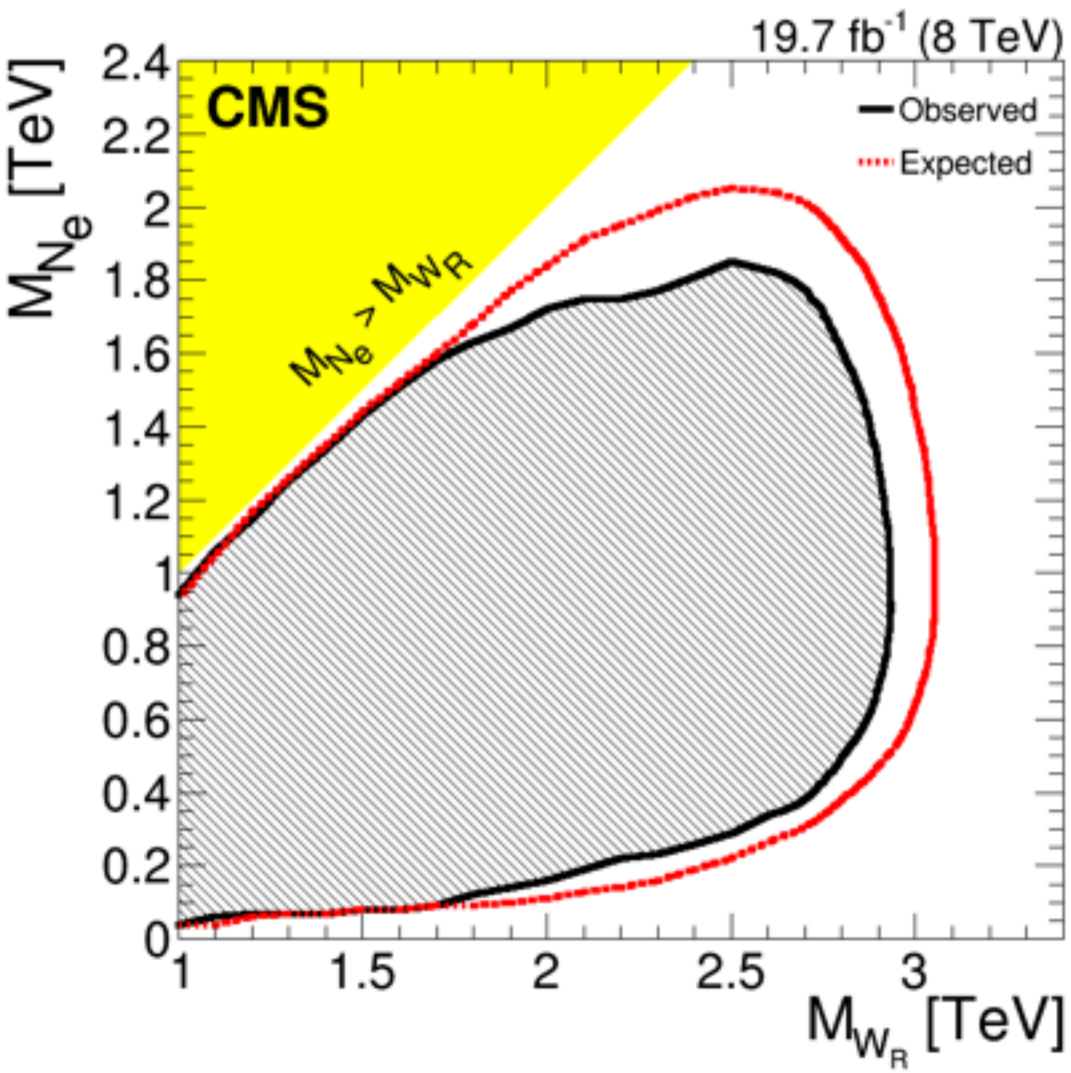
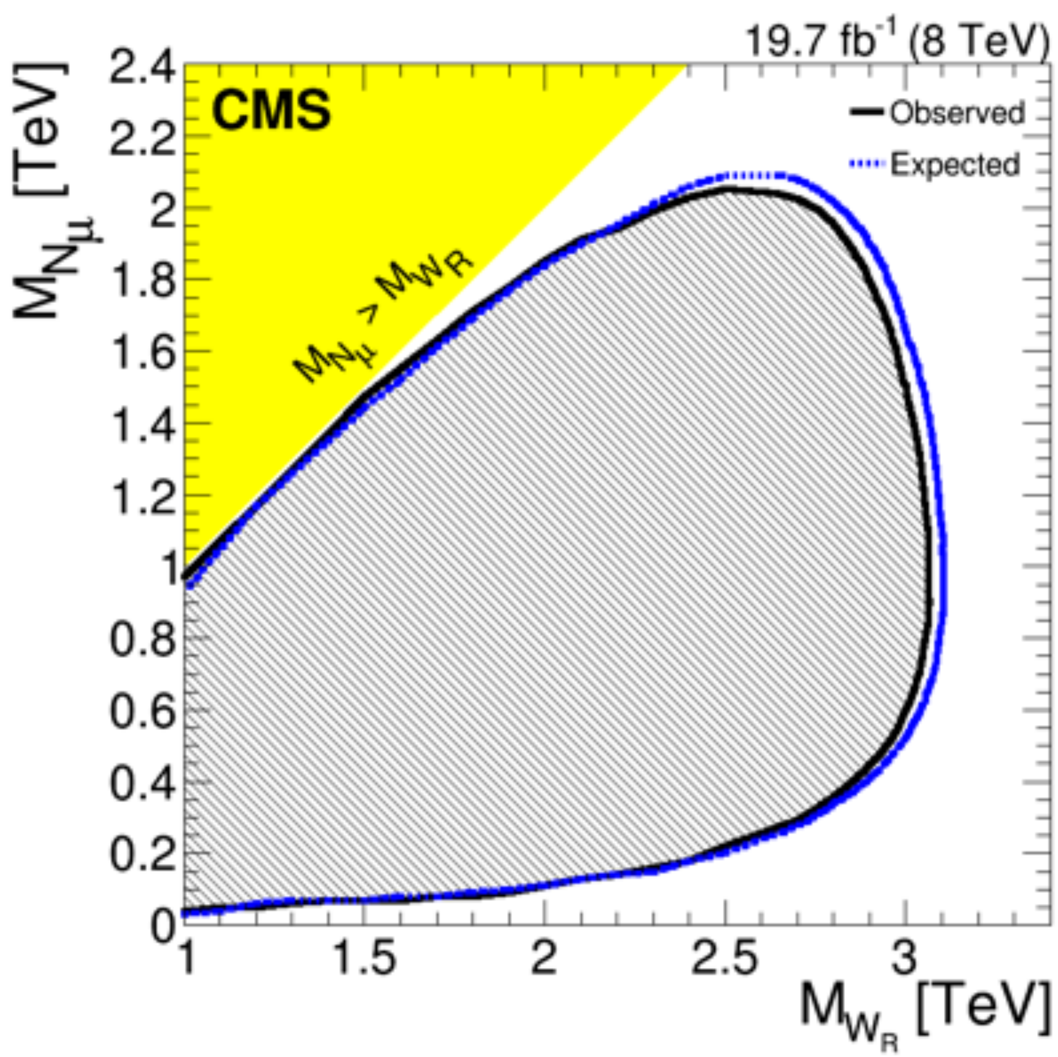
Limits in the LRSM

- Shape of reconstructed W_R is used to calculate limit.
- Used multibin CL_S limit setting technique.
- Exclusion in M_N and M_{WR} plane:
  - M(WR) < 3.00 (2.87) TeV for muon (electron) channel.
  - CMS has best sensitivity at 8 TeV.





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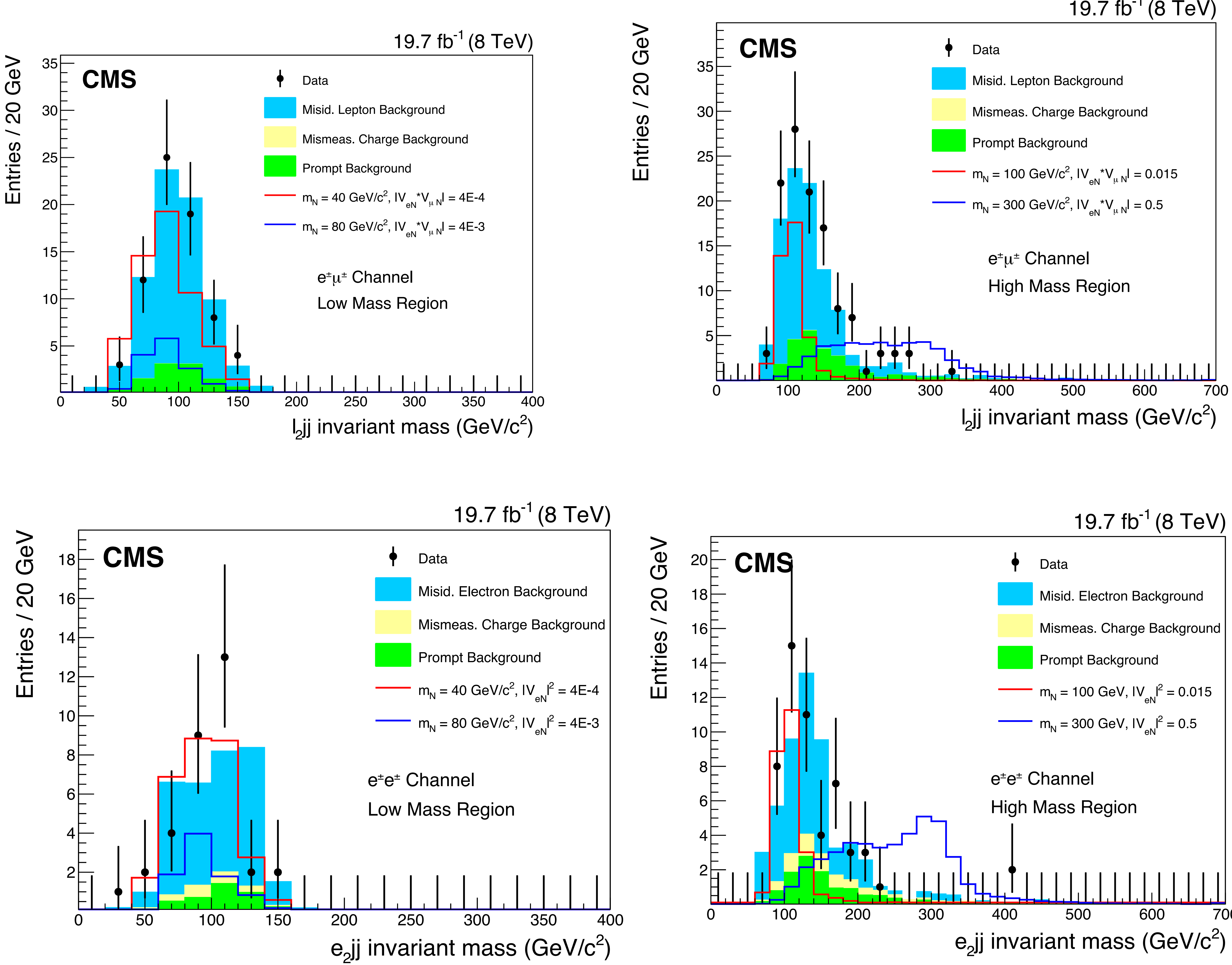
Conclusion

- CMS have searched for heavy neutrinos in events with 2 leptons, two jets and no missing transverse energy.
- No excess seen in the data, 95% CL upper limits have been set:
  - LRSM: on the mass of heavy neutrino (up to 2 TeV) and W_R mass (up to 3.0 TeV).

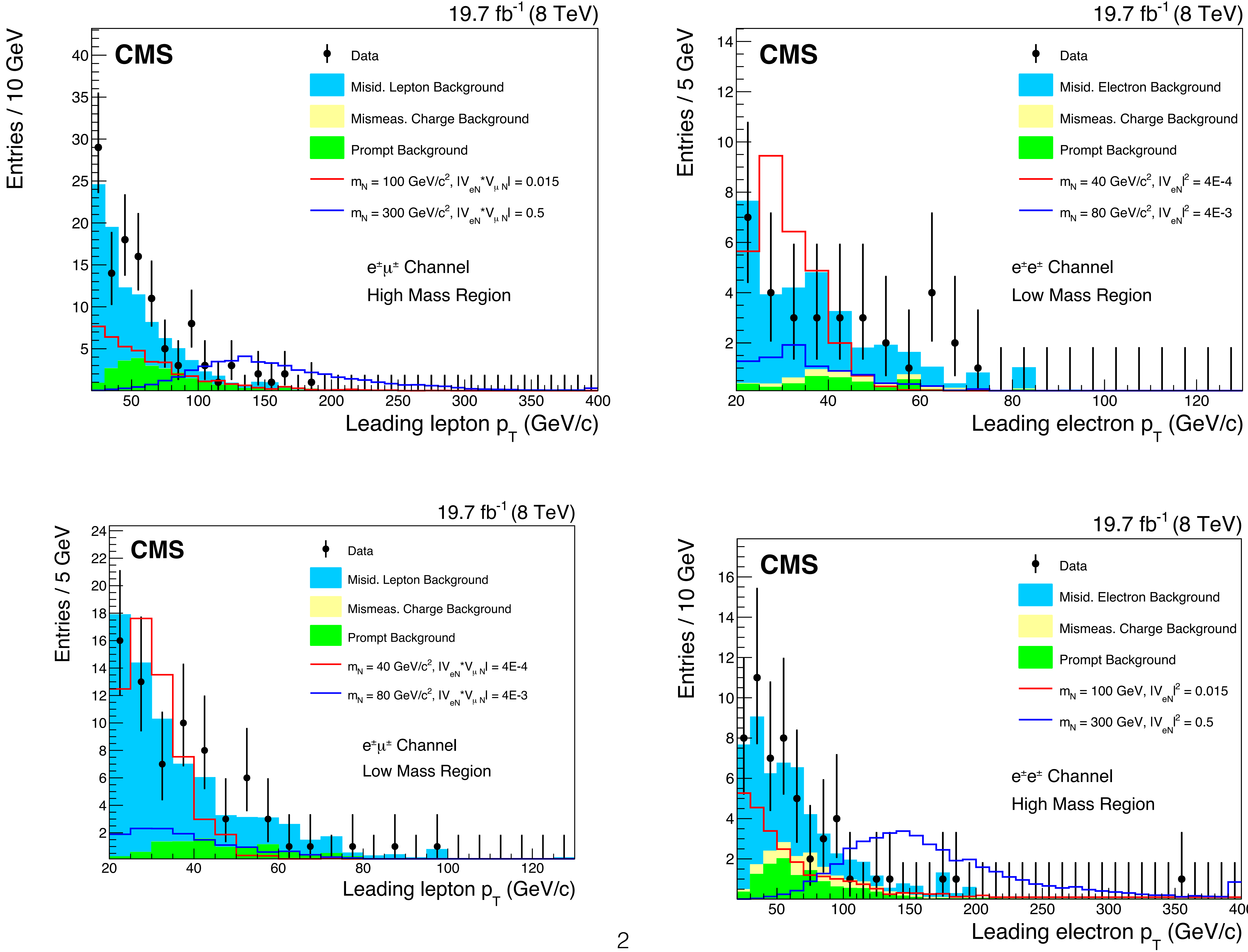
  - SeeSaw type-1: on the coupling of heavy neutrino and lepton vs m_N.
    - ee and μμ channel: most stringent direct limits to date for $m_N > 90$ GeV.
    - eμ channel: first direct limits set for $m_N > 90$ GeV.

- 13 TeV data taking has started. Exciting times ahead.

Backup



19.7 fb^{-1} (8 TeV)
CMS
Data
Misid. Lepton Background
Mismeas. Charge Background
Prompt Background
m_N = 40 GeV/c^2, $|V_{eN}*V_{\mu N}|$ = 4E-4
m_N = 80 GeV/c^2, $|V_{eN}*V_{\mu N}|$ = 4E-3
$e^{\pm}\mu^{\pm}$ Channel
Low Mass Region
Entries / 20 GeV
l_2jj invariant mass (GeV/c^2)
19.7 fb^{-1} (8 TeV)
CMS
Data
Misid. Lepton Background
Mismeas. Charge Background
Prompt Background
m_N = 100 GeV/c^2, $|V_{eN}*V_{\mu N}|$ = 0.015
m_N = 300 GeV/c^2, $|V_{eN}*V_{\mu N}|$ = 0.5
$e^{\pm}\mu^{\pm}$ Channel
High Mass Region
Entries / 20 GeV
l_2jj invariant mass (GeV/c^2)
19.7 fb^{-1} (8 TeV)
CMS
Data
Misid. Electron Background
Mismeas. Charge Background
Prompt Background
m_N = 40 GeV/c^2, $|V_{eN}|^2$ = 4E-4
m_N = 80 GeV/c^2, $|V_{eN}|^2$ = 4E-3
$e^{\pm}e^{\pm}$ Channel
Low Mass Region
Entries / 20 GeV
e_2jj invariant mass (GeV/c^2)
19.7 fb^{-1} (8 TeV)
CMS
Data
Misid. Electron Background
Mismeas. Charge Background
Prompt Background
m_N = 100 GeV, $|V_{eN}|^2$ = 0.015
m_N = 300 GeV, $|V_{eN}|^2$ = 0.5
$e^{\pm}e^{\pm}$ Channel
High Mass Region
Entries / 20 GeV
e_2jj invariant mass (GeV/c^2)



19.7 fb-1 (8 TeV)
CMS
Entries / 10 GeV
Data
Misid. Lepton Background
Mismeas. Charge Background
Prompt Background
mN = 100 GeV/c2, IVeN*VμNI = 0.015
mN = 300 GeV/c2, IVeN*VμNI = 0.5
e±μ± Channel
High Mass Region
Leading lepton pT (GeV/c)
19.7 fb-1 (8 TeV)
CMS
Entries / 5 GeV
Data
Misid. Electron Background
Mismeas. Charge Background
Prompt Background
mN = 40 GeV/c2, IVeNI2 = 4E-4
mN = 80 GeV/c2, IVeNI2 = 4E-3
e±e± Channel
Low Mass Region
Leading electron pT (GeV/c)
19.7 fb-1 (8 TeV)
CMS
Entries / 5 GeV
Data
Misid. Lepton Background
Mismeas. Charge Background
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mN = 40 GeV/c2, IVeN*VμNI = 4E-4
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Low Mass Region
Leading lepton pT (GeV/c)
19.7 fb-1 (8 TeV)
CMS
Entries / 10 GeV
Data
Misid. Electron Background
Mismeas. Charge Background
Prompt Background
mN = 100 GeV, IVeNI2 = 0.015
mN = 300 GeV, IVeNI2 = 0.5
e±e± Channel
High Mass Region
Leading electron pT (GeV/c)

ee channel

N_R Mass (GeV/c^2)	$m(e^\pm e^\pm jj)$ (GeV/c^2)	$p_T^{e_1}$ (GeV/c)	$p_{T2}^{e_2}$ (GeV/c)	$m(e_2jj)$ (GeV/c^2)	$m(e^\pm e^\pm)$ (GeV/c^2)	Acc.*Eff. (%)
40	80 - 160	> 20	> 15	< 120	10 – 60	0.19
50	80 - 160	> 20	> 15	< 120	10 – 60	0.26
60	80 - 160	> 20	> 15	< 120	10 – 60	0.22
70	80 - 160	> 20	> 15	< 120	10 – 60	0.09
80	80 - 160	> 20	> 15	< 120	10 – 60	0.32
90	> 120	> 20	> 15	60 – 120	> 15	0.46
100	> 120	> 20	> 15	80 – 120	> 15	1.9
125	> 140	> 25	> 25	105 – 145	> 15	4.2
150	> 195	> 40	> 25	125 – 175	> 15	6.5
175	> 235	> 45	> 30	155 – 200	> 15	6.4
200	> 280	> 65	> 40	160 – 255	> 15	8.4
250	> 300	> 110	> 40	-	> 15	11
300	> 320	> 120	> 40	-	> 15	14
350	> 360	> 120	> 40	-	> 15	16
400	> 360	> 120	> 40	-	> 15	17
500	> 360	> 120	> 40	-	> 15	17

N_R Mass (GeV/c^2)	SM Bkgd.	Misid. Lep. Bkgd.	Mismeas. Charge Bkgd.	Tot. Bkgd.	N_{obs}
40	0.8 ± 0.2 ± 0.1	7.5 ± 2.0 ± 3.0	0.3 ± 0.0 ± 0.1	8.6 ± 2.0 ± 3.0	11
50	0.8 ± 0.2 ± 0.1	7.5 ± 2.0 ± 3.0	0.3 ± 0.0 ± 0.1	8.6 ± 2.0 ± 3.0	11
60	0.8 ± 0.2 ± 0.1	7.5 ± 2.0 ± 3.0	0.3 ± 0.0 ± 0.1	8.6 ± 2.0 ± 3.0	11
70	0.8 ± 0.2 ± 0.1	7.5 ± 2.0 ± 3.0	0.3 ± 0.0 ± 0.1	8.6 ± 2.0 ± 3.0	11
80	0.8 ± 0.2 ± 0.1	7.5 ± 2.0 ± 3.0	0.3 ± 0.0 ± 0.1	8.6 ± 2.0 ± 3.0	11
90	2.8 ± 0.3 ± 0.3	13.4 ± 2.2 ± 5.4	1.7 ± 0.0 ± 0.2	17.8 ± 2.2 ± 5.4	23
100	2.6 ± 0.3 ± 0.3	11.0 ± 2.1 ± 4.5	1.6 ± 0.0 ± 0.2	15.3 ± 2.1 ± 4.5	23
125	3.3 ± 0.4 ± 0.4	6.1 ± 1.3 ± 2.4	1.7 ± 0.0 ± 0.2	11.1 ± 1.3 ± 2.5	11
150	3.3 ± 0.4 ± 0.4	4.7 ± 1.1 ± 1.9	1.9 ± 0.1 ± 0.2	9.9 ± 1.2 ± 1.9	7
175	2.0 ± 0.3 ± 0.3	0.9 ± 0.5 ± 0.4	1.1 ± 0.1 ± 0.1	4.0 ± 0.6 ± 0.5	3
200	1.3 ± 0.2 ± 0.2	2.0 ± 1.3 ± 0.8	1.0 ± 0.0 ± 0.1	4.3 ± 1.3 ± 0.8	3
250	1.1 ± 0.2 ± 0.2	1.8 ± 1.4 ± 0.8	0.8 ± 0.0 ± 0.1	3.8 ± 1.4 ± 0.7	4
300	0.8 ± 0.2 ± 0.1	1.2 ± 1.3 ± 0.5	0.7 ± 0.0 ± 0.1	2.6 ± 1.3 ± 0.5	4
350	0.6 ± 0.2 ± 0.1	1.2 ± 1.3 ± 0.5	0.6 ± 0.0 ± 0.1	2.4 ± 1.3 ± 0.5	4
400	0.6 ± 0.2 ± 0.1	1.2 ± 1.3 ± 0.5	0.6 ± 0.0 ± 0.1	2.4 ± 1.3 ± 0.5	4
500	0.6 ± 0.2 ± 0.1	1.2 ± 1.3 ± 0.5	0.6 ± 0.0 ± 0.1	2.4 ± 1.3 ± 0.5	4

eμ channel

N_R Mass (GeV/c^2)	$m(e^\pm \mu^\pm jj)$ (GeV/c^2)	$p_T^{\ell_1}$ (GeV/c)	$p_T^{\ell_2}$ (GeV/c)	$m(\ell_2 jj)$ (GeV/c^2)	Acc. * Eff. (%)
40	80 - 150	> 20	> 15	-	0.39
50	80 - 150	> 20	> 15	-	0.46
60	80 - 150	> 20	> 15	-	0.38
70	80 - 150	> 20	> 15	-	0.14
80	80 - 150	> 20	> 15	-	0.58
90	> 120	> 40	> 15	< 130	0.57
100	> 130	> 40	> 30	< 135	1.7
125	> 140	> 40	> 30	< 160	5.2
150	> 150	> 45	> 30	< 230	9.5
175	> 170	> 60	> 35	< 240	11
200	> 200	> 75	> 35	< 330	12
250	> 260	> 80	> 40	< 390	16
300	> 310	> 110	> 40	< 490	16
350	> 360	> 110	> 40	< 550	16
400	> 380	> 120	> 40	< 600	16
500	> 380	> 120	> 40	< 700	14

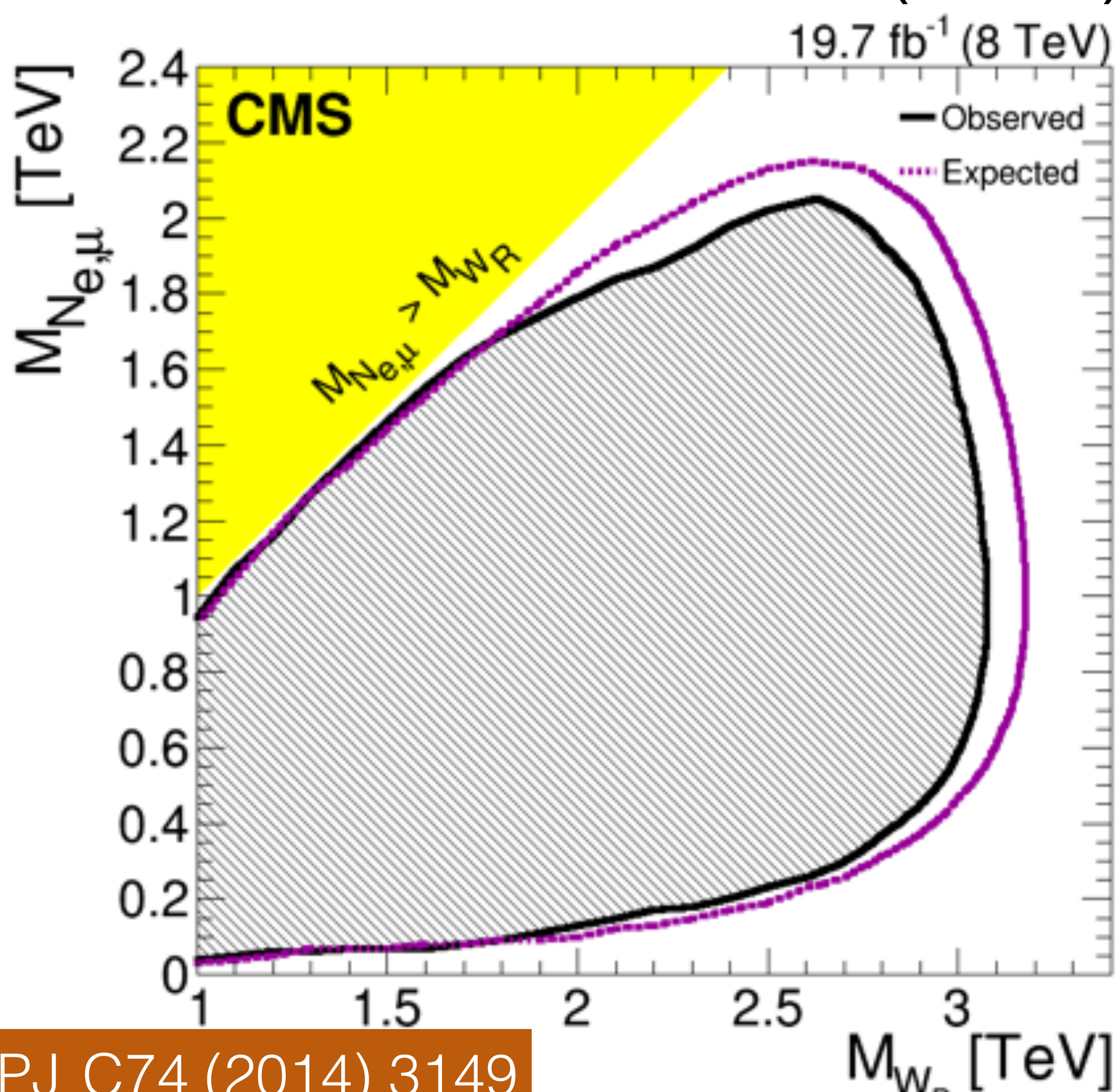
N_R Mass (GeV/c^2)	SM Bkgd.	Misid. Lep. Bkgd.	Tot. Bkgd.	N_{obs}
40	3.1 ± 0.3 ± 0.5	30.6 ± 3.0 ± 10.4	33.7 ± 3.0 ± 10.4	33
50	3.1 ± 0.3 ± 0.5	30.6 ± 3.0 ± 10.4	33.7 ± 3.0 ± 10.4	33
60	3.1 ± 0.3 ± 0.5	30.6 ± 3.0 ± 10.4	33.7 ± 3.0 ± 10.4	33
70	3.1 ± 0.3 ± 0.5	30.6 ± 3.0 ± 10.4	33.7 ± 3.0 ± 10.4	33
80	8.1 ± 0.6 ± 1.2	17.2 ± 1.8 ± 5.9	25.3 ± 1.9 ± 6.0	29
90	6.6 ± 0.6 ± 1.0	13.4 ± 1.4 ± 4.6	20.1 ± 1.6 ± 4.6	25
100	6.7 ± 0.6 ± 1.1	8.1 ± 1.0 ± 2.7	14.8 ± 1.2 ± 2.9	20
125	7.2 ± 0.6 ± 1.2	5.1 ± 0.9 ± 1.7	12.3 ± 1.1 ± 1.9	17
150	8.2 ± 0.6 ± 1.2	5.6 ± 0.9 ± 1.9	13.8 ± 1.1 ± 2.3	16
175	5.6 ± 0.5 ± 0.8	3.6 ± 0.7 ± 1.2	9.3 ± 0.9 ± 1.5	11
200	3.7 ± 0.4 ± 0.6	2.5 ± 0.6 ± 0.8	6.2 ± 0.7 ± 1.0	7
250	3.1 ± 0.4 ± 0.5	1.5 ± 0.5 ± 0.5	4.7 ± 0.6 ± 0.6	7
300	1.4 ± 0.2 ± 0.2	0.7 ± 0.3 ± 0.2	2.2 ± 0.4 ± 0.3	4
350	0.9 ± 0.2 ± 0.1	0.7 ± 0.3 ± 0.2	1.6 ± 0.4 ± 0.3	4
400	0.8 ± 0.2 ± 0.1	0.7 ± 0.3 ± 0.2	1.6 ± 0.4 ± 0.3	4
500	0.8 ± 0.2 ± 0.1	0.7 ± 0.3 ± 0.2	1.6 ± 0.4 ± 0.3	4

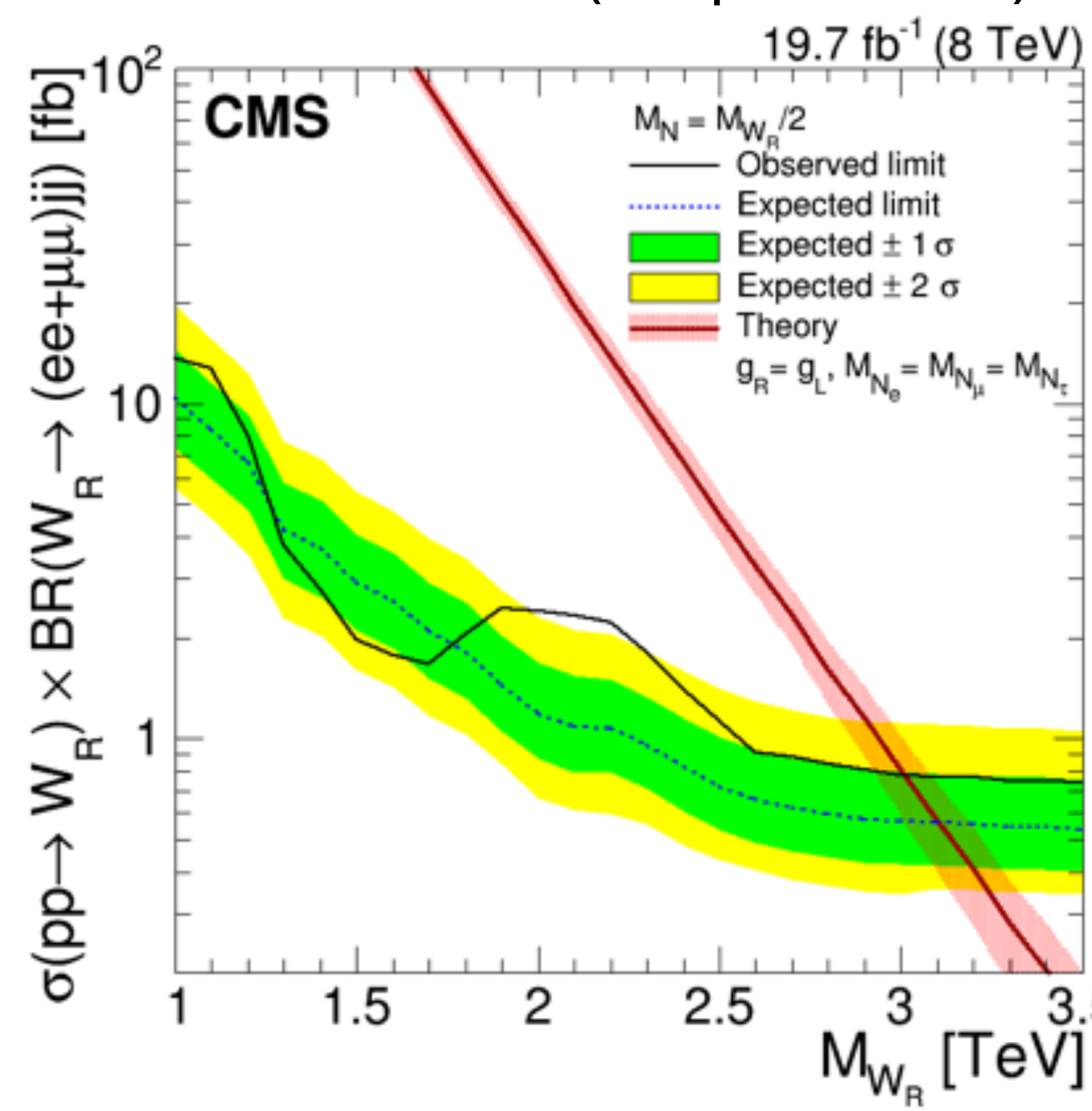
Channel		Misid. Bkgd. (%)	Mismeas. Charge Bkgd. (%)	SM Bkgd. (%)
ee	Systematics for m_{N}=100 GeV/c^2selection	99.4	0.2	0.4
	Systematics for m_{N}=500 GeV/c^2selection	95.2	2.0	2.8
eμ	Systematics for m_{N}=100 GeV/c^2selection	90.7	0.0	9.3
	Systematics for m_{N}=500 GeV/c^2selection	84.5	0.0	15.5

Source	ee		eμ	
	Signal (%)	SM Bkgd. (%)	Signal (%)	SM Bkgd. (%)
Simulation				
SM cross section	–	9-25 [9-25]	–	9-25 [9-25]
Jet energy scale	6-8 [1-3]	5 [7]	4-8 [1-2]	8 [7]
Jet energy resolution	3-7 [2-3]	10 [7]	3-10 [2-3]	10 [6]
Event pileup	2-3 [0-2]	4 [1]	2-3 [0-2]	3 [2]
Unclustered energy	1-3 [1-2]	4 [5]	1-3 [1-2]	5 [1]
Integrated luminosity	2.6 [2.6]	2.6 [2.6]	2.6 [2.6]	2.6 [2.6]
Electron selection	2 [2]	2 [2]	2 [2]	2 [2]
Trigger selection	6 [6]	6 [6]	6 [6]	6 [6]
b tagging	0-1 [1-2]	2 [1]	0-1 [1-2]	1 [1]
PDF (shape)	2.0 [2.0]	–	2.0 [2.0]	–
PDF (rate)	3.5 [3.5]	–	3.5 [3.5]	–
Renormalization /Factorization scales	8-10 [1-6]	–	8-10 [1-6]	–
Signal MC statistics	5-15 [1-6]	–	3-7 [1-3]	–
Data-Driven				
Misidentified leptons	–	40 [40]	–	35 [35]
Mismeasured charge	–	12 [12]	–	12 [12]

Limits in the LRSM

- Limits slightly improved when assuming N_l are degenerate.
- Muon and electron channels are combined assuming $m_N = 1/2\ M_{WR}$
- Limit: $M_{WR} < 3.01\ (3.10)$ TeV for observed(expected)





EPJ C74 (2014) 3149

SeeSaw Mechanism

- Neutrino Majorana mass terms can be added to SM Lagrangain ‘for free’,

$$M_\nu \approx \frac{m_{\text{Dirac}}}{M_N}$$

- Normally means for M_ν that M_N >> TeV (i.e., not interesting at the LHC)

- There are frameworks that allow for smaller heavy neutrino mass.

- One attractive model, minimal Type-1 seesaw (mT1SM).
  - No additional gauge bosons
  - TeV scale neutrino

$$m_\nu^{\text{light}} \sim \frac{m_e^2}{m_N} \sim 0.1\text{eV}$$

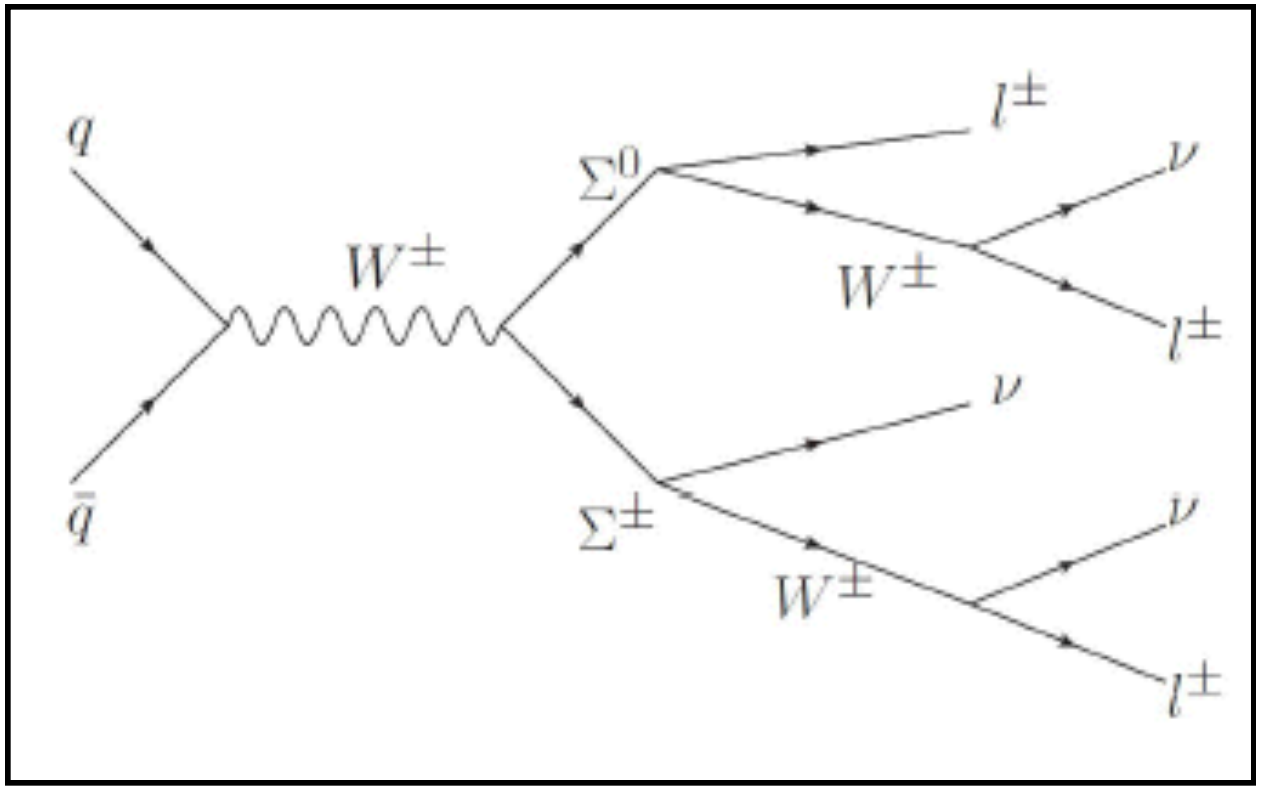
[Pilaftsis '92; Kersten, Smirnov '07; Ibarra, Molinaro, Petcov '10; Mitra, Senjanović, Vissani '11; ...]

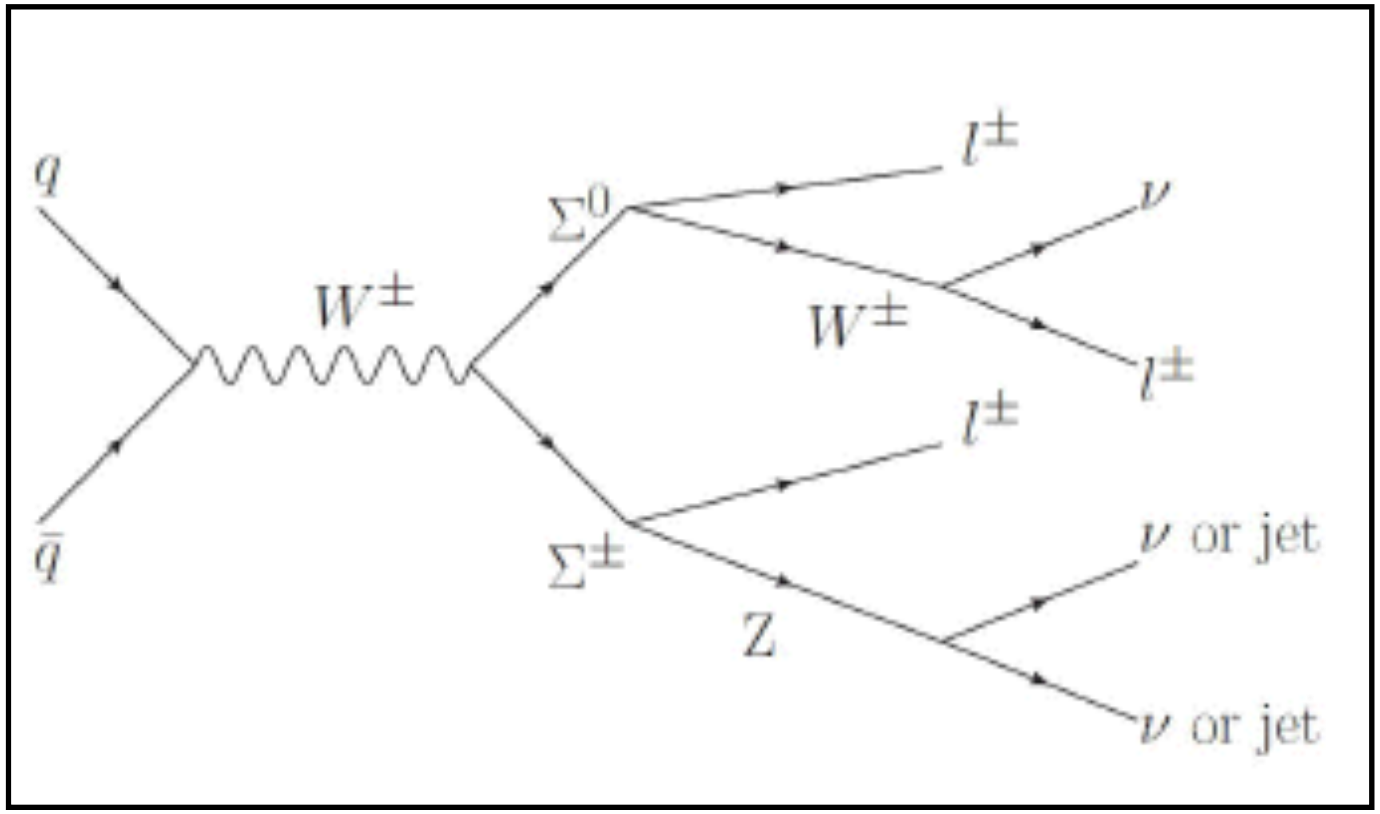
- and frameworks that embed the neutrino mass scale into a more fundamental theory:

- Left-Right Symmetric Model (**LRSM**) which adds a chiral SU2 symmetry to SM
  - Introduces 3 new gauge bosons
  - TeV scale neutrinos

Type-3 SeeSaw: Heavy N production

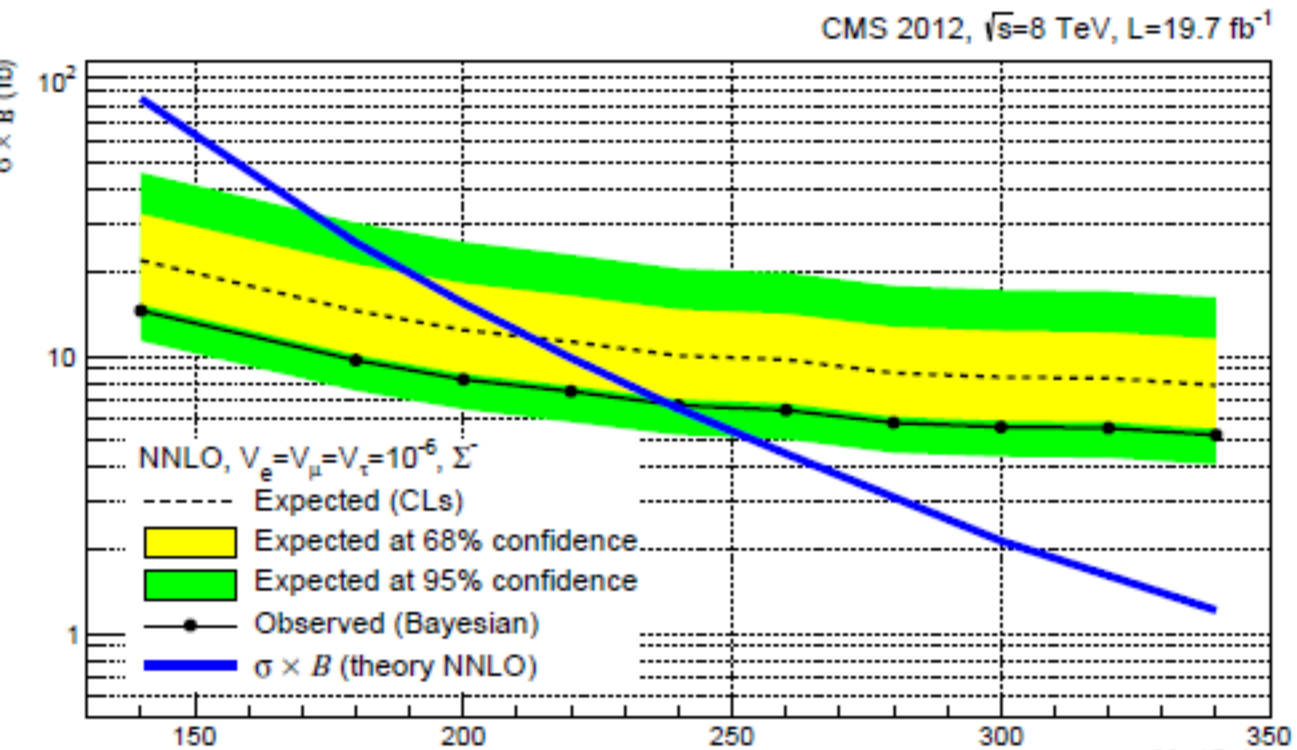
- **Type 3**
  - Production of $\Sigma^{0}, \Sigma^{+/-}$ via s-channel W*
  - Trilepton final state

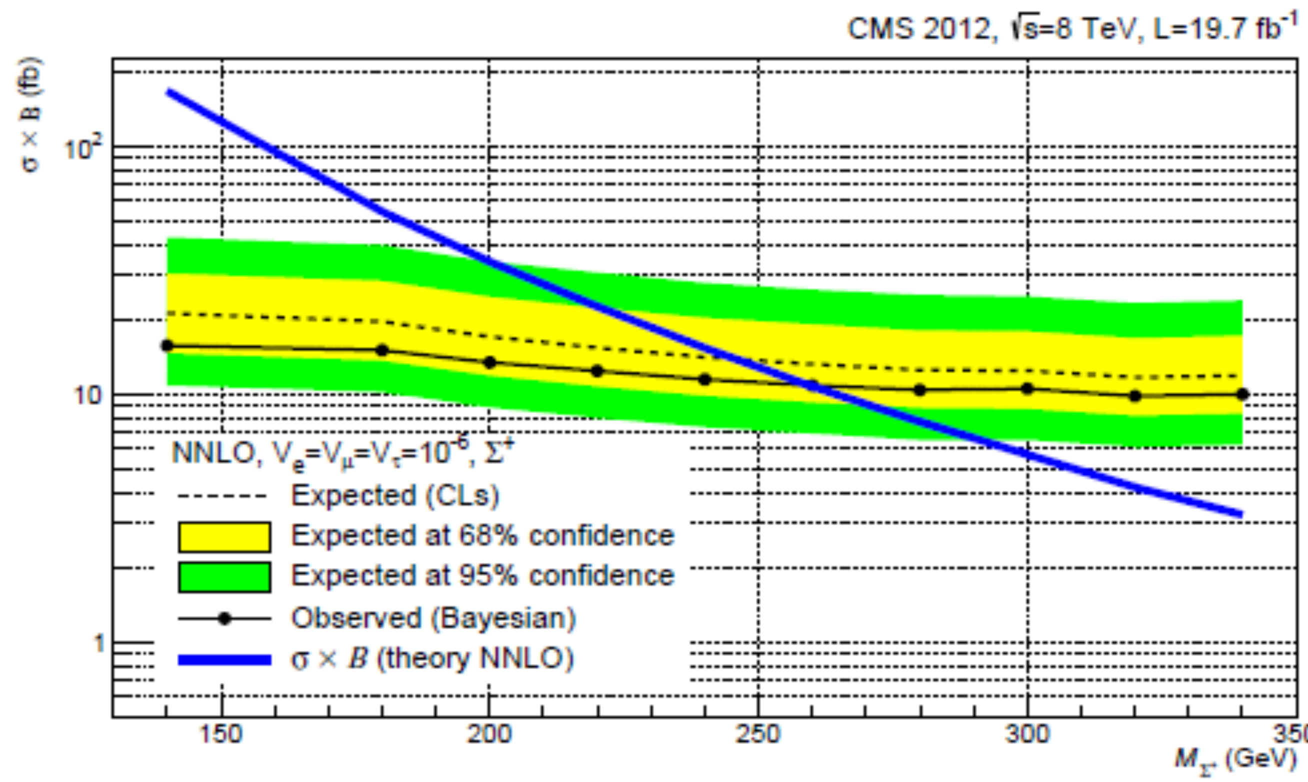


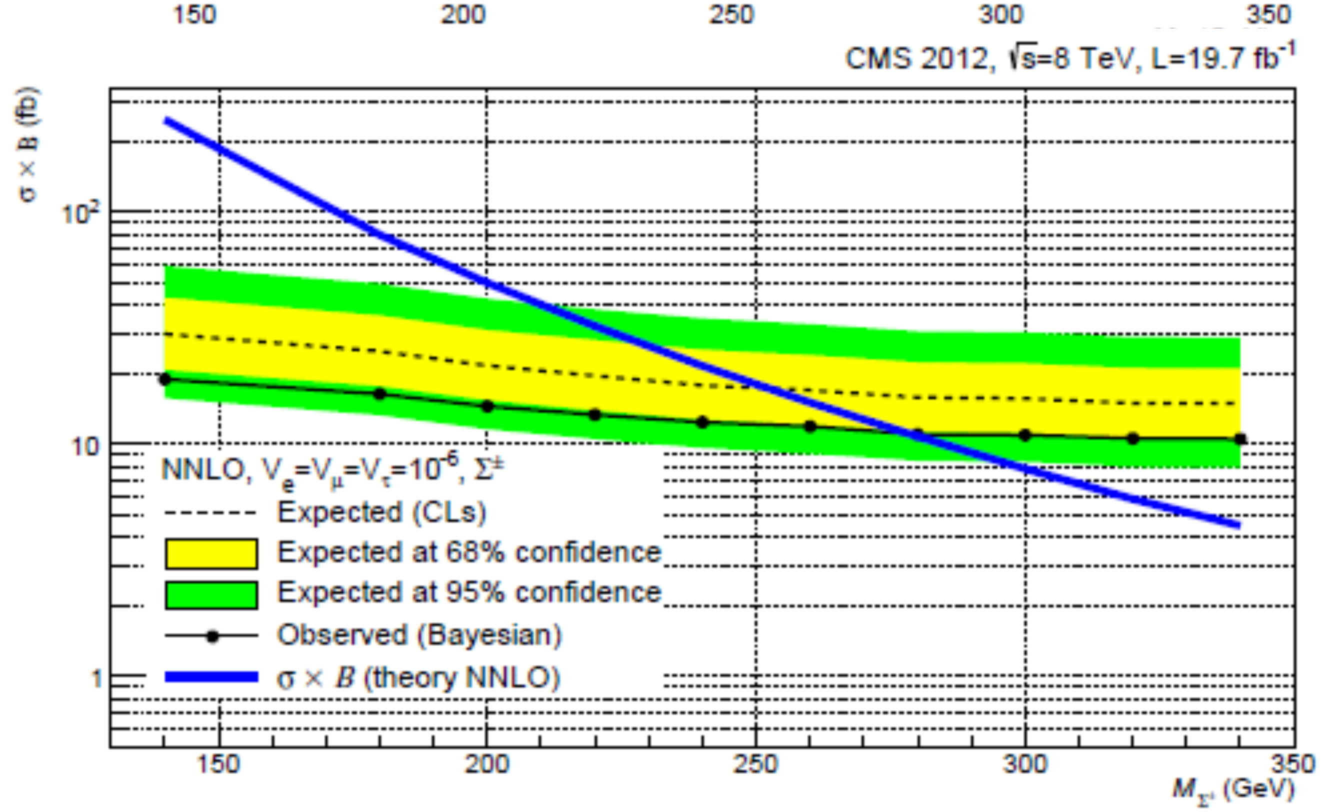


EXO-14-001

Limits in Type-3 seesaw

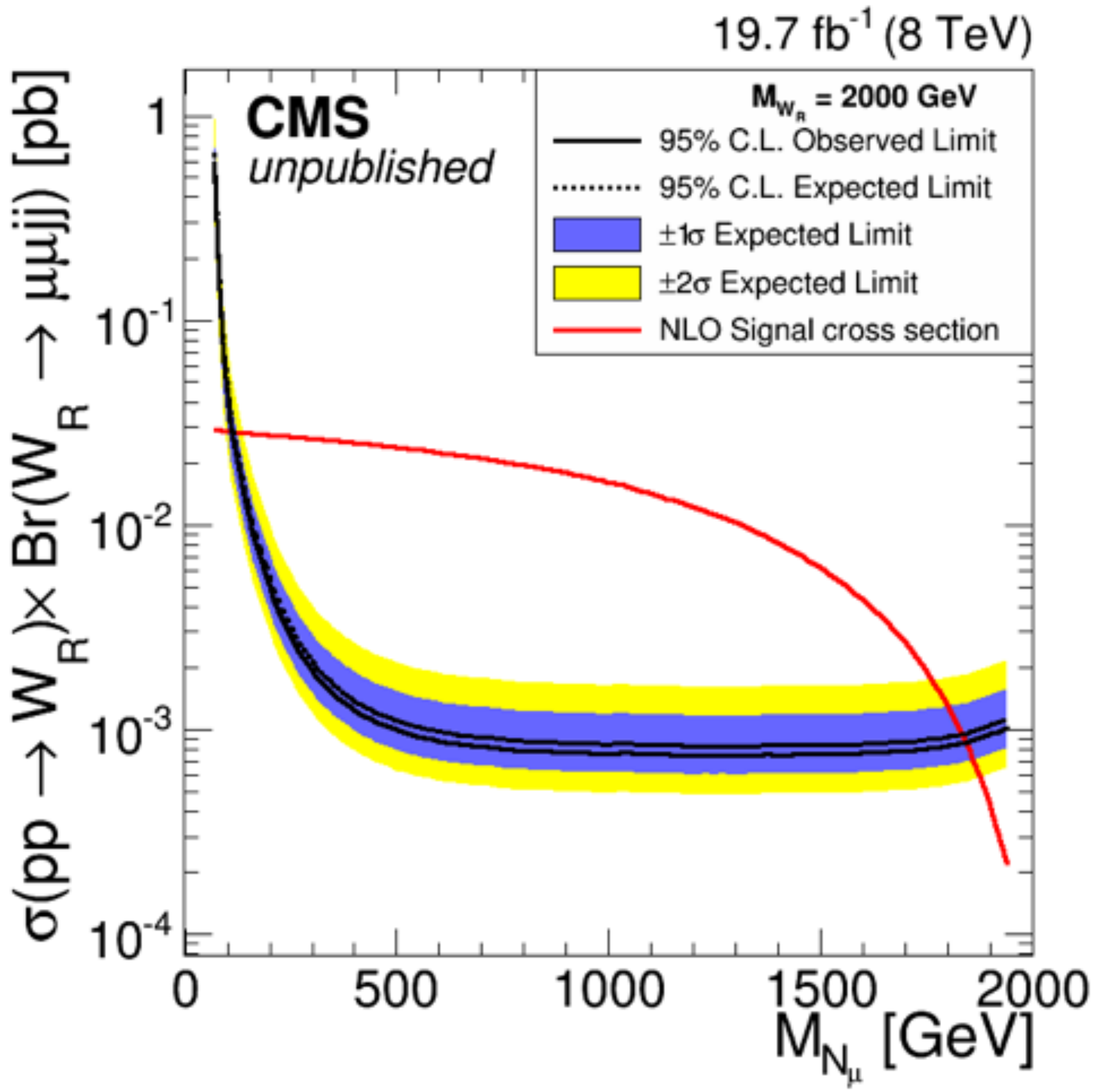


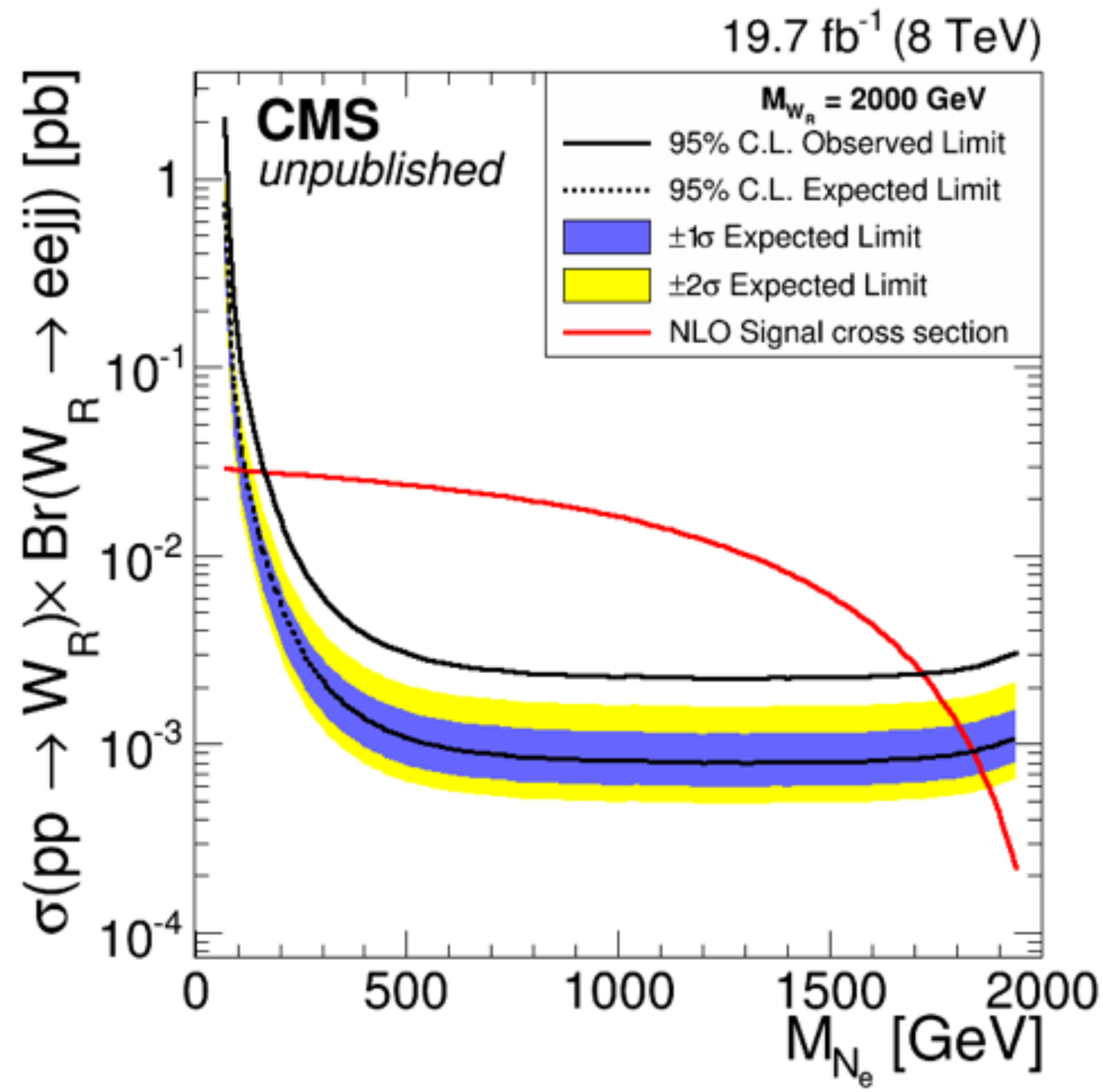




EXO-14-001

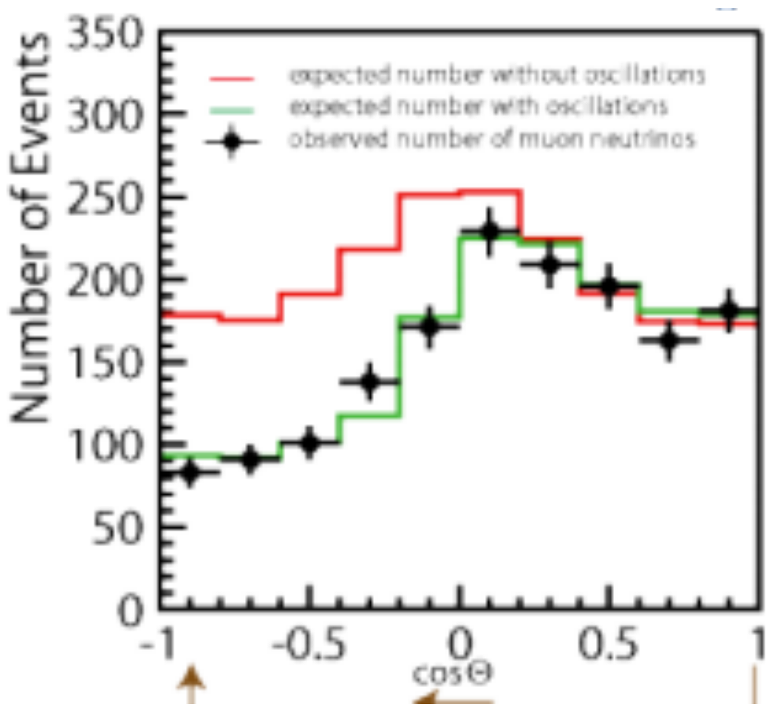
Additional plots for LRSM EXO-13-008

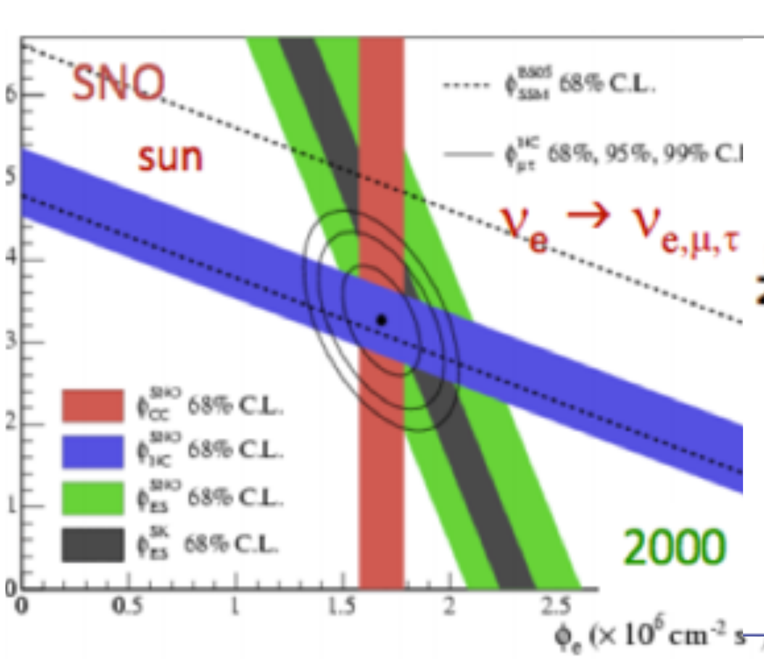


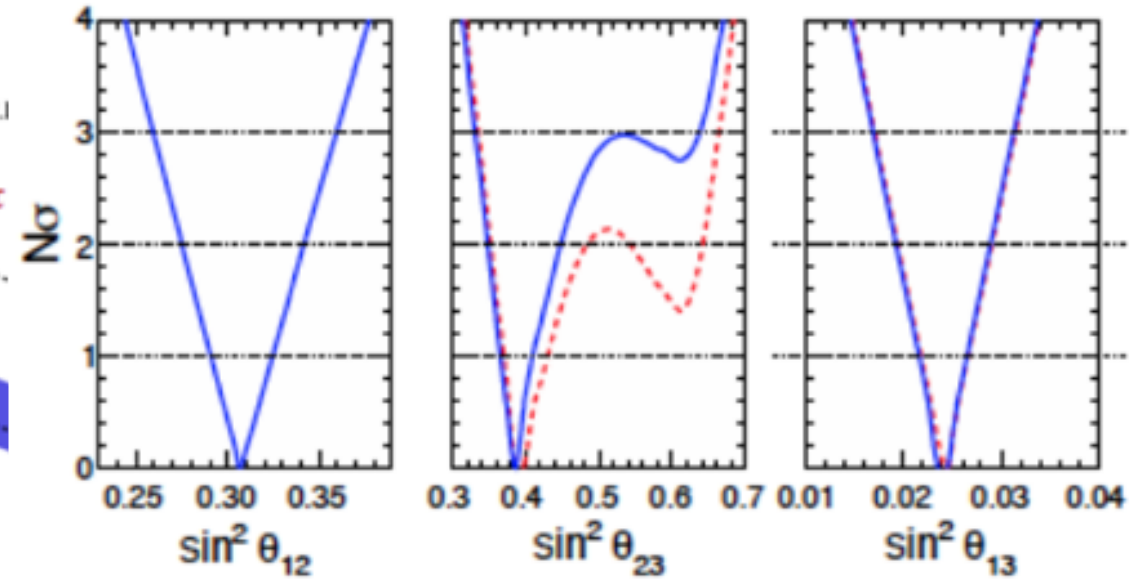


EXO-13-008

Why Look For Heavy Neutrinos?







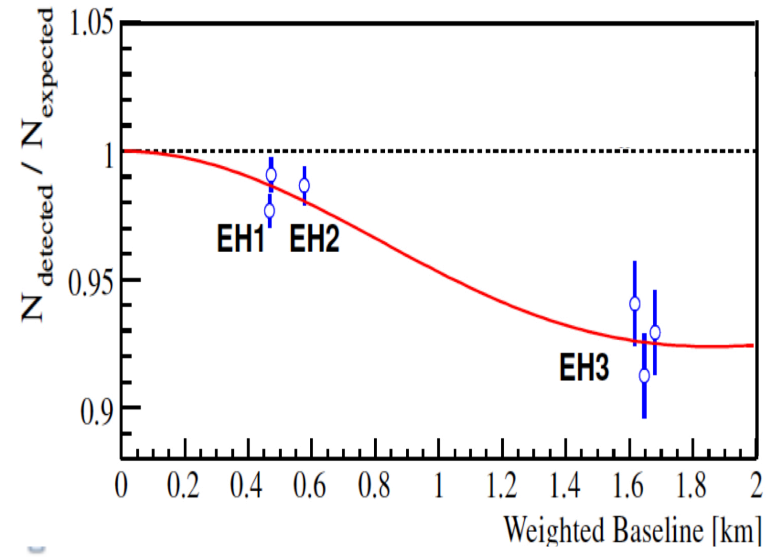
- Small neutrino mass -> heavy neutrino (NR) by "SeeSaw"

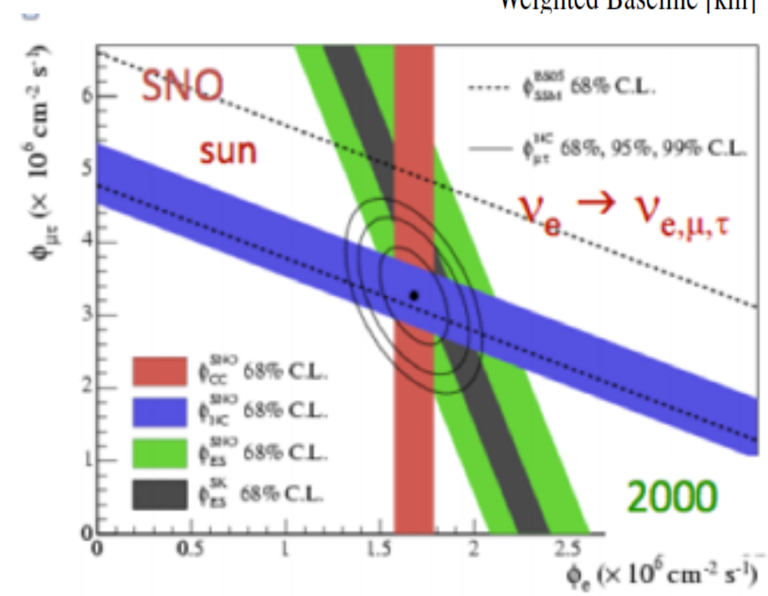
- Type 1: weak-singlet fermion (N)
  EXO-12-057 EXO-14-014
- Left-Right Symmetric Model (LRSM): $SU(2)_R$ symmetry to the SM: N, W_R, Z'
  EXO-13-008
- Type 3 : weak-triplet fermion ($\Sigma^0\Sigma^{+/-}$)
  EXO-14-001

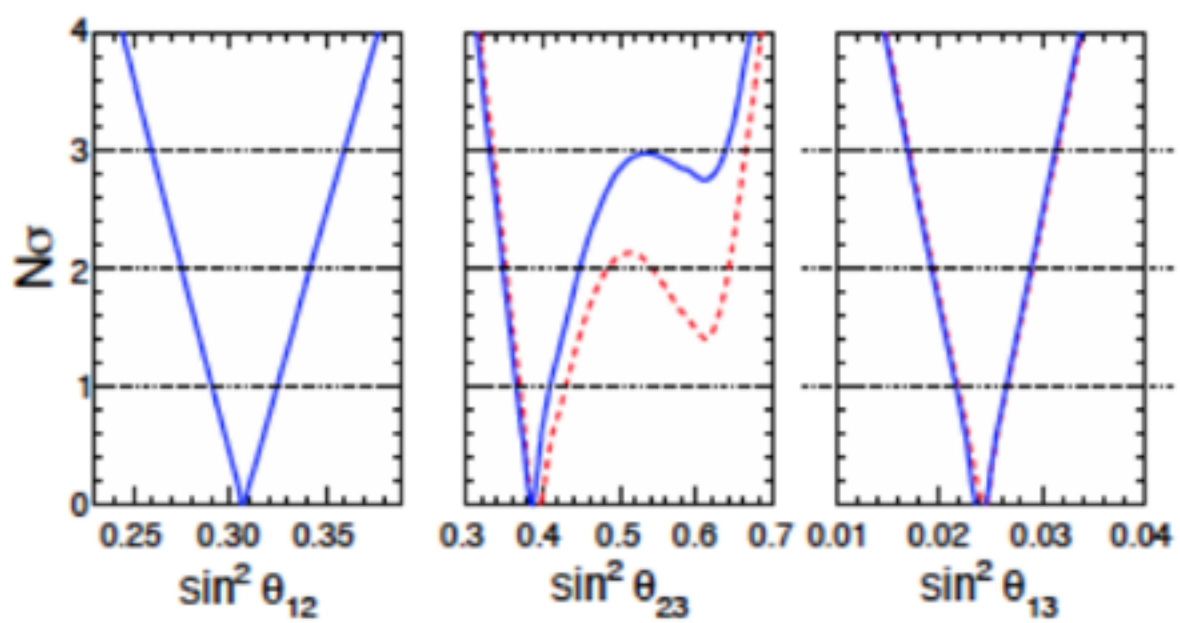
Type 3 In Back Up slides

Why Look For Heavy Neutrinos?

- Neutrinos oscillate between all three flavours.
    - At least two massive neutrinos
- First conclusive experimental evidence for BSM physics.
- Sum of light neutrino masses < 0.3 eV from cosmology.
- Small neutrino mass can be naturally explained by the SeaSaw mechanism with heavy Majorana neutrinos.
- Heavy neutrinos can also provide a Dark Matter candidate.







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