Searches for Heavy Neutrinos at CMS

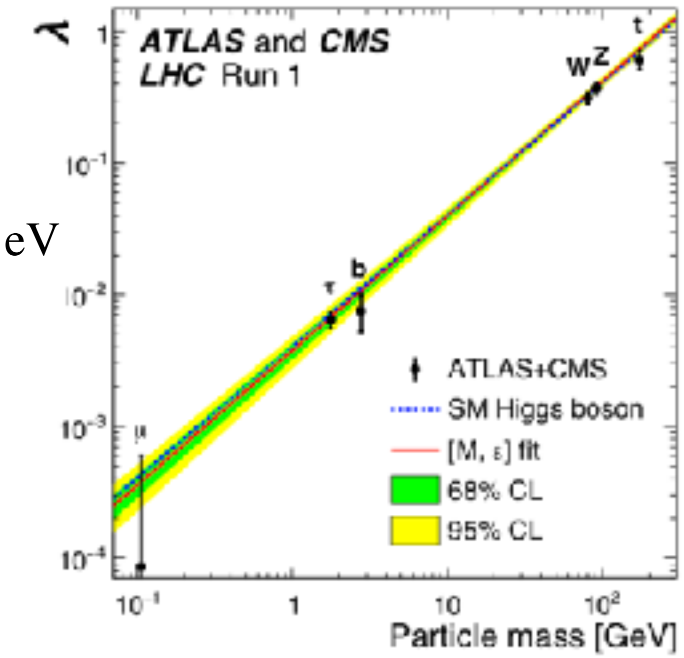
John Almond (Seoul National University) On behalf of CMS Collaboration

7th July, Neutrino Physics session

39th International Conference on **High Energy** Physics, July 4-11

Why look for heavy neutrinos?

10.1007/JHEP08(2016)045



- **Neutrino oscillations:** Standard Model (SM) neutrino masses are non-zero
  - First observed by Super K **1998** and SNO **2001** Collaborations
  - Most recently by the OPERA collaboration (10.1103/PhysRevLett.120.211801)
- **… but, very small**: In line with observations in cosmology and meson decays -> $\mathrm{m}_\nu \lesssim \mathrm{O\,eV}$
- If a right handed (RH) neutrino is postulated:
  - m_ν can have a Dirac mass (accommodated in SM via EWSB).

$$\lambda_\nu \lesssim 10^{-12} \quad \text{vs} \quad \lambda_e \sim 10^{-6}$$

→ possible but not very satisfying!

  - OR can add a Majorana mass term ($\mathrm{m_N}$), small neutrino masses naturally explained by the **Seesaw mechanism**: $\mathrm{m}_\nu \simeq \mathrm{m}^2_{\mathrm{Dirac}}/\mathrm{m_N}$
- Three types of seesaw models, this talk will discuss CMS Type-I and Type-III searches.
  - expect new **heavy Majorana** neutrino(s) than can be probed at LHC.
  - not only address neutrino masses, but can also provide DM candidates, help leptogenesis,…

Model	New Particles	Search Signature	Latest Results	
Type-I	Weak-singlet fermion (N)	Same-sign dilepton (SS2l)	**CMS-EXO-17-028** https://arxiv.org/abs/1806.10905	**13 TeV, 2016 data**
		Trilepton	**CMS-EXO-17-012** **10.1103/Phys.Rev.Lett.120.221801**	**13 TeV, 2016 data**
Type-III	Weak-triplet fermion $\Sigma^{0,\pm}$	Multileptons	**CMS-EXO-17-006** **10.1103/PhysRevLett.119.221802**	**13 TeV, 2016 data**

New!

Backgrounds in Seesaw searches: SS2l/3/4 lepton events

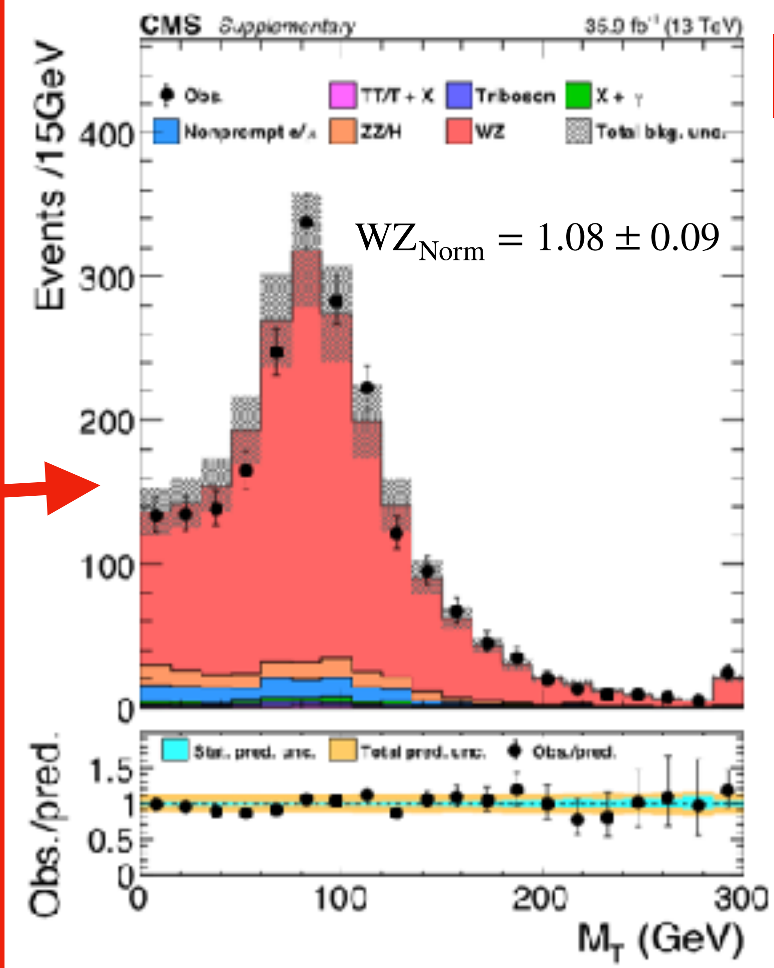
- All CMS seesaw searches probe events with either same-sign 2lepton (SS2l), 3 or 4+ charged leptons.
- These are split into three categories of backgrounds:

1) Irreducible "prompt" backgrounds

$$WZ/\gamma^* \rightarrow 3\ell\nu$$
$$ZZ/\gamma^* \rightarrow 4\ell$$
$$Z/\gamma^* \text{ or } t\bar{t} \rightarrow 2\ell \text{ (+FSR)}$$

Contaminates SS2l if leptons are missing

- **From MC (usually $\geq$ NLO precision)**
- Major bkg **normalized to data** in dedicated control regions (see top right box).



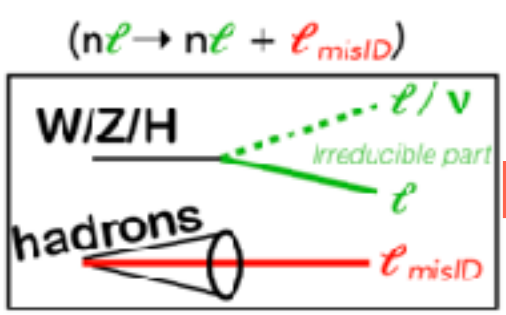
CMS-EXO-17-012

WZ/γ^* CR

- 3 leptons
- $50 < P_T^{miss}$
- $M_{OSSF} \approx M_Z$**

** Mass requirement surpasses signal contamination

2) "Non-Prompt" backgrounds with misidentified leptons



$$Z/\gamma^* \rightarrow 2\ell + \ell_{\text{misID}}$$
$$t\bar{t} \rightarrow 2\ell + \ell_{\text{misID}}$$
$$W^{\pm} \rightarrow \ell^{\pm}\nu_{\ell} + \ell_{\text{misID}}$$

- Backgrounds due to misidentified leptons, mostly b-hadron decays or EM & Jets misreconstruced as a lepton
- **Estimated using data only.**
- Dominant in events with soft leptons.

3) "Prompt" backgrounds with mismeasured sign

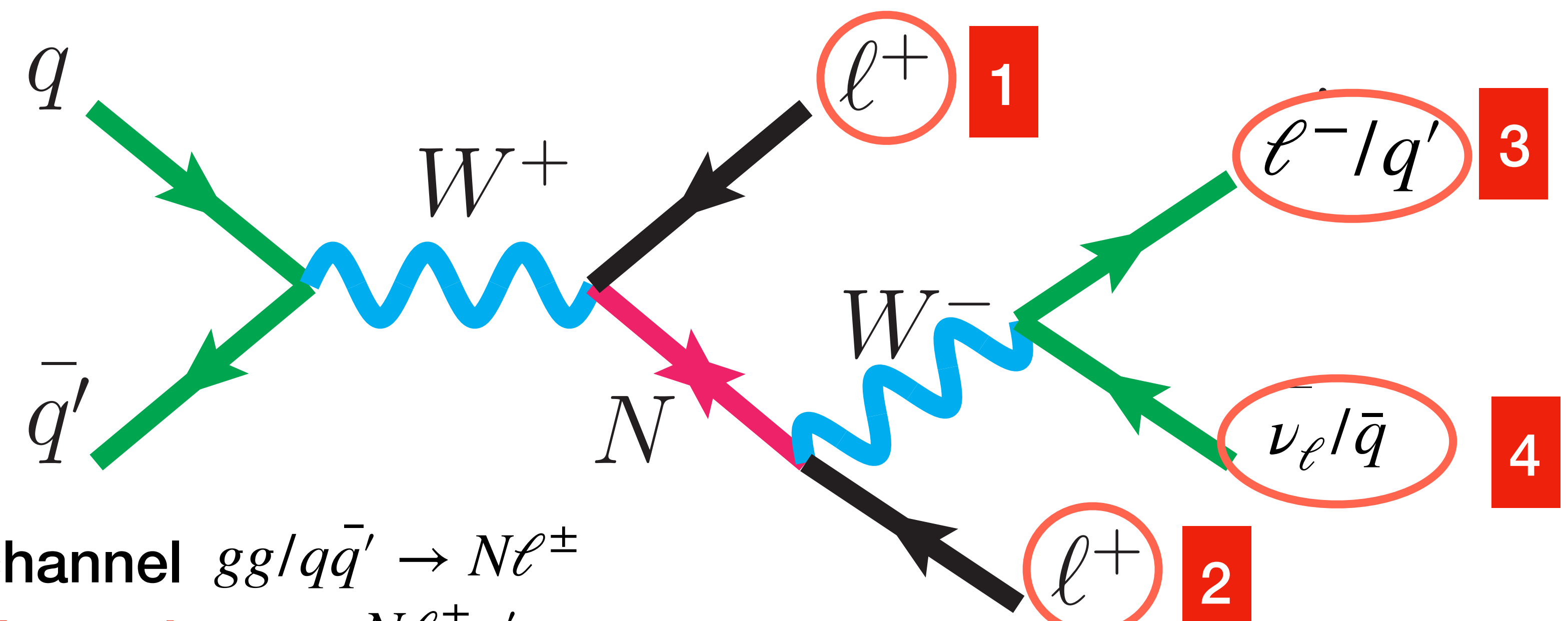
$$Z/\gamma^* \rightarrow e^{\pm}_{\text{truth}} e^{\mp}_{\text{truth}} \rightarrow e^{\pm}_{\text{reco}} e^{\pm}_{\text{reco}} \text{ (SS2e)}$$

- Considered exclusively in electron channel.
- **Studied in data and MC.**
- Only relevant in 2_{SS} events .

Type-I seesaw: Searches at CMS

CMS-EXO-17-012
CMS-EXO-17-028
[1] 10.1103/Phys.Rev.Lett.112.081801

- Search for a neutrino (N) in **νMSM**, N is produced via mixing with SM neutrinos.
  - Consider s- and **t-channel** [1] (new to 2016 analysis) production modes .
  - Production cross-section and N lifetime depend on mass & mixing $|V_{\ell N}|^2$



s-channel $gg/q\bar{q}' \to N\ell^\pm$

t-channel $q\gamma \to N\ell^\pm q'$

- CMS probes N masses 1-1600 GeV
- Analyses needs to consider change in signal characteristics for different mass regimes (see table).
- Analysis split into two regions
  - $m_N \leq m_W$: low-mass
  - $m_N > m_W$: **high-mass**

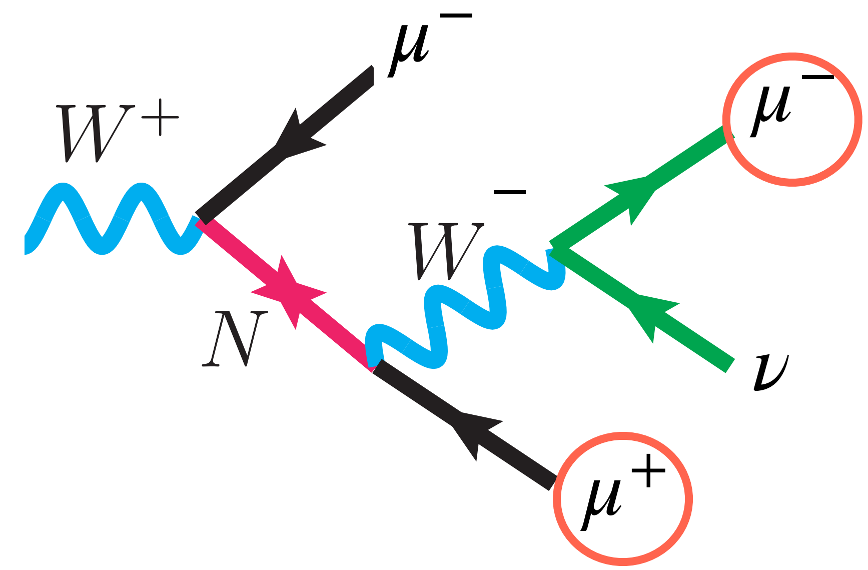
Mass region (GeV)	$W_{propagator}$	W_N	Decay Kinematics	Signal characteristics	Dominant Mode	
$m_N < 20$	On-shell	Off-shell	Soft & displaced #2,3,4	**Long-lived N**, displaced decay products	s-channel	low-mass
$20 < m_N < m_W$	On-shell	Off-shell	Low p_T #2	M(1+2+3+4) ~ m_W	s-channel	
$m_N \lessapprox m_W$	On-shell	Off-shell	Low p_T #1,2	Compressed p_T spectra	s-channel	
$m_W < m_N \lesssim 600$	Off-shell	On-shell	Low p_T #1, high p_T #2	M(2+3+4) ~ m_W	s-channel	**high-mass**
$m_N \gtrsim 600$	Off-shell	On-shell	**Boosted #3,4**	Merged W decay produce	**t-channel**	

10.1103/Phys.Rev.Lett.120.221801

Type-I seesaw: Trilepton channels

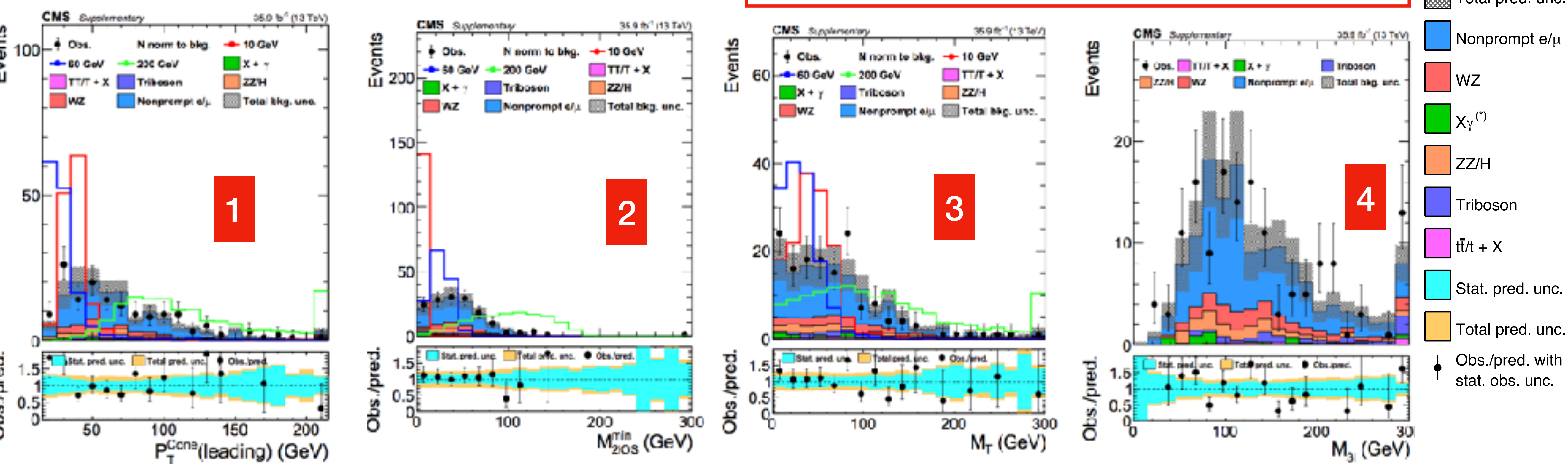
- Looks at final states with 3 leptons in a mass range $1 < m_N < 1200$ GeV.
  - Probes $|V_{eN}|^2$ and $|V_{\mu N}|^2$ in (**eee**,**eeμ**,**eμμ**,**μμμ**) events.
- Use combination of 1/2/3 lepton triggers allows sensitivity in range $m_N << m_W$.
  - p_T > 25-15 (leading lep.), 15-10 (second lep.), 10-5 GeV (trailing lep):

    p_T^{min} (e) = 10 GeV, p_T^{min} (μ) = 5 GeV
- No N mass peak-> SM neutrino decay from W: discriminate signal.
  1. leading lepton p_T,
  2. M_{2lOS}^{min}, minimum mass of opposite-sign lepton pairs.
  3. M_T (using lepton not used in M_{2lOS}^{min}).
  4. M_{3l} to discriminate signal.



Baseline signal selection :

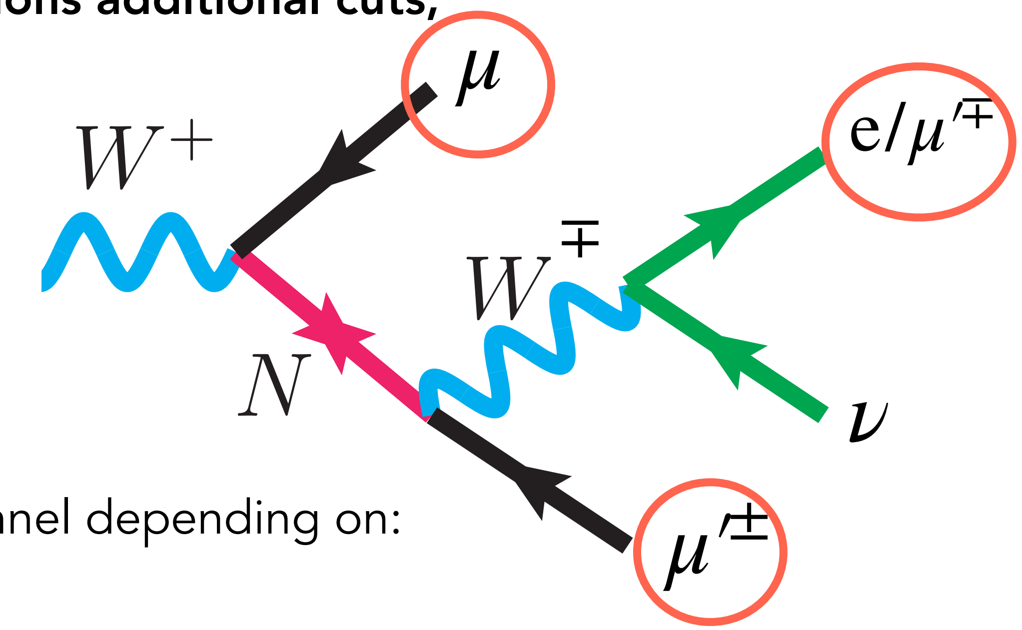
- At least one opposite-sign lepton pair.
- No b-jet in event. (Suppress top bkgd.)



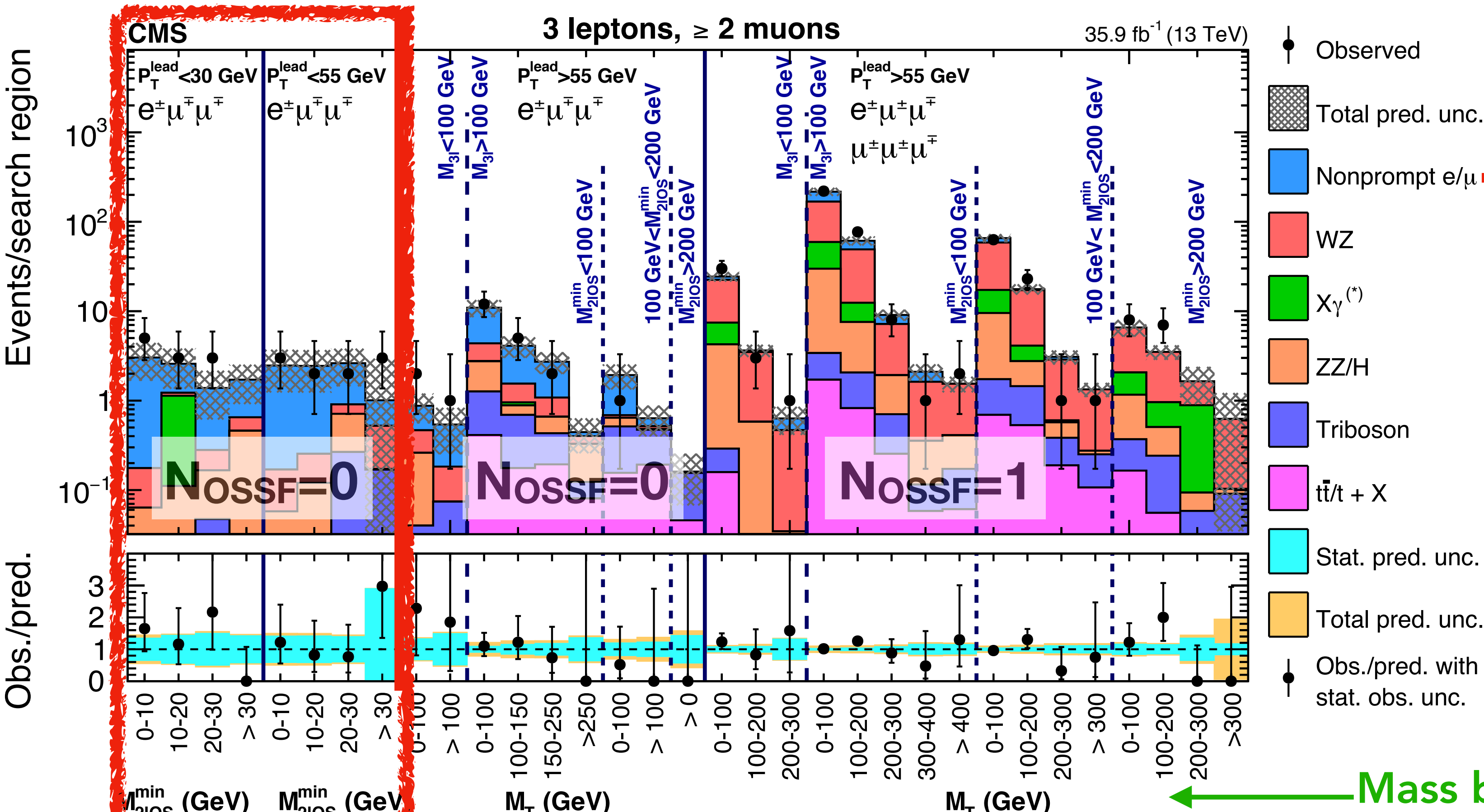
Type-I seesaw: Trilepton channel Search regions ($|V_{\mu N}|^2$)

*all units are GeV $|V_{\mu N}|^2$ →		$N_{OSSF}=0$ eμμ	$N_{OSSF}=1$ μμμ, eμμ
Low-mass $m_N < m_W$	Leading $p_T < 55$	$M_{3\ell} < 80$ $p_T^{miss} < 75$	⊗
High-mass $m_N > m_W$	Leading $p_T > 55$	—	$M_{2\ell OS}^{min} > 5$ $|M_{\ell\ell}(M_{\ell\ell\ell}) - M_Z| > 15$

Search regions additional cuts;



>> **33 orthogonal search bins** (8 low-mass, 25 high-mass) per lepton channel depending on: N_{OSSF} pairs, and 4 discriminant variables



Nonprompt e/μ → Dominant in $N_{OSSF}=0$

← Mass bins

Further Details:

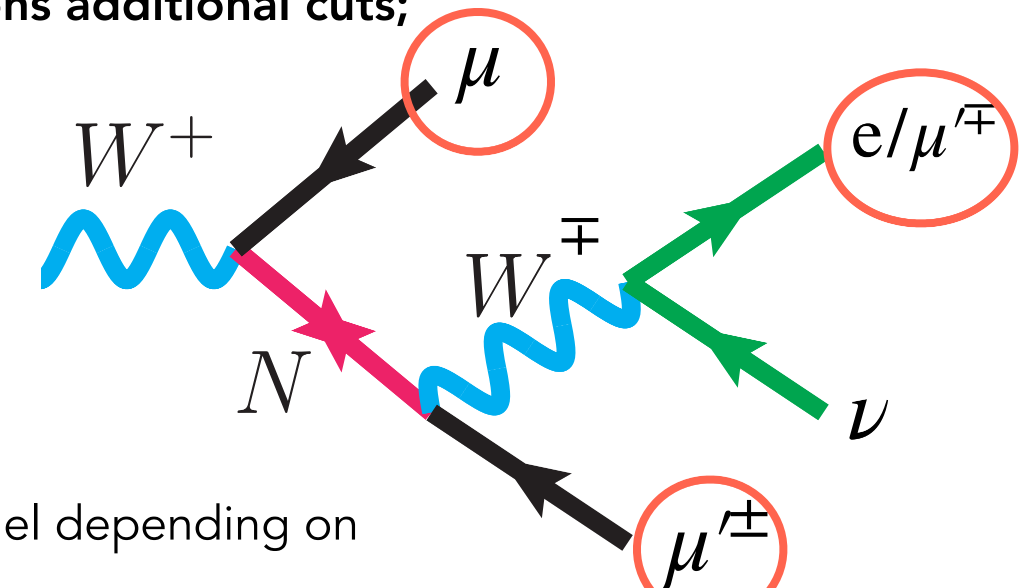
- Assume $|V_{eN}|$ is zero.
- This selection probes $|V_{\mu N}|^2$.
- Dominant systematic uncertainty from non-prompt lepton background (30%)

Type-I seesaw: Trilepton channel Search regions ($|V_{\mu N}|^2$)

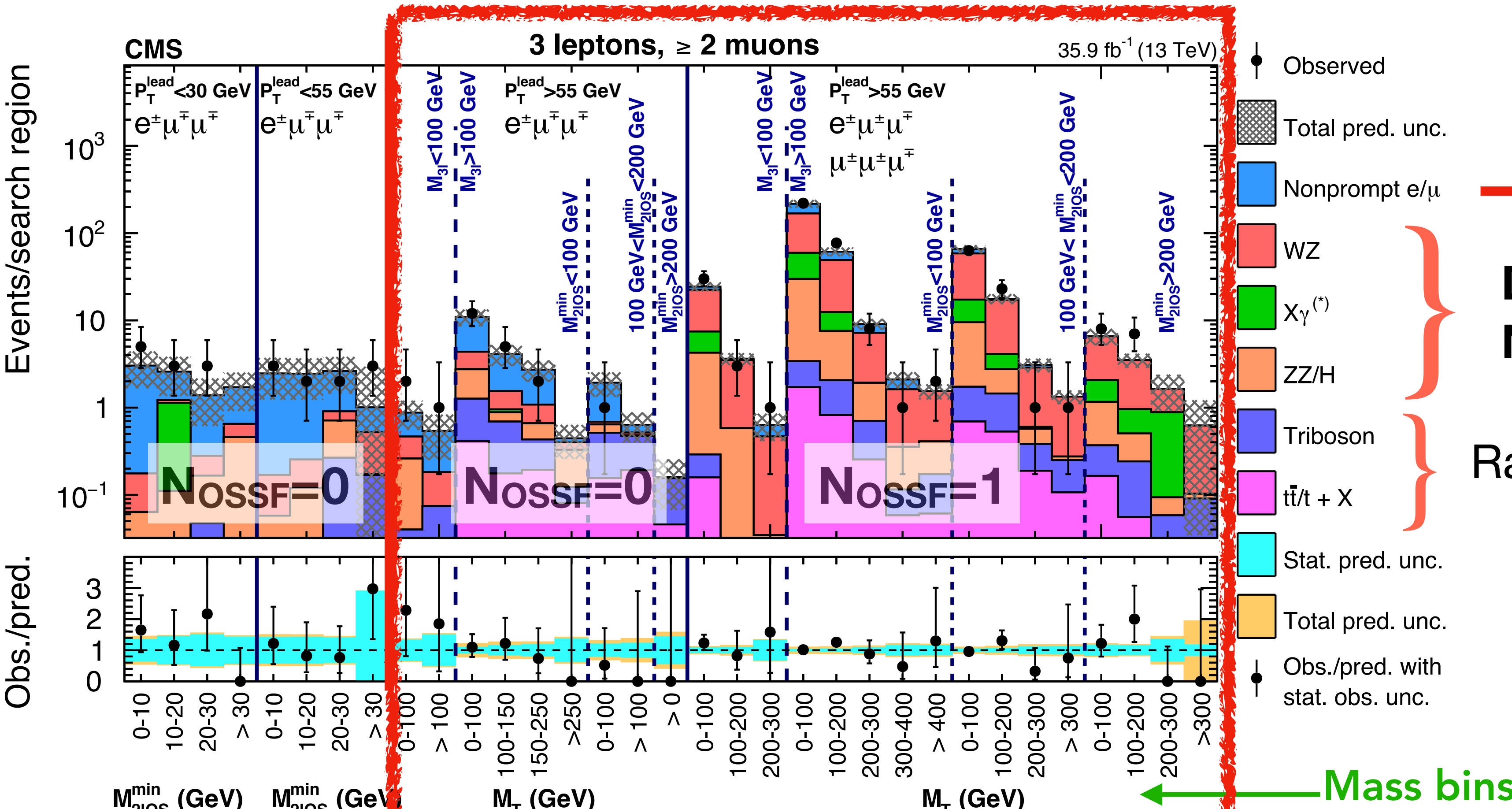
*all units are GeV

$|V_{\mu N}|^2$ →		$N_{OSSF}=0$ eμμ	$N_{OSSF}=1$ μμμ, eμμ
Low-mass $m_N < m_W$	Leading $p_T < 55$	$M_{3\ell} < 80$, $p_T^{miss} < 75$	⊗
High-mass $m_N > m_W$	Leading $p_T > 55$	—	$M_{2\ell OS}^{min} > 5$, $|M_{\ell\ell}(M_{\ell\ell\ell}) - M_Z| > 15$

Search regions additional cuts;



>> **33 orthogonal search bins** (8 low-mass, 25 high-mass) per lepton channel depending on N_{OSSF} pairs, and 4 discriminant variables



→ **Dominant in $N_{OSSF}=0$**

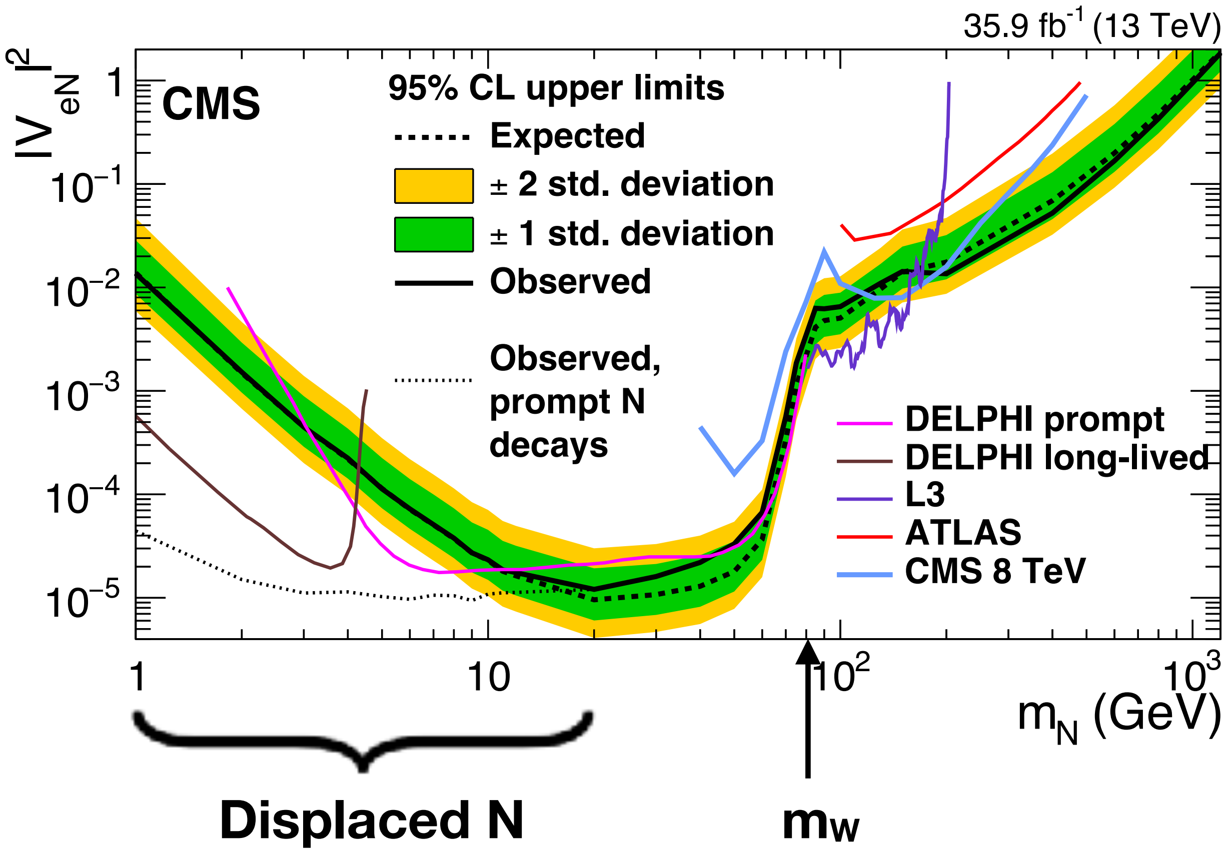
Dominant in $N_{OSSF}=1$

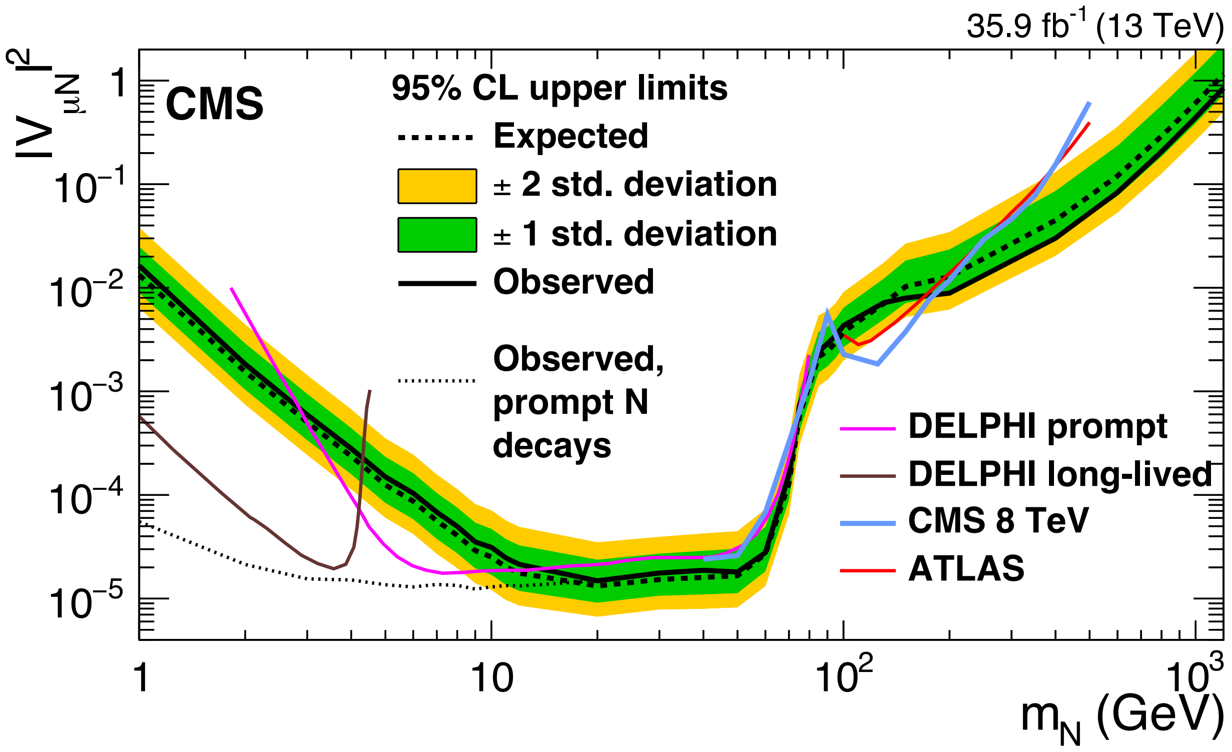
Rare processes

Further Details:

- Assume $|V_{eN}|$ is zero.
- This selection probes $|V_{\mu N}|^2$.
- eμμ is most sensitive.

Type-I seesaw: Trilepton results ($|V_{lN}|^2$)





- No evidence of significant excess beyond SM background.
- Limits set on using asymptotic CLs criteria.
  - Simultaneous fit to all 33 signal regions are performed.
- Less sensitivity when N becomes displaced --> harder to select leptons.
- **First results in this channel at the LHC, and first in any channel below 40 GeV.**

CMS-EXO-17-012
10.1103/Phys.Rev.Lett.120.221801

Type-I seesaw: SS Dilepton channel

CMS-EXO-17-028
https://arxiv.org/abs/1806.10905

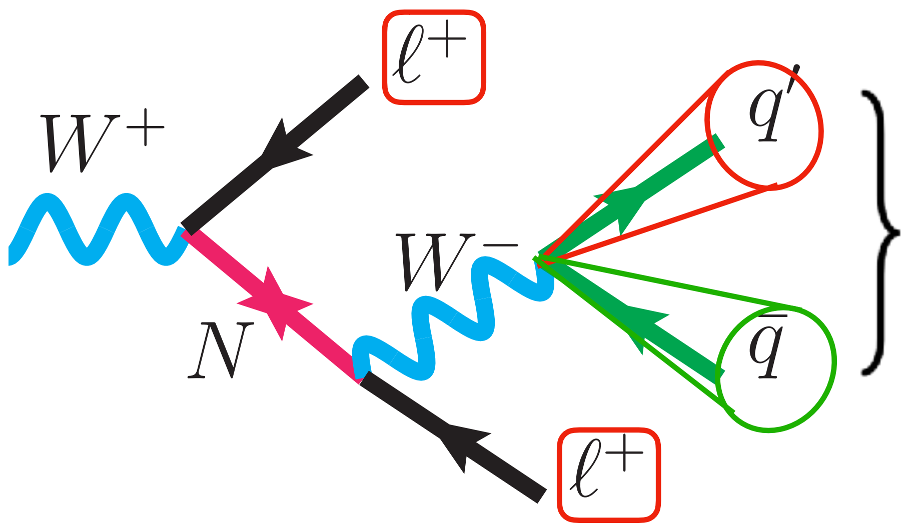
- Targets a N in the mass range 20-1600 GeV.
  - Mass of N < 20 GeV, no acceptance for reconstructing 2 leptons and a jet.

Signal Topology

- 2 same-sign leptons (effective way to suppress prompt backgrounds)

- 2 AK4 jets

- Uses dilepton triggers, cannot use low p_T requirements as trilepton searches :ee, μμ, eμ ($p_T^{leading} \geq 20$ $p_T^{trailing} \geq 15$)
- Use AK4 and AK8 jetT : AK4 $p_T \geq 20$, AK8 $p_T \geq 200$ (min p_T cuts available; no low p_T jet trigger available)



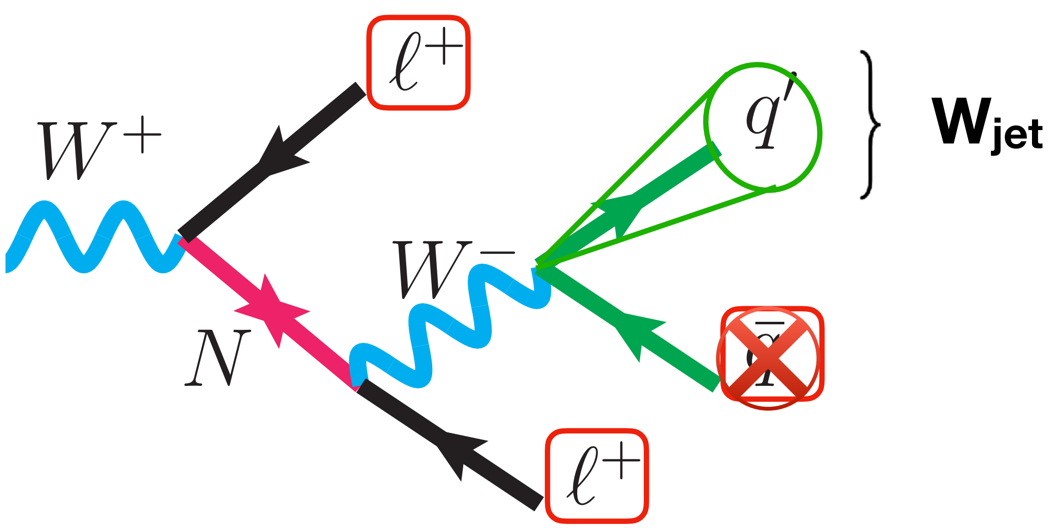
W_{jet}

Low-mass	$m_N < m_W$
High-mass	$m_N > m_W$

- Can reconstruct N when correct jets are selected.
- Can have OS2l (N=Majorana) signal events, but more bkg.

Type-I seesaw: SS Dilepton channel SRs

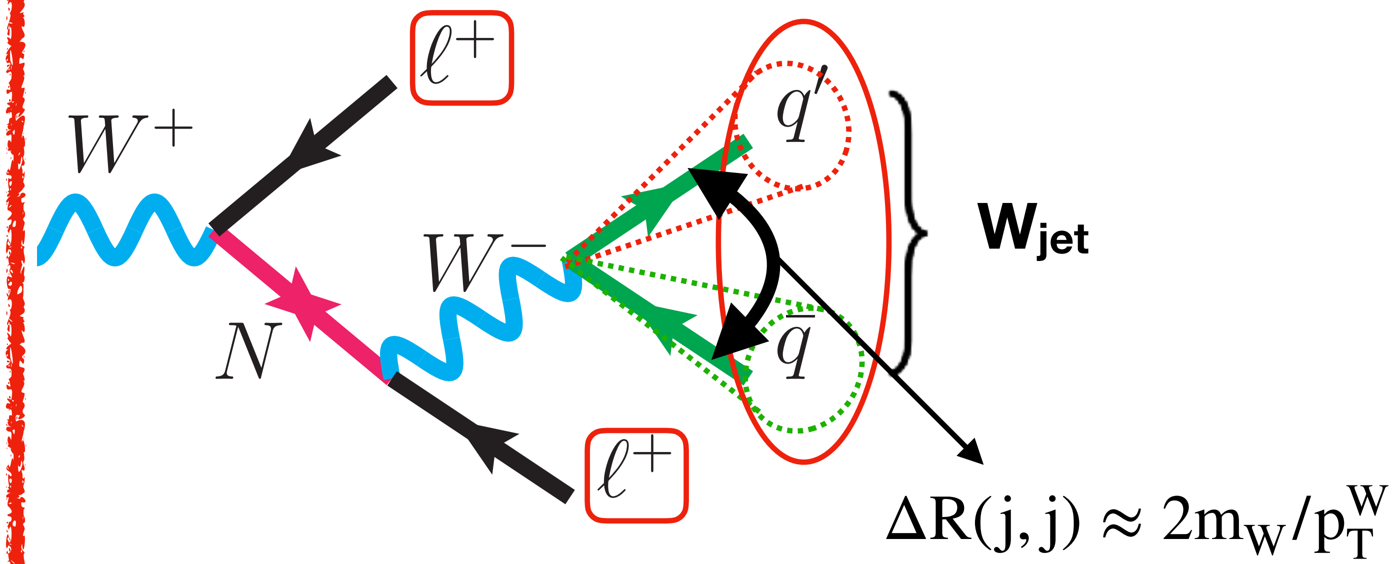
Low-mass $m_N < m_W$



Recover events when soft jets from W are not selected (mainly due to jet p_T).

Low-Mass SR2: SS2l + 1 AK4 jet

High-mass $m_N > m_W$



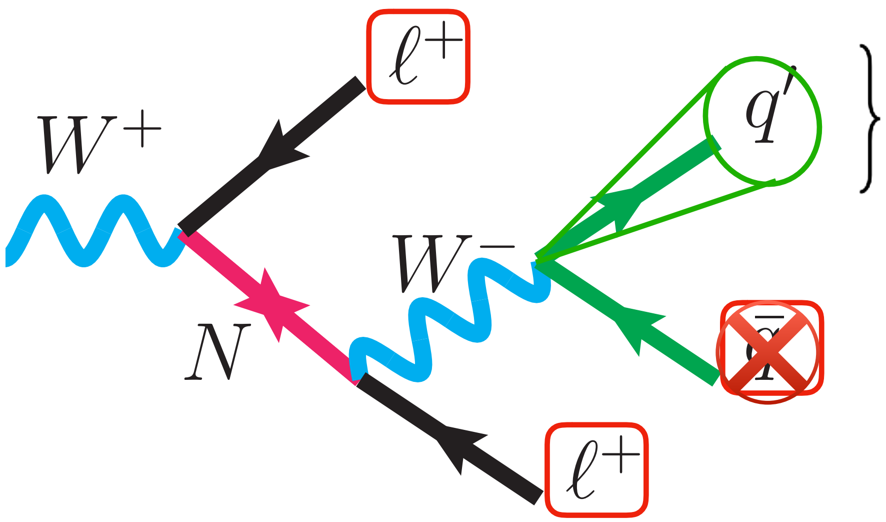
Recover events when jets from W are merged. Use wide jet+jet substructure.

High-Mass SR2: SS2l + 1 AK8 jet

Signal Region	N masses	Jet kinematics	SS2l	N_{AK4}	N_{AK8}
Low-mass SR1	$20 < m_N < m_W$	2 soft resolved jets	✓	≥ 2	0
Low-mass SR2		2 soft jets (1 jet lost)	✓	$= 1$	0
High-mass SR1	$m_W < m_N < 1600$	2 resolved jets	✓	≥ 2	0
High-mass SR2		2 merged jets (1 "fat" jet)	✓	≥ 0	≥ 1

Type-I seesaw: SS Dilepton channel SR2

Low-mass $m_N < m_W$



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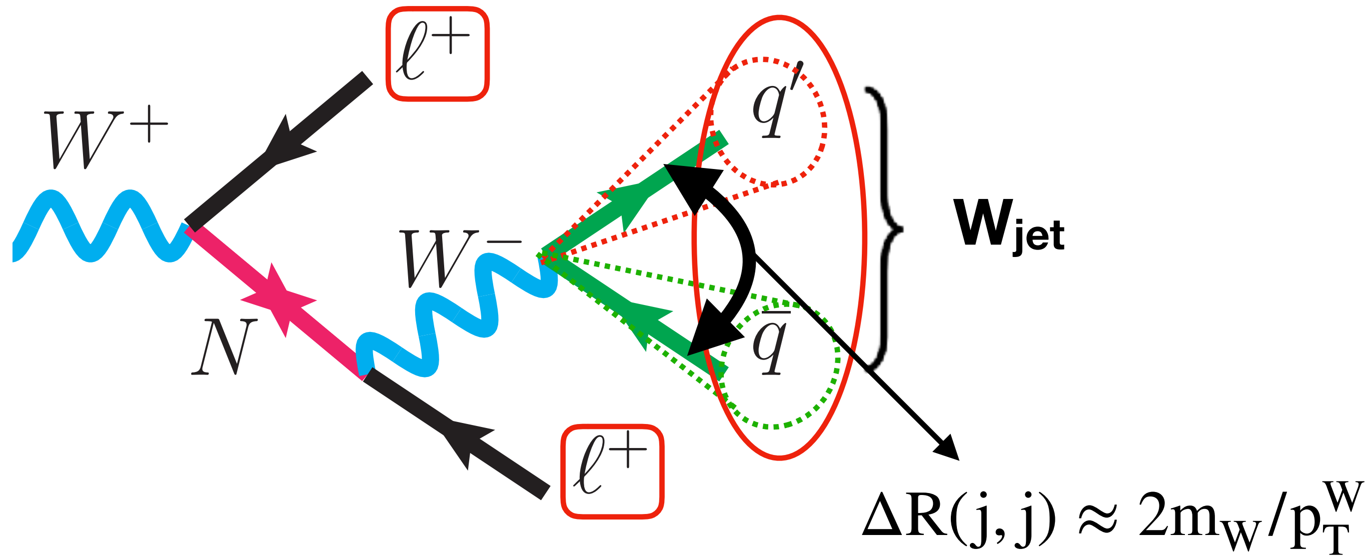
Low-Mass SR2: SS2l + 1 AK4 jet

High-mass $m_N > m_W$

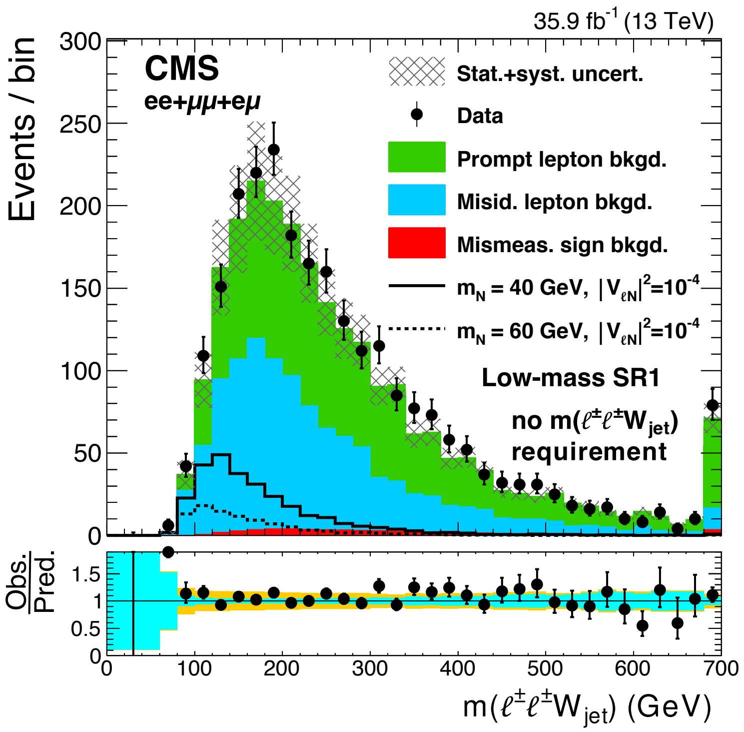


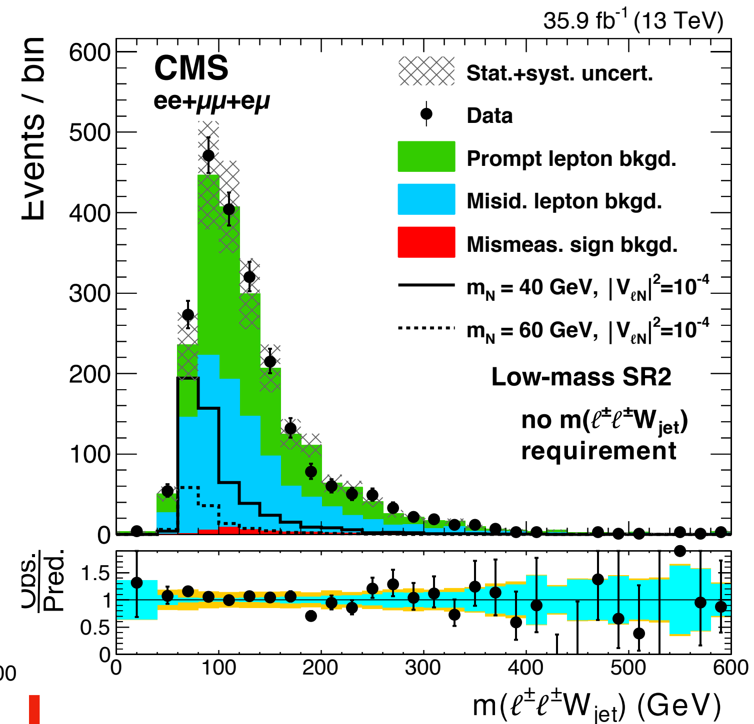
Recover events when jets from W are merged. Use wide jet+jet substructure.

High-Mass SR2: SS2l + 1 AK8 jet

Signal Region	N masses	Jet kinematics	SS2l	N_{AK4}	N_{AK8}
Low-mass SR1	$20 < m_N < m_W$	2 soft resolved jets	✓	≥ 2	0
Low-mass SR2		2 soft jets (1 jet lost)	✓	$= 1$	0
High-mass SR1	$m_W < m_N < 1600$	2 resolved jets	✓	≥ 2	0
High-mass SR2		2 merged jets (1 "fat" jet)	✓	≥ 0	≥ 1

Type-I seesaw: SS2l channel Search Regions





Require baseline selection

Region	p_T^{miss} (GeV)	$(p_T^{miss})^2/S_T$ (GeV)	$m(\ell^\pm\ell^\pm W_{jet})$ (GeV)	$m(W_{jet})$ (GeV)	p_T^j (GeV)
Low-mass SR1+SR2	<80	—	<300	—	>20
~~High-mass SR1~~		~~<15~~	~~—~~	~~30–150~~	~~>25~~
~~High-mass SR2~~		~~<15~~		~~40–130~~	~~>200~~

Low-mass $m_N < m_W$

- Large irreducible background with ℓ_{misid}.
- m(ll+jets) should peak at m_W.

Optimize signal per mass hypothesis*:

- lepton p_T
- **m(ll+jets)**, m(l+jets) ,m(ll)

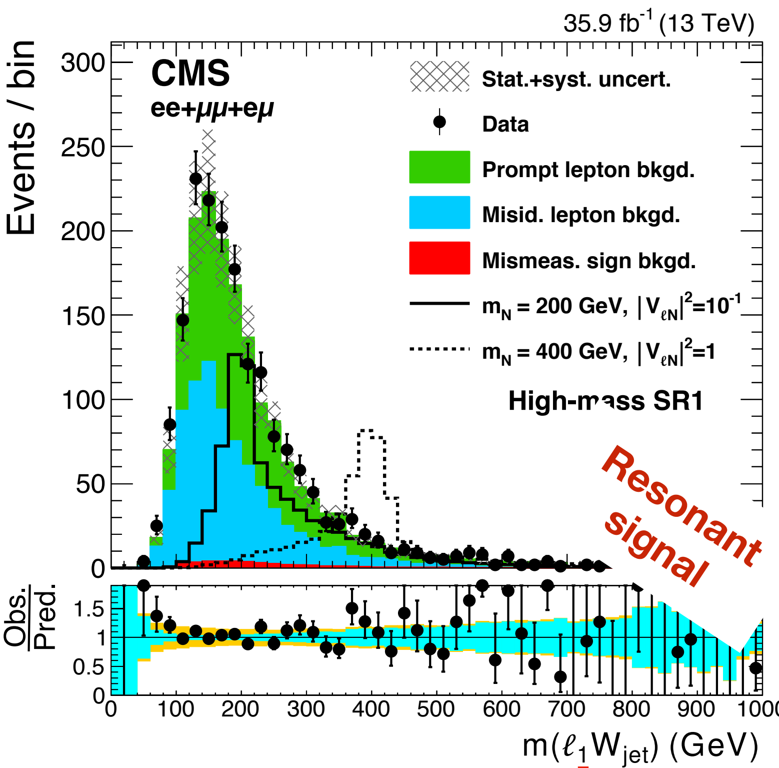
> Total: 7 masses* 2 (SRs) (per flavour channel)

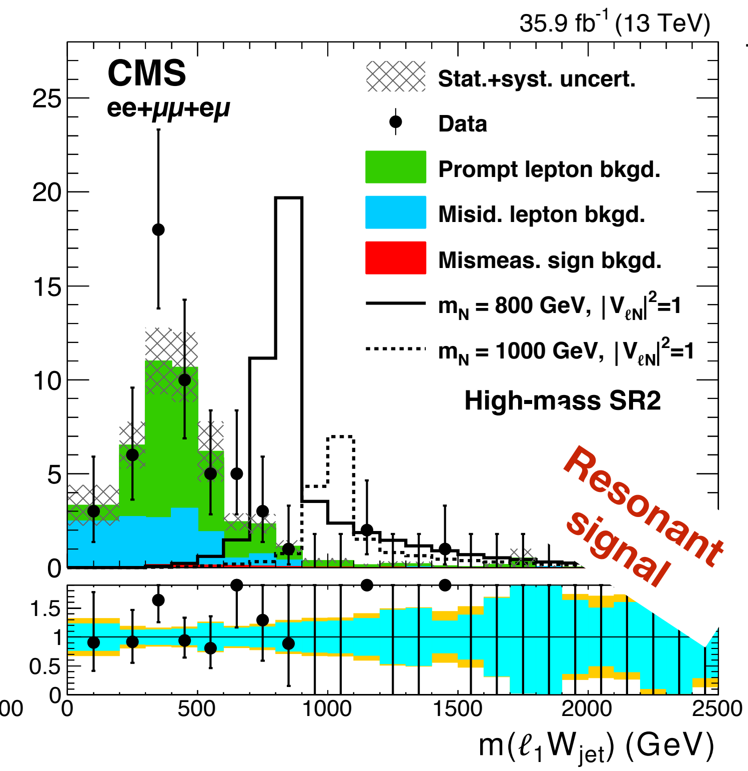
m_N (GeV)	$p_T^{\ell_1}$ (GeV)	$p_T^{\ell_2}$ (GeV)	$m(\ell^\pm\ell^\pm W_{jet})$ (GeV)	$m(\ell_1 W_{jet})$ (GeV)	$m(\ell_2 W_{jet})$ (GeV)	$m(\ell^\pm\ell^\pm)$ (GeV)	Total bkgd.	N_{obs}	DY $A\epsilon$ (%)
ee channel SR1									
20	25–70	60	<190	<160	<160	10–60	48.9 ± 9.5	45	0.12 ± 0.02
30	25–70	60	<190	<160	<160	10–60	48.9 ± 9.5	45	0.13 ± 0.02
40	25–70	60	<190	<160	<160	10–60	48.9 ± 9.5	45	0.21 ± 0.03
50	25–70	60	<190	<160	<160	10–60	48.9 ± 9.5	45	0.24 ± 0.03
60	25–70	60	<190	<160	<160	10–60	48.9 ± 9.5	45	0.18 ± 0.02
70	25–70	60	<190	<160	<160	10–75	64 ± 12	58	0.10 ± 0.01
75	25–70	60	<190	<160	<160	10–100	68 ± 12	67	0.13 ± 0.02
ee channel SR2									
20	25–70	60	<100	<70	<70	10–60	50.3 ± 8.5	55	0.26 ± 0.03
30	25–70	60	<100	<70	<70	10–60	50.3 ± 8.5	55	0.30 ± 0.04
40	25–70	60	<100	<70	<70	10–60	50.3 ± 8.5	55	0.35 ± 0.04
50	25–70	60	<100	<70	<70	10–60	50.3 ± 8.5	55	0.32 ± 0.03
60	25–70	60	<100	<70	<70	10–60	50.3 ± 8.5	55	0.24 ± 0.03
70	25–70	60	<100	<70	<70	10–75	65 ± 10	70	0.06 ± 0.01
75	25–70	60	<100	<70	<70	10–80	67 ± 10	70	0.11 ± 0.02

***Table for ee channel: See backup B5-B6 for full optimisation tables**

***See backup B5-B6 for optimisation tables**

Type-I seesaw: SS2l channel Search Regions





Require baseline selection

Region	p_T^{miss} (GeV)	$(p_T^{miss})^2/S_T$ (GeV)	$m(\ell^\pm\ell^\pm W_{jet})$ (GeV)	$m(W_{jet})$ (GeV)	p_T^j (GeV)
~~Low-mass SR1+SR2~~	~~<80~~	~~—~~	~~<300~~	~~—~~	~~>20~~
High-mass SR1	—	<15	—	30–150	>25
High-mass SR2	—	<15	—	40–130	>200

High-mass $m_N > m_W$

- m(l+jets) should peak at m_W.
- Low-background in SR2 (merged jets events)

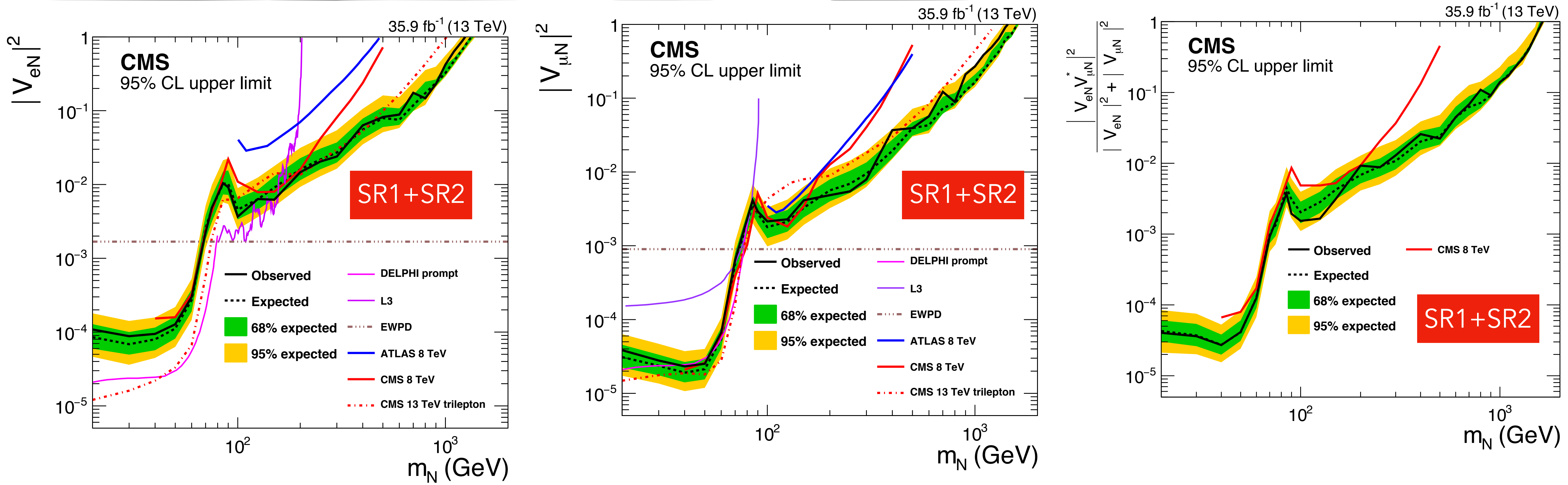
Optimize signal per mass hypothesis*:

- lepton p_T
- m(ll+jets)
- **m(l+jets) window cut**

m_N (GeV)	$p_T^{\ell_1}$ (GeV)	$p_T^{\ell_2}$ (GeV)	$m(\ell^\pm\ell^\pm W_{jet})$ (GeV)	$m(\ell W_{jet})$ (GeV)	$(p_T^{miss})^2/S_T$ (GeV)	Total bkgd.	N_{obs}	DY $A\epsilon$ (%)	VBF $A\epsilon$ (%)
$\mu\mu$ channel SR1									
85	>25	>10	>90	40–100	<9	26.0 ± 6.3	30	0.50 ± 0.05	—
90	>25	>10	>90	45–105	<9	34.5 ± 7.5	35	1.2 ± 0.1	—
100	>25	>15	>110	55–115	<9	18.6 ± 4.2	20	2.6 ± 0.2	—
125	>25	>25	>140	85–140	<7	11.7 ± 2.7	12	5.1 ± 0.4	—
150	>35	>35	>150	110–170	<7	8.9 ± 1.9	11	6.6 ± 0.5	—
200	>50	>40	>250	160–215	<7	4.6 ± 1.2	4	8.1 ± 0.6	—
250	>85	>45	>310	215–270	<7	3.0 ± 0.9	2	11.0 ± 0.8	—
300	>100	>50	>370	225–340	<7	2.6 ± 1.0	2	13.2 ± 0.9	5.2 ± 0.4
400	>110	>60	>490	295–490	<7	0.9 ± 0.4	3	11.7 ± 0.8	5.1 ± 0.4
500	>110	>60	>610	370–550	<7	$0.4^{+0.6}_{-0.4}$	3	8.6 ± 0.6	4.1 ± 0.3
600	>110	—	>680	370–630	<7	$0.3^{+0.3}_{-0.3}$	3	7.4 ± 0.5	4.1 ± 0.3
700	>110	—	>800	370–885	<7	$0.2^{+0.4}_{-0.2}$	2	6.7 ± 0.4	3.9 ± 0.3
800	>110	—	>800	370–890	<7	$0.2^{+0.4}_{-0.2}$	2	6.0 ± 0.4	5.4 ± 0.3
900	>110	—	>800	370–1225	<7	$0.3^{+0.4}_{-0.3}$	2	5.4 ± 0.4	5.0 ± 0.3
1000	>110	—	>800	370–1230	<7	$0.3^{+0.4}_{-0.3}$	2	4.6 ± 0.3	4.2 ± 0.3
1100	>110	—	>800	370–1245	<7	$0.3^{+0.4}_{-0.3}$	2	4.1 ± 0.3	3.8 ± 0.3
1200	>110	—	>800	370–1690	<7	$0.3^{+0.4}_{-0.3}$	2	3.6 ± 0.2	3.4 ± 0.3
1300	>110	—	>800	370–1890	<7	$0.3^{+0.4}_{-0.3}$	2	3.2 ± 0.2	3.0 ± 0.2
1400	>110	—	>800	370–1940	<7	$0.3^{+0.4}_{-0.3}$	2	2.7 ± 0.2	2.7 ± 0.2
1500	>110	—	>800	370–2220	<7	$0.3^{+0.4}_{-0.3}$	2	2.5 ± 0.2	2.3 ± 0.2

m_N (GeV)	$p_T^{\ell_1}$ (GeV)	$p_T^{\ell_2}$ (GeV)	$m(\ell^\pm\ell^\pm W_{jet})$ (GeV)	$m(\ell W_{jet})$ (GeV)	$(p_T^{miss})^2/S_T$ (GeV)	Total bkgd.	N_{obs}	DY $A\epsilon$ (%)	VBF $A\epsilon$ (%)
$\mu\mu$ channel SR2									
85	>25	>10	—	—	<15	11.4 ± 3.5	13	0.001 ± 0.001	—
90	>25	>10	—	90–170	<15	4.1 ± 1.3	4	0.003 ± 0.003	—
100	>25	>15	—	98–145	<15	1.0 ± 0.3	0	0.006 ± 0.003	—
125	>60	>15	—	110–150	<15	0.8 ± 0.3	0	0.08 ± 0.01	—
150	>70	>15	—	145–175	<15	1.0 ± 0.4	2	0.28 ± 0.04	—
200	>100	>20	—	175–235	<15	1.3 ± 0.8	0	1.4 ± 0.1	—
250	>140	>25	—	226–280	<15	0.3 ± 0.2	0	3.0 ± 0.3	—
300	>140	>40	—	280–340	<15	0.4 ± 0.3	0	5.4 ± 0.5	0.7 ± 0.1
400	>140	>65	—	340–445	<15	0.5 ± 0.3	2	13.3 ± 1.3	2.7 ± 0.3
500	>140	>65	—	445–560	<15	0.8 ± 0.5	0	22.4 ± 2.2	6.8 ± 0.7
600	>140	—	—	560–685	<15	0.7 ± 0.4	0	30.2 ± 2.9	20.4 ± 1.8
700	>140	—	—	635–825	<15	0.8 ± 0.4	2	34.6 ± 3.4	24.7 ± 2.2
800	>140	—	—	755–960	<15	0.4 ± 0.3	0	34.8 ± 3.5	24.9 ± 2.3
900	>140	—	—	840–1055	<15	$0.2^{+0.2}_{-0.2}$	1	35.8 ± 3.6	26.9 ± 2.5
1000	>140	—	—	900–1205	<15	$0.1^{+0.2}_{-0.1}$	1	38.4 ± 3.9	28.9 ± 2.7
1100	>140	—	—	990–1250	<15	$0.1^{+0.2}_{-0.1}$	1	36.7 ± 3.7	29.2 ± 2.7
1200	>140	—	—	1035–1430	<15	$0.2^{+0.3}_{-0.2}$	1	38.5 ± 4.0	30.1 ± 2.8
1300	>140	—	—	1100–1595	<15	0.3 ± 0.3	1	38.5 ± 4.0	30.7 ± 3.0
1400	>140	—	—	1285–1700	<15	$0.1^{+0.2}_{-0.1}$	1	35.9 ± 3.8	29.4 ± 2.8
1500	>140	—	—	[illegible]	<15	$0.1^{+0.2}_{-0.1}$	1	36.4 ± 3.9	30.0 ± 2.9

Type-I seesaw: SS Dilepton channel Results



- No significant excess above SM (largest deviation of 2.3σ local significance in SR1 μμ 600 GeV)
- Set upper limits combining SR1 and SR2, with cut and count using Full CLs method.
  - **Significant improvement** on sensitivity for high-mass compared to past SS2l searches.
  - First limits for masses above 1200 GeV.

Complimentary with EXO-17-012 (Trilepton channel)

- SS2l channel has better sensitivity than trilepton channel for high-mass:
  - BR(W->qq) > 4*BR(W->lν)
  - **Mass dependent** optimisation
- Trilepton channel has best sensitivity for low-mass:
  - Lower backgrounds from misidentified leptons
  - SS2l channel needs to reconstruct 4 soft objects, and **lepton p_T^{min} < jet p_T^{min}**

Previous limits up to 500 GeV

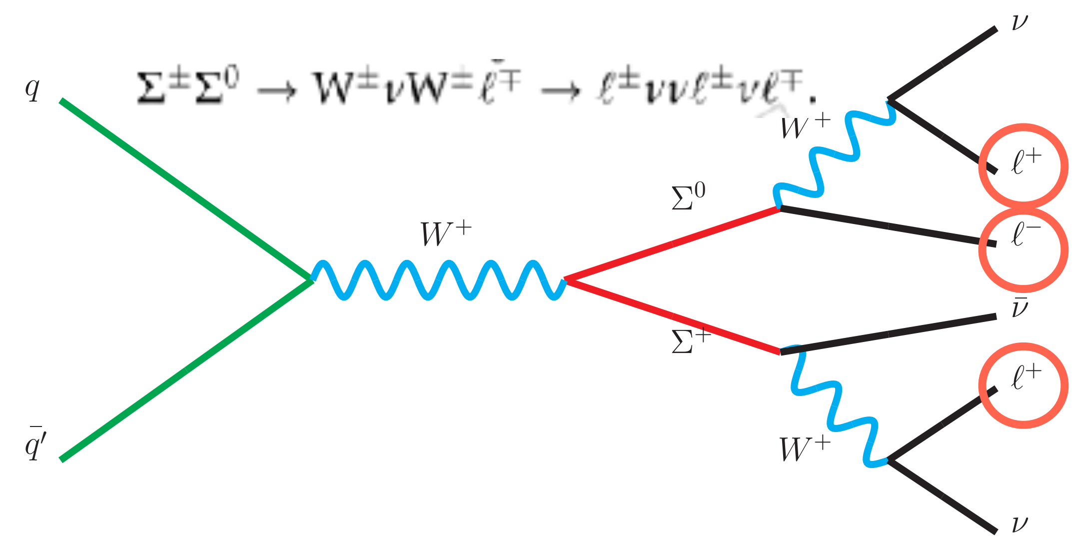
CMS-EXO-17-006,
10.1103/PhysRevLett.119.221802

Type-III seesaw: Multilepton channel

- Type-III seesaw, three new fermion triplet ($\Sigma^{0,\pm}$)
  - Pair produced via gauge interactions.
  - $\Sigma^{0,\pm}$ are **degenerate** in mass

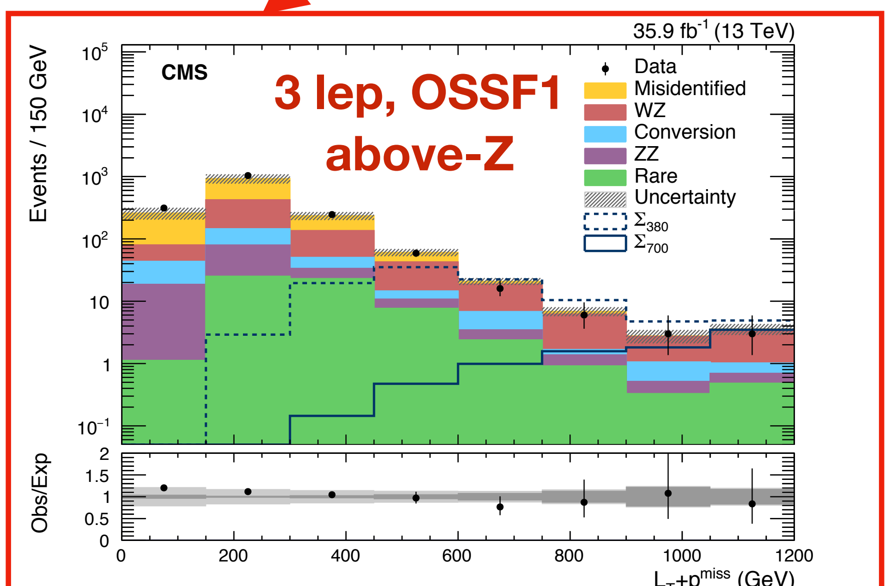
$$pp \rightarrow \Sigma^{0/\pm}\Sigma^{\mp} \otimes \begin{array}{l} \Sigma^0 \rightarrow W^{\pm}\ell^{\mp} \\ \Sigma^0 \rightarrow Z/H\,\nu \\ \Sigma^{\pm} \rightarrow W^{\pm}\nu \\ \Sigma^{\pm} \rightarrow Z/H\ell^{\pm} \end{array}$$

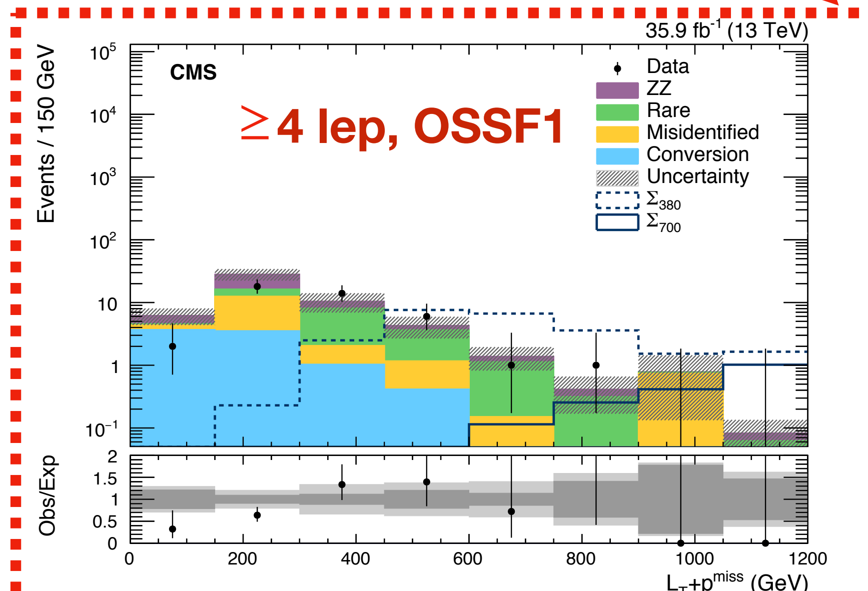
- 27 channels in total
- Mixing with 1, 2 & 3 generations allowed



N_{leptons}	OSSF & mass	Variable	p_T^{miss} requirement
3	OSSF1, on-Z	M_T	$p_T^{\text{miss}} > 100\,\text{GeV}$
3	OSSF1, above-Z	$L_T + p_T^{\text{miss}}$	—
	OSSF1, below-Z	$L_T + p_T^{\text{miss}}$	$p_T^{\text{miss}} > 50\,\text{GeV}$
	OSSF0	$L_T + p_T^{\text{miss}}$	—
≥ 4	OSSF1	$L_T + p_T^{\text{miss}}$	—
	OSSF2	$L_T + p_T^{\text{miss}}$	$p_T^{\text{miss}} > 50\,\text{GeV}$ if on-Z

- Look for a striking multilepton signature.
  - $N_\nu + N_{lep} = 6$.
- $L_T + p_T^{miss}$ used as main signal discriminant.
- 6 signal regions, depending on
  - N_{lep}, N_{OSSF}, M_{OSSF} on/off Z peak.
  - each with 8 bins



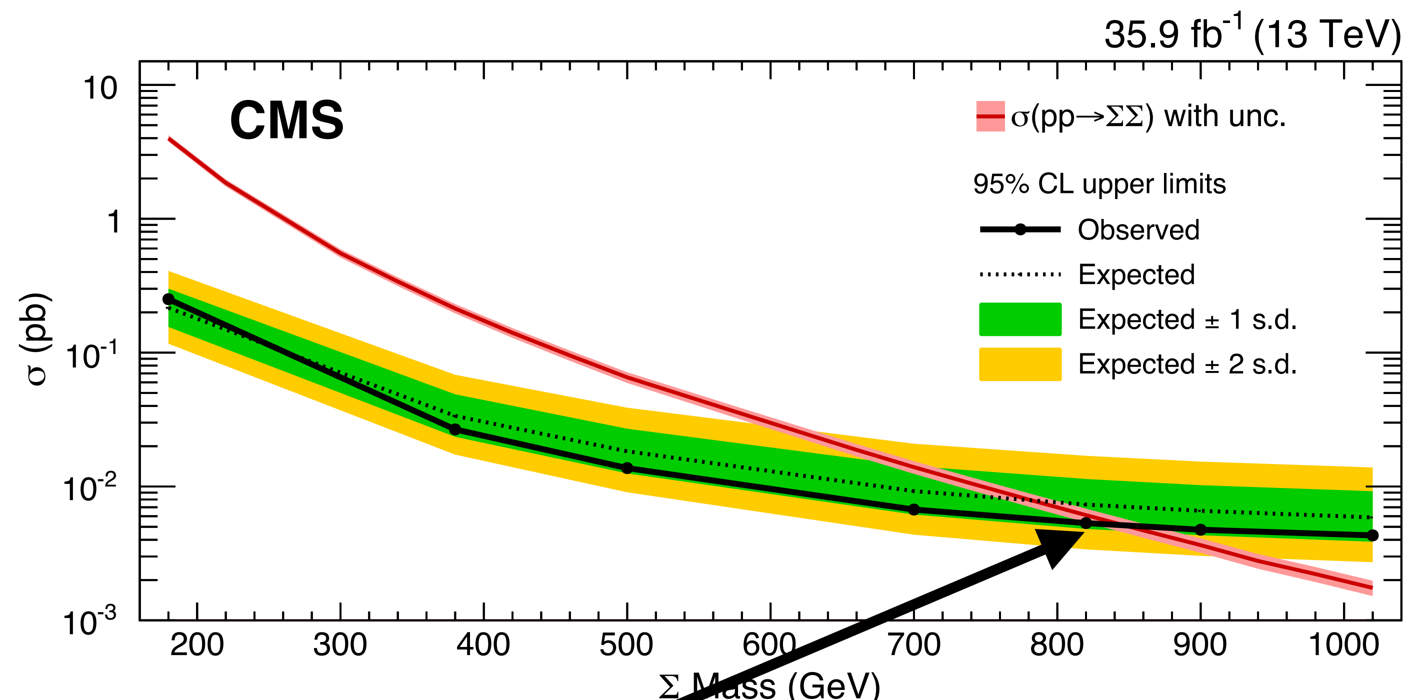


Major backgrounds:

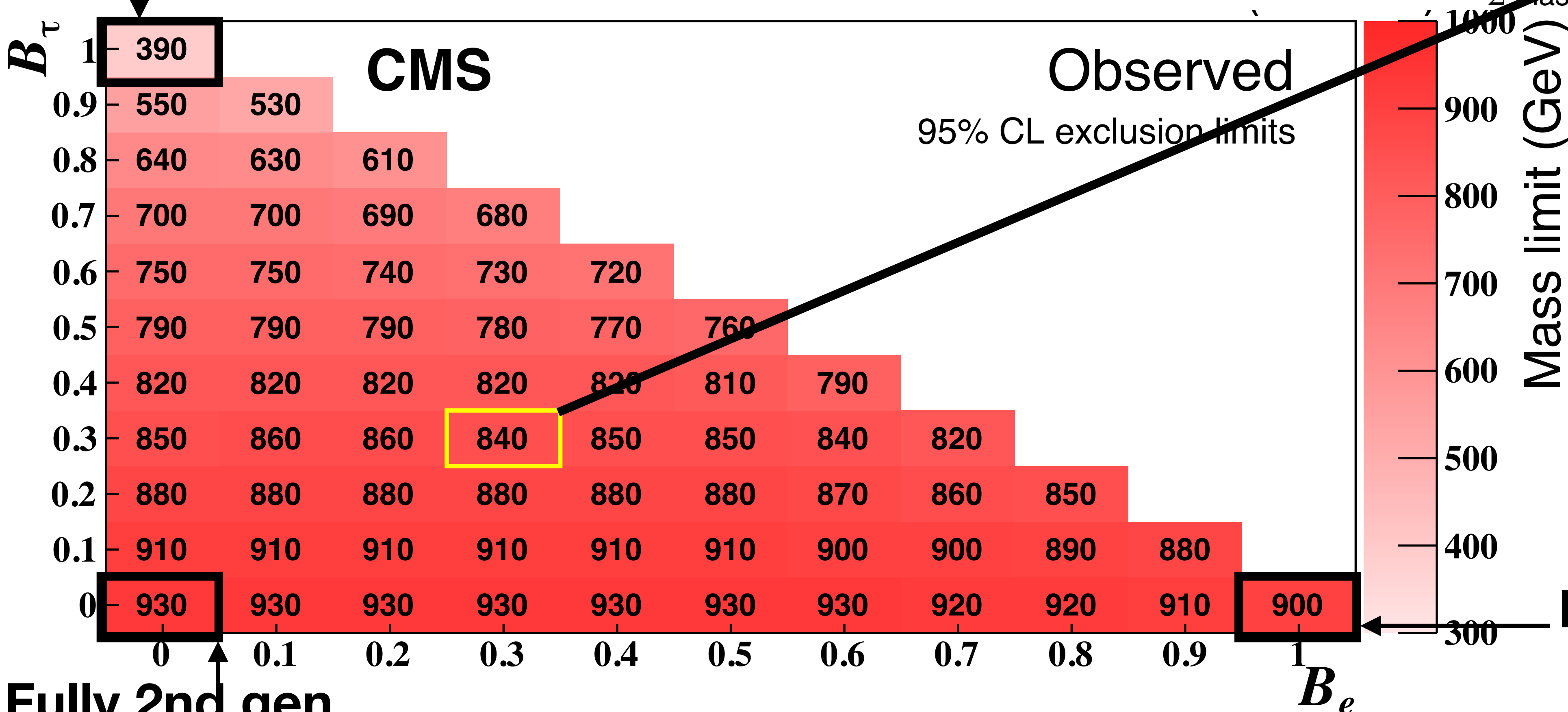
- irreducible WZ and ZZ (*norm. In CR*)
- Reducible DY and tt + misID lepton

Type-III seesaw: Multilepton channel

- Upper limits are set on $\sigma(pp \to \Sigma\Sigma)$ as a function of B*.
  - Use CLs criteria and perform a simultaneous fit across all search regions.
- τ contribute to signal yields from leptonic decays.
- m_Σ < 840 GeV excluded for **flavour-democratic** scenario.
- Most stringent limits on m_Σ to date.



Fully 3rd gen.



Fully 2nd gen.

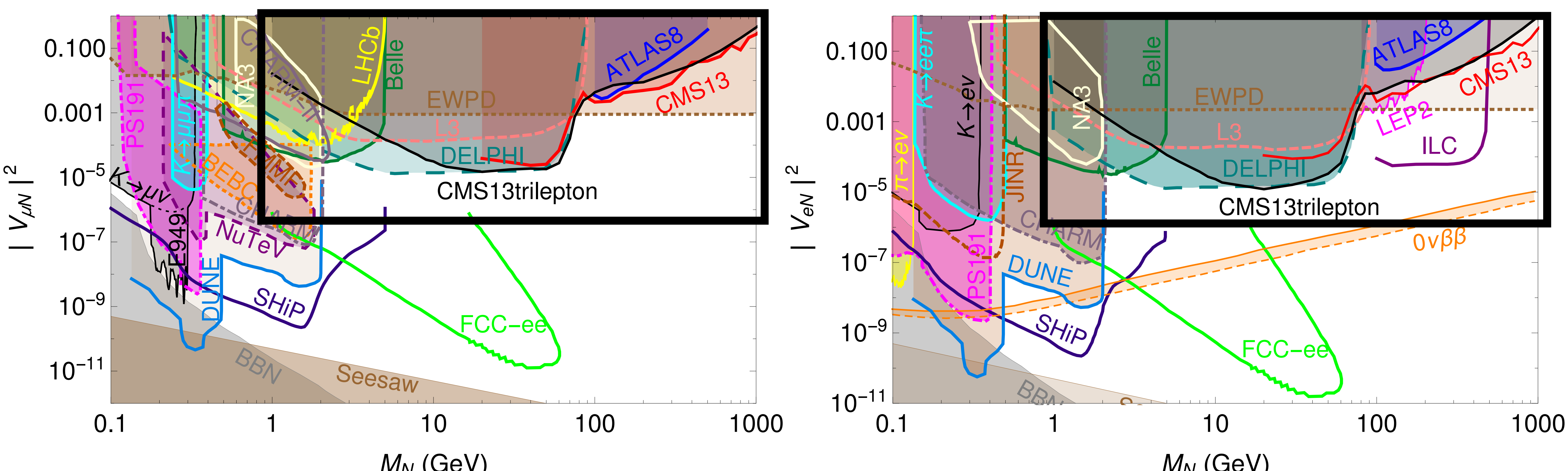
Fully 1st gen.

$$* B_\mu = 1 - [B_e + B_\tau]$$

Summary of N searches at CMS

- A **variety of final states** are under scrutiny in the searching for heavy Majorana neutrinos in the context of Seesaw models
  - Type-I Seesaw*:
    - **probed in mass range ~ 1-1600 GeV and** $10^{-5} < |V_{\ell N}|^2 < 1$ **.**
    - **complementary signatures in low (trileptons) and high (dilepton+jets) masses.**
    - dedicated search planned **to target low-masses with displaced signatures.**

* Also see other analyses (See backup B7-B8) where Seesaw is embedded in:
Type-1+LR-Symmetric model: **CMS-EXO-17-011, arXiv:1803.11116**



Deppisch, Dev, Pilaftsis [New J. Phys. 17, 075019 (2015)] , updated by Dev Mar. 2018.

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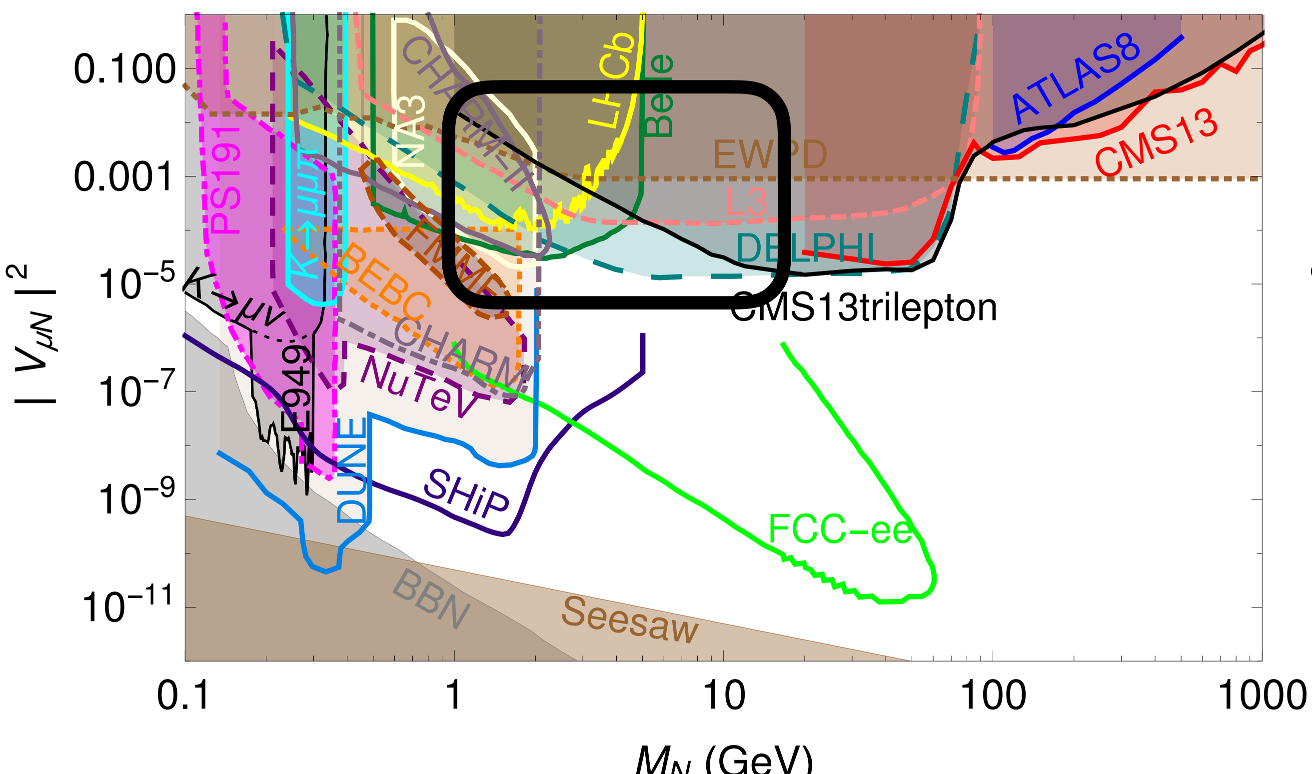

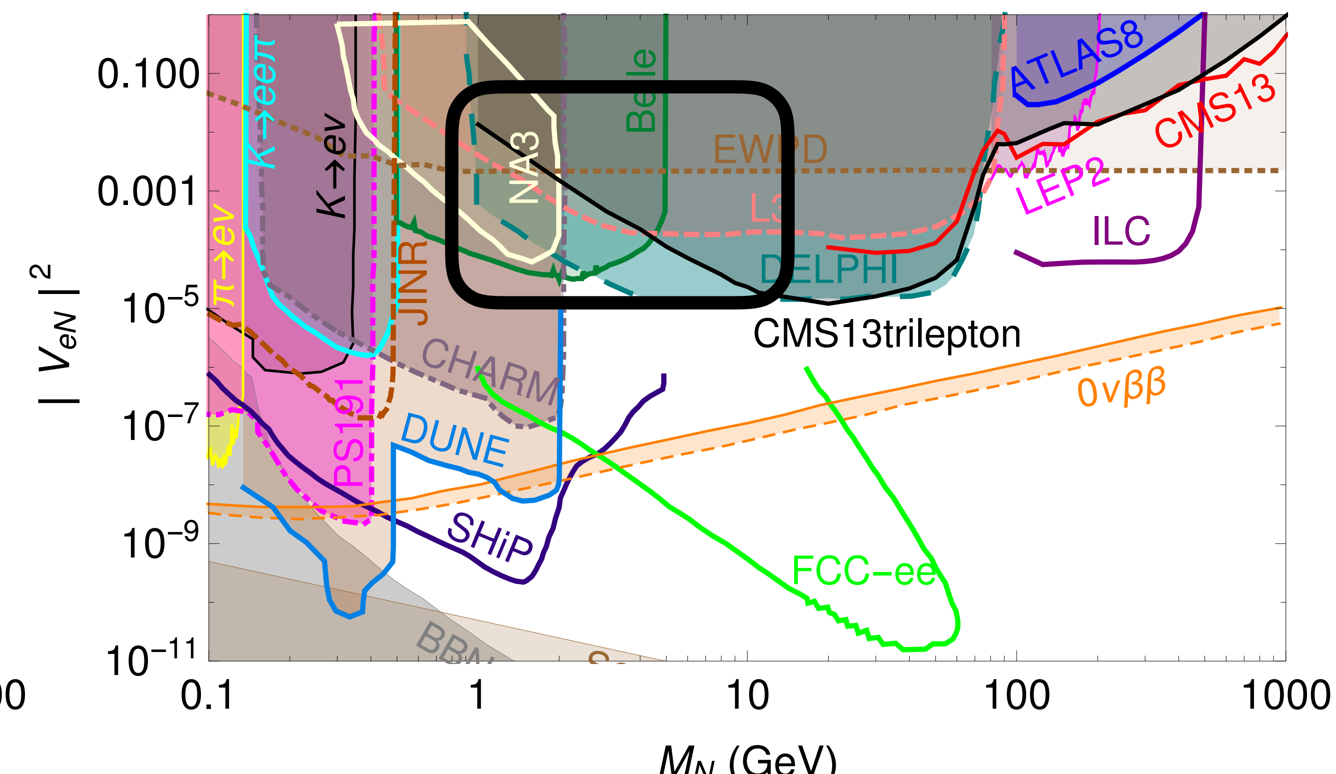

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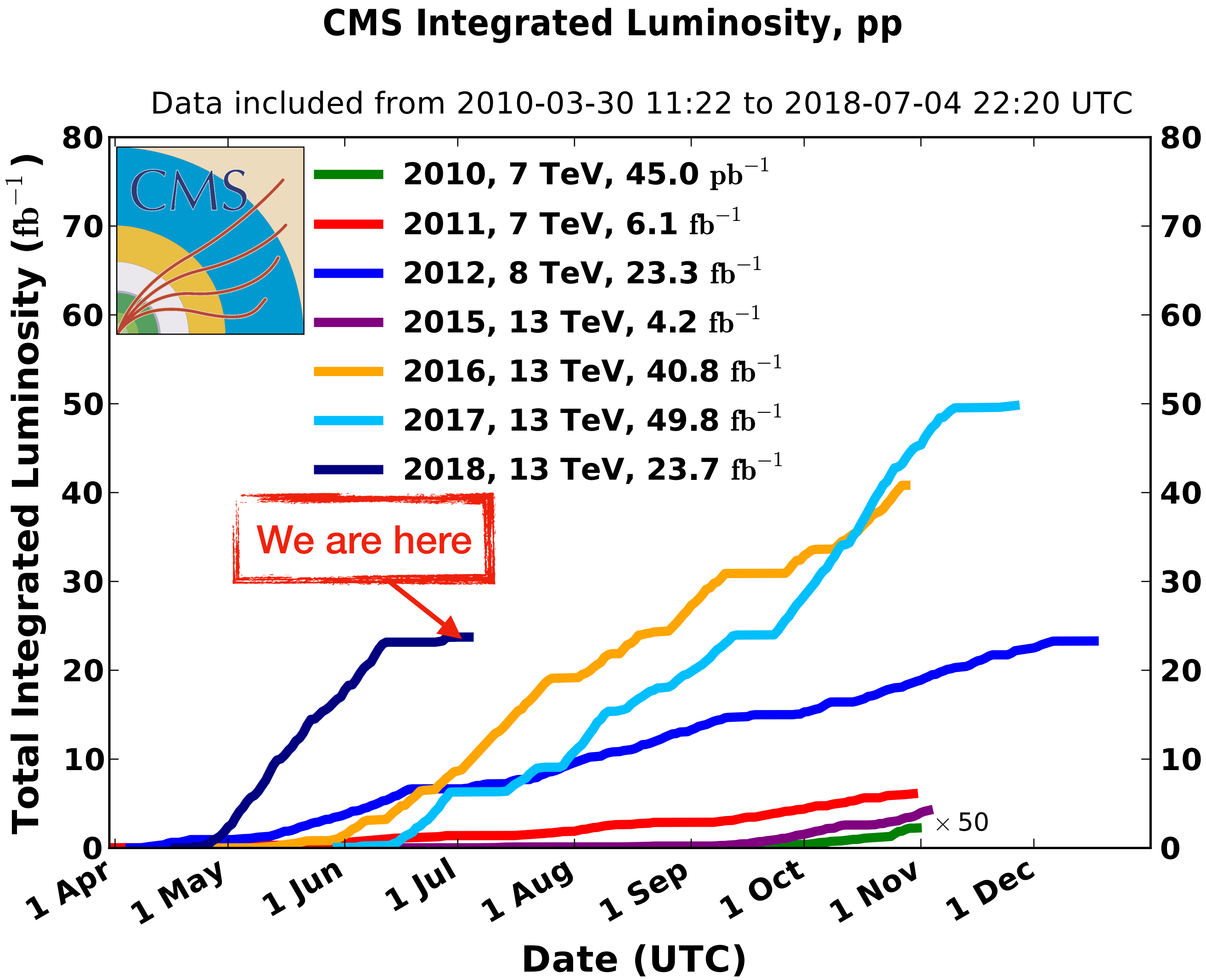
Summary of N searches at CMS

- A **variety of final states** are under scrutiny in the searching for heavy Majorana neutrinos in the context of Seesaw models
  - Type-I Seesaw*:
    - Probed in mass range ~ **1-1600 GeV** and $\mathbf{10^{-5} < |V_{\ell N}|^2 < 1}$
    - complementary signatures in **low (trileptons) and high (dilepton+jets) masses**.
    - Dedicated search planned **to target low-masses with displaced signatures.**
  - Type-III Seesaw:
    - Probed new fermion mass range ~**100-1000 GeV.**
    - **Most stringent limits to date in flavour-demectric scenario.**
    - Mixings to third generation of fermions are also probed via light-lepton channels.
    - Addition of dedicated **hadronic tau channels** is planned.

Summary of N searches at CMS

- A **variety of final states** are under scrutiny in the searching for heavy Majorana neutrinos in the context of Seesaw models
  - Type-I Seesaw*:
    - Probed in mass range ~ **1-1600 GeV**
    - complementary signatures in **low (tril** **(dilepton+jets) masses**.
    - Dedicated search planned **to target l**
  - Type-III Seesaw:
    - Probed new fermion mass range ~**10**
    - **Mixings to third generation of fermi**
    - Addition of dedicated **hadronic tau c**



- More to come with the complete Run-2 dataset!

Backup

Backgrounds in Seesaw searches: SS2l/3/4 lepton events

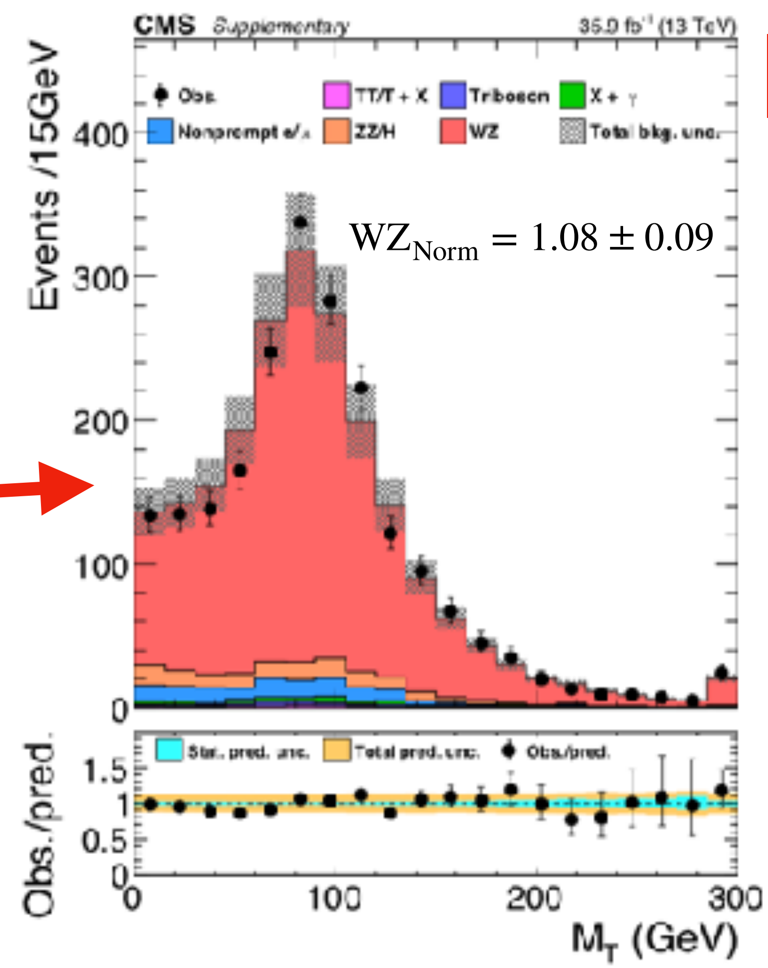
- All CMS seesaw searches probe events with either same-sign 2lepton (SS2l), 3 or 4+ charged leptons.
- These are split into three categories of backgrounds:

1) Irreducible "prompt" backgrounds

$$WZ/\gamma^* \rightarrow 3\ell\nu$$
$$ZZ/\gamma^* \rightarrow 4\ell$$
$$Z/\gamma^* \text{ or } t\bar{t} \rightarrow 2\ell \ (+\text{FSR})$$

Contaminates SS2l if leptons are missing

- **From MC (usually $\geq$ NLO precision)**
- Major bkg **normalized to data** in dedicated control regions (see top right box).



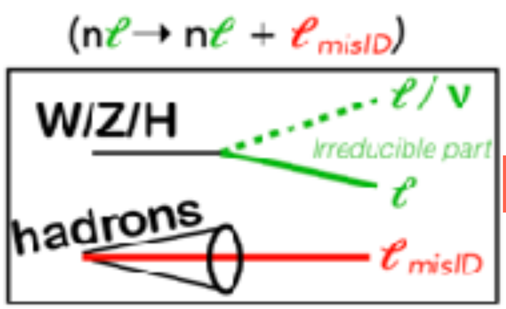
CMS-EXO-17-012

WZ/γ^* CR

- 3 leptons
- $50 < P_T^{miss}$
- $M_{OSSF} \approx M_Z$**

** Mass requirement surpasses signal contamination

2) "Non-Prompt" backgrounds with misidentified leptons



$$Z/\gamma^* \rightarrow 2\ell + \ell_{\text{misID}}$$
$$t\bar{t} \rightarrow 2\ell + \ell_{\text{misID}}$$
$$W^\pm \rightarrow \ell^\pm\nu_\ell + \ell_{\text{misID}}$$

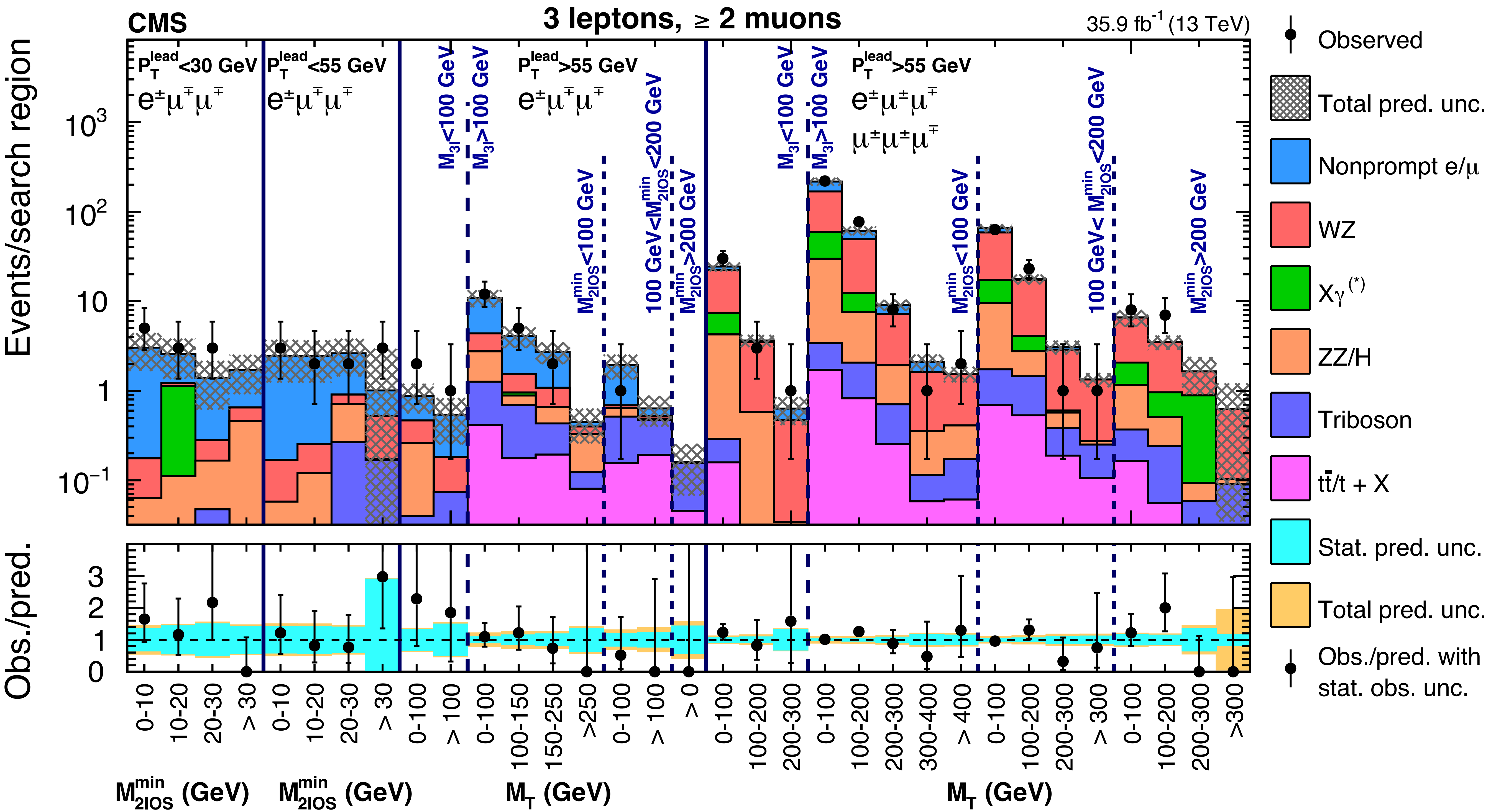
- Backgrounds due to misidentified leptons, mostly b-hadron decays or EM & Jets misreconstruced as a lepton
- **Estimated using data only.**
- Dominant in events with soft leptons.

3) "Prompt" backgrounds with mismeasured sign

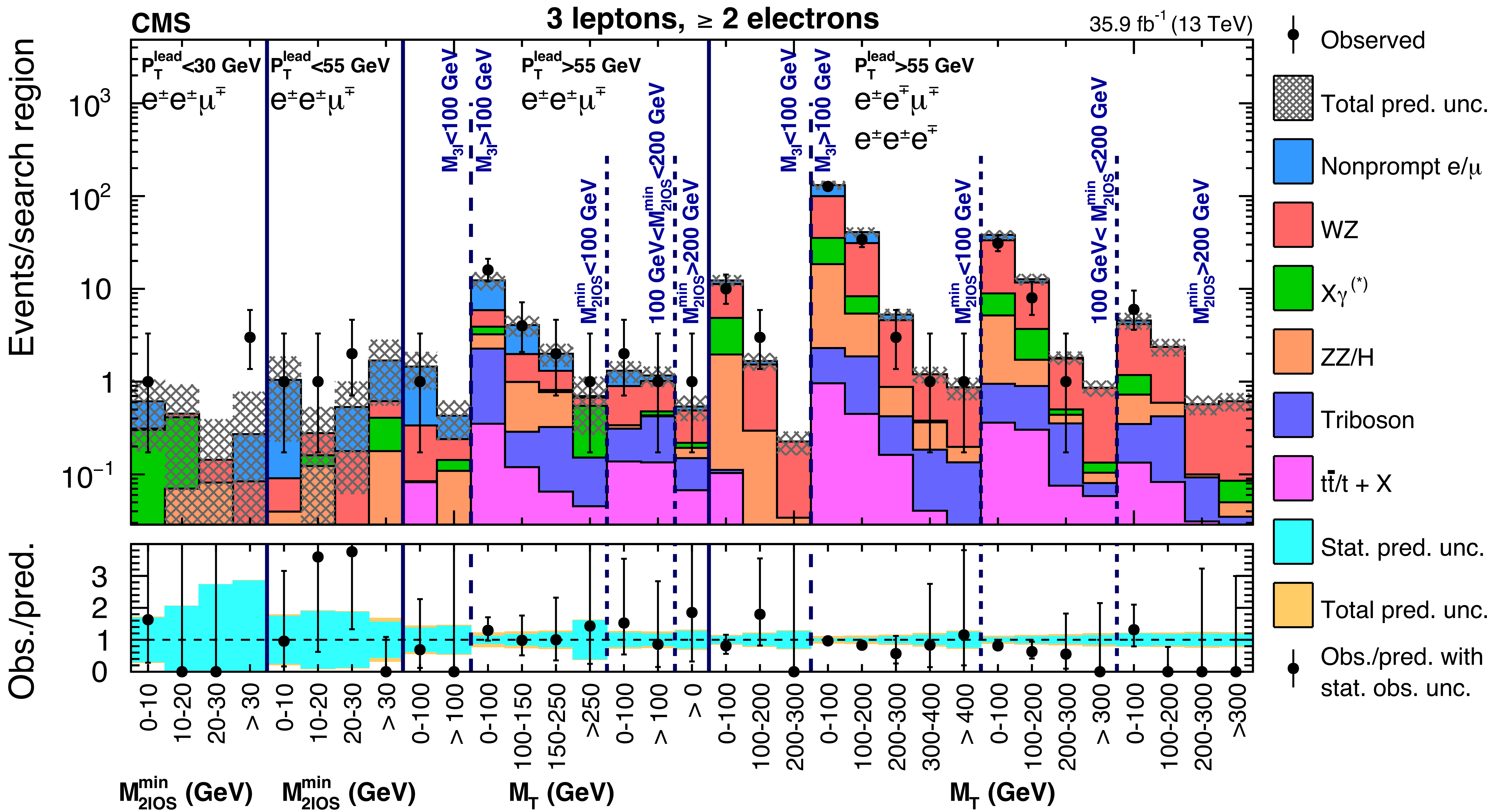
$$Z/\gamma^* \rightarrow e^\pm_{\text{truth}} e^\mp_{\text{truth}} \rightarrow e^\pm_{\text{reco}} e^\pm_{\text{reco}} \ (\text{SS2e})$$

- Considered exclusively in electron channel.
- **Studied in data and MC.**
- Only relevant in 2_{SS} events .

Type-I seesaw: Trilepton channel Search regions ($|V_{\mu N}|^2$)



Type-I seesaw: Trilepton channel Search regions ($|V_{eN}|^2$)



Production modes for N at the LHC

$q\bar{q}' \to N\ell^\pm$

$q\gamma \to N\ell^\pm q'$

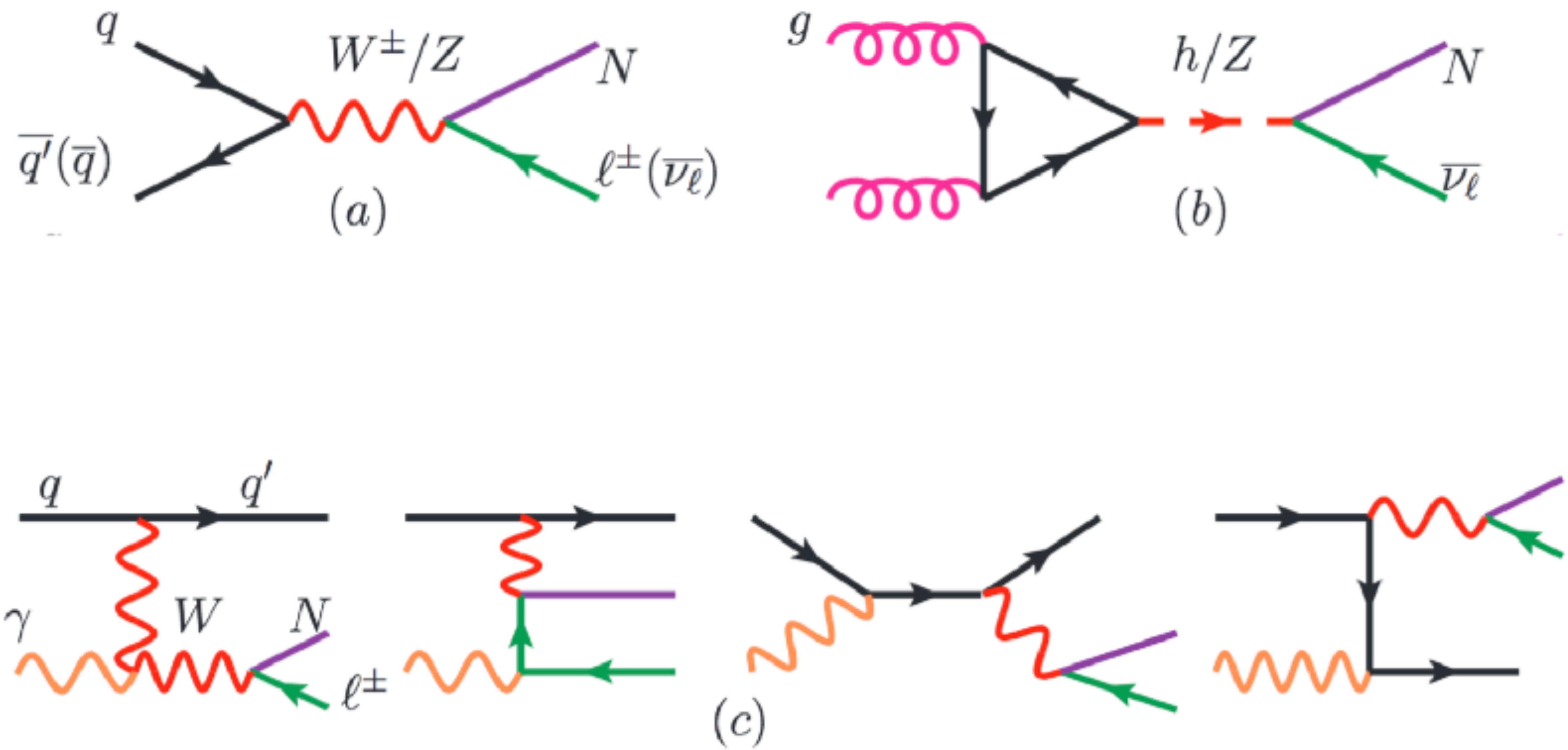


FIG. 1: Heavy neutrino production via (a) charge (neutral) current Drell-Yan, (b) gluon fusion, and (c) $W\gamma$ fusion.

10.1103/PhysRevD.94.053002, arXiv:1602.06957

Systematics for SS Dilepton Search

Channel / Source	ee signal [%]	ee bkgd. [%]	$\mu\mu$ signal [%]	$\mu\mu$ bkgd. [%]	$e\mu$ signal [%]	$e\mu$ bkgd. [%]
Simulation:						
SM cross section	–	12–14 (15–27)	–	13–18 (22–41)	–	12–14 (16–30)
Jet energy scale	2–5 (0–1)	2–6 (5–6)	2–8 (0–1)	3–5 (4–7)	1–6 (0–1)	1–4 (3)
Jet energy resolution	1–2 (0–0.3)	1–2 (2–6)	1–2 (0–0.3)	0–0.8 (1–3)	0.8 (0–0.3)	0–0.8 (0–3)
Jet mass scale	0–0.3 (0–0.1)	0–1 (1–3)	0–0.2 (0–0.1)	0–0.3 (0.7)	0–0.1 (0–0.1)	0–0.2 (0–5)
Jet mass resolution	0–0.4 (0–0.3)	0–1 (0–2)	0–0.1 (0–0.2)	0–0.1 (0–0.5)	0–0.4 (0–0.3)	0–0.4 (0–3)
Subjettiness	0–1 (0–8)	0–1.0 (1–7)	0–0.3 (0–8)	0–0.1 (0–8)	0–0.2 (0–8)	0–0.4 (0–8)
Event pileup	2–3 (1)	2 (0–2)	0–1 (0–1)	0–1 (0–3)	0.7 (0.8)	2 (2–4)
Unclustered energy	0–0.7 (0–0.1)	1 (2–5)	0–1 (0–0.1)	0–1 (3–4)	0–0.5 (0–0.1)	0.9 (1–2)
Integrated luminosity	2.5 (2.5)	2.5 (2.5)	2.5 (2.5)	2.5 (2.5)	2.5 (2.5)	2.5 (2.5)
Lepton selection	2–4 (4)	2–4 (2–6)	3 (3–4)	3 (3–5)	2 (3)	2 (2–6)
Trigger selection	3–4 (1)	3 (3–5)	0–0.9 (0–0.4)	0–1 (0–0.8)	3 (0–0.2)	3 (2)
b tagging	0–0.8 (0–1)	0.7 (1)	0–0.5 (0–0.6)	0–1 (1–3)	0–0.7 (0–0.7)	0–1 (1–4)
Theory:						
PDF	0–1.0 (1)		1 (1)		0.9 (1)	
α_S	0–0.9 (0–0.03)	<15 (<20)	0–0.9 (0–0.05)	<15 (<20)	0–0.9 (0–0.06)	<15 (<20)
PDF Scale	5–8 (1–2)		5–7 (1–2)		4–8 (1–2)	
Estimated from data:						
Misidentified leptons	–	30 (30)	–	30 (30)	–	30 (30)
Mismeasured charge	–	29–41 (53–88)	–	–	–	–

- Numbers in brackets are for high-mass, others are all low-mass.
- Dominant source is from misidentified leptons in low-mass.
- High-mass dominant systematics from jets and bkg cross-section.

Results for Signal Regions: Type-1 Dilepton

m_N (GeV)	$p_T^{\ell_1}$ (GeV)	$p_T^{\ell_2}$ (GeV)	$m(\ell^\pm\ell^\pm W_{jet})$ (GeV)	$m(\ell_1 W_{jet})$ (GeV)	$m(\ell_2 W_{jet})$ (GeV)	$m(\ell^\pm\ell^\pm)$ (GeV)	Total bkgd.	N_{obs}	DY $A\epsilon$ (%)
ee channel SR1									
20	25–70	60	<190	<160	<160	10–60	48.9 ± 9.5	45	0.12 ± 0.02
30	25–70	60	<190	<160	<160	10–60	48.9 ± 9.5	45	0.13 ± 0.02
40	25–70	60	<190	<160	<160	10–60	48.9 ± 9.5	45	0.21 ± 0.03
50	25–70	60	<190	<160	<160	10–60	48.9 ± 9.5	45	0.24 ± 0.03
60	25–70	60	<190	<160	<160	10–60	48.9 ± 9.5	45	0.18 ± 0.02
70	25–70	60	<190	<160	<160	10–75	64 ± 12	58	0.10 ± 0.01
75	25–70	60	<190	<160	<160	10–100	68 ± 12	67	0.13 ± 0.02
ee channel SR2									
20	25–70	60	<100	<70	<70	10–60	50.3 ± 8.5	55	0.26 ± 0.03
30	25–70	60	<100	<70	<70	10–60	50.3 ± 8.5	55	0.30 ± 0.04
40	25–70	60	<100	<70	<70	10–60	50.3 ± 8.5	55	0.35 ± 0.04
50	25–70	60	<100	<70	<70	10–60	50.3 ± 8.5	55	0.32 ± 0.03
60	25–70	60	<100	<70	<70	10–60	50.3 ± 8.5	55	0.24 ± 0.03
70	25–70	60	<100	<70	<70	10–75	65 ± 10	70	0.06 ± 0.01
75	25–70	60	<100	<70	<70	10–80	67 ± 10	70	0.11 ± 0.02
$\mu\mu$ channel SR1									
20	20–80	15–50	<160	<150	<150	20–60	15.3 ± 3.4	18	0.10 ± 0.02
30	20–80	15–50	<160	<150	<150	20–60	15.3 ± 3.4	18	0.18 ± 0.03
40	20–80	15–50	<160	<150	<150	20–60	15.3 ± 3.4	18	0.34 ± 0.05
50	20–80	15–50	<160	<150	<150	20–60	15.3 ± 3.4	18	0.40 ± 0.04
60	20–80	15–50	<160	<150	<150	20–60	15.3 ± 3.4	18	0.33 ± 0.04
70	20–80	15–50	<160	<150	<150	10–75	20.3 ± 4.4	21	0.17 ± 0.02
75	20–80	15–50	<160	<150	<150	20–100	18.9 ± 4.0	19	0.19 ± 0.03
$\mu\mu$ channel SR2									
20	20–80	15–50	<100	<70	<70	20–60	25.9 ± 5.9	29	0.28 ± 0.03
30	20–80	15–50	<100	<70	<70	20–60	25.9 ± 5.9	29	0.51 ± 0.05
40	20–80	15–50	<100	<70	<70	20–60	25.9 ± 5.9	29	0.8 ± 0.1
50	20–80	15–50	<100	<70	<70	20–60	25.9 ± 5.9	29	1.1 ± 0.1
60	20–80	15–50	<100	<70	<70	20–60	25.9 ± 5.9	29	0.73 ± 0.07
70	20–80	15–50	<100	<70	<70	10–75	37.5 ± 7.1	41	0.20 ± 0.03
75	20–80	15–50	<100	<70	<70	20–80	29.7 ± 6.7	34	0.24 ± 0.03
$e\mu$ channel SR1									
20	25–60	15–40	<185	<135	<135	20–60	34.0 ± 6.4	34	0.08 ± 0.02
30	25–60	15–40	<185	<135	<135	20–60	34.0 ± 6.4	34	0.12 ± 0.02
40	25–60	15–40	<185	<135	<135	20–60	34.0 ± 6.4	34	0.21 ± 0.02
50	25–60	15–40	<185	<135	<135	20–60	34.0 ± 6.4	34	0.20 ± 0.03
60	25–60	15–40	<185	<135	<135	20–60	34.0 ± 6.4	34	0.17 ± 0.02
70	25–60	15–40	<185	<135	<135	10–75	51 ± 10	49	0.09 ± 0.01
75	25–60	15–40	<185	<135	<135	20–100	46.5 ± 8.7	49	0.17 ± 0.03
$e\mu$ channel SR2									
20	25–60	15–40	<100	<65	<65	20–60	51.7 ± 9.2	50	0.21 ± 0.02
30	25–60	15–40	<100	<65	<65	20–60	51.7 ± 9.2	50	0.27 ± 0.03
40	25–60	15–40	<100	<65	<65	20–60	51.7 ± 9.2	50	0.45 ± 0.04
50	25–60	15–40	<100	<65	<65	20–60	51.7 ± 9.2	50	0.40 ± 0.03
60	25–60	15–40	<100	<65	<65	20–60	51.7 ± 9.2	50	0.24 ± 0.03
70	25–60	15–40	<100	<65	<65	10–75	75.8 ± 12.4	65	0.09 ± 0.01
75	25–60	15–40	<100	<65	<65	20–80	62.8 ± 10.9	57	0.12 ± 0.03

Low-Mass

m_N (GeV)	$p_T^{\ell_1}$ (GeV)	$p_T^{\ell_2}$ (GeV)	$m(\ell^\pm\ell^\pm W_{jet})$ (GeV)	$m(\ell W_{jet})$ (GeV)	$(p_T^{miss})^2/S_T$ (GeV)	Total bkgd.	N_{obs}	DY $A\epsilon$ (%)	VBF $A\epsilon$ (%)
ee channel SR1									
85	>25	>15	>110	45–95	<6	9.5 ± 2.8	9	0.11 ± 0.02	—
90	>25	>15	>110	50–100	<6	12.5 ± 3.5	10	0.23 ± 0.05	—
100	>25	>15	>120	50–110	<6	20.3 ± 5.0	15	1.1 ± 0.1	—
125	>30	>25	>120	90–140	<6	17.7 ± 4.5	17	2.6 ± 0.2	—
150	>40	>25	>180	130–160	<6	14.7 ± 3.8	9	3.1 ± 0.2	—
200	>55	>40	>220	160–225	<6	12.4 ± 2.7	10	4.9 ± 0.4	—
250	>70	>60	>310	220–270	<6	6.0 ± 1.7	4	5.9 ± 0.4	—
300	>80	>60	>370	235–335	<6	8.2 ± 2.1	6	7.6 ± 0.5	3.0 ± 0.3
400	>100	>65	>450	335–450	<6	2.5 ± 1.4	4	6.6 ± 0.5	3.0 ± 0.2
500	>125	>65	>560	400–555	<6	1.5 ± 0.8	5	5.5 ± 0.4	2.7 ± 0.2
600	>125	—	>760	400–690	<6	0.9 ± 0.6	1	3.8 ± 0.3	1.7 ± 0.2
700	>125	—	>760	400–955	<6	1.7 ± 0.7	1	4.0 ± 0.3	2.8 ± 0.2
800	>125	—	>760	400–1130	<6	1.7 ± 0.7	1	3.6 ± 0.3	3.0 ± 0.3
900	>125	—	>760	400–1300	<6	1.7 ± 0.7	1	3.2 ± 0.2	2.9 ± 0.2
1000	>125	—	>760	400–1490	<6	1.7 ± 0.7	1	2.6 ± 0.2	2.4 ± 0.2
1100	>125	—	>760	400–1490	<6	1.7 ± 0.7	1	2.2 ± 0.2	2.0 ± 0.2
1200	>125	—	>760	400–1600	<6	1.7 ± 0.7	1	2.0 ± 0.2	1.8 ± 0.2
1300	>125	—	>760	400–1930	<6	1.7 ± 0.7	1	1.8 ± 0.1	1.6 ± 0.2
1400	>125	—	>760	400–1930	<6	1.7 ± 0.7	1	1.5 ± 0.1	1.3 ± 0.1
1500	>125	—	>760	400–1930	<6	1.7 ± 0.7	1	1.3 ± 0.1	1.2 ± 0.2
ee channel SR2									
85	>25	>15	—	—	<15	10.9 ± 2.9	10	0.001 ± 0.001	—
90	>25	>15	—	90–220	<15	3.4 ± 1.0	2	0.003 ± 0.002	—
100	>25	>15	—	100–220	<15	3.4 ± 1.0	2	0.005 ± 0.003	—
125	>60	>15	—	123–145	<15	0.2 ± 0.1	0	0.04 ± 0.01	—
150	>90	>15	—	125–185	<15	1.3 ± 0.5	0	0.19 ± 0.03	—
200	>100	>20	—	173–220	<15	0.8 ± 0.3	1	0.60 ± 0.07	—
250	>100	>25	—	220–305	<15	2.1 ± 1.2	3	2.2 ± 0.2	—
300	>100	>30	—	270–330	<15	1.3 ± 0.6	1	3.5 ± 0.4	0.6 ± 0.1
400	>100	>35	—	330–440	<15	3.1 ± 1.3	3	9.1 ± 0.9	2.9 ± 0.3
500	>120	>35	—	440–565	<15	2.8 ± 1.0	1	14.3 ± 1.4	6.1 ± 0.6
600	>120	—	—	565–675	<15	0.8 ± 0.3	1	17.4 ± 1.8	11.0 ± 1.0
700	>140	—	—	635–775	<15	0.8 ± 0.3	2	19.4 ± 2.0	13.1 ± 1.3
800	>140	—	—	740–1005	<15	0.9 ± 0.4	0	20.8 ± 2.1	14.0 ± 1.3
900	>140	—	—	865–1030	<15	0.2 ± 0.1	0	19.2 ± 2.0	13.2 ± 1.3
1000	>140	—	—	890–1185	<15	0.3 ± 0.1	1	21.5 ± 2.2	15.3 ± 1.5
1100	>140	—	—	1035–1395	<15	0.1 ± 0.1	1	20.3 ± 2.1	14.7 ± 1.4
1200	>140	—	—	1085–1460	<15	0.1 ± 0.0	1	20.8 ± 2.2	15.3 ± 1.5
1300	>140	—	—	1140–1590	<15	0.1 ± 0.0	1	20.5 ± 2.2	15.5 ± 1.6
1400	>140	—	—	1245–1700	<15	0.1 ± 0.0	0	19.6 ± 2.1	15.1 ± 1.6
1500	>140	—	—	1300–1800	<15	0.04 ± 0.02	0	19.5 ± 2.1	15.2 ± 1.6

High-Mss

Results for Signal Regions: Type-1 Dilepton

m_N (GeV)	$p_T^{\ell_1}$ (GeV)	$p_T^{\ell_2}$ (GeV)	$m(\ell^\pm\ell^\pm W_{jet})$ (GeV)	$m(\ell W_{jet})$ (GeV)	$(p_T^{miss})^2/S_T$ (GeV)	Total bkgd.	N_{obs}	DY $A\epsilon$ (%)	VBF $A\epsilon$ (%)
$\mu\mu$ channel SR1									
85	>25	>10	>90	40–100	<9	26.0 ± 6.3	30	0.50 ± 0.05	—
90	>25	>10	>90	45–105	<9	34.5 ± 7.5	35	1.2 ± 0.1	—
100	>25	>15	>110	55–115	<9	18.6 ± 4.2	20	2.6 ± 0.2	—
125	>25	>25	>140	85–140	<7	11.7 ± 2.7	12	5.1 ± 0.4	—
150	>35	>35	>150	110–170	<7	8.9 ± 1.9	11	6.6 ± 0.5	—
200	>50	>40	>250	160–215	<7	4.6 ± 1.2	4	8.1 ± 0.6	—
250	>85	>45	>310	215–270	<7	3.0 ± 0.9	2	11.0 ± 0.8	—
300	>100	>50	>370	225–340	<7	2.6 ± 1.0	2	13.2 ± 0.9	5.2 ± 0.4
400	>110	>60	>490	295–490	<7	0.9 ± 0.4	3	11.7 ± 0.8	5.1 ± 0.4
500	>110	>60	>610	370–550	<7	$0.4^{+0.6}_{-0.4}$	3	8.6 ± 0.6	4.1 ± 0.3
600	>110	—	>680	370–630	<7	$0.3^{+0.3}_{-0.3}$	3	7.4 ± 0.5	4.1 ± 0.3
700	>110	—	>800	370–885	<7	$0.2^{+0.4}_{-0.2}$	2	6.7 ± 0.4	3.9 ± 0.3
800	>110	—	>800	370–890	<7	$0.2^{+0.4}_{-0.2}$	2	6.0 ± 0.4	5.4 ± 0.3
900	>110	—	>800	370–1225	<7	$0.3^{+0.4}_{-0.3}$	2	5.4 ± 0.4	5.0 ± 0.3
1000	>110	—	>800	370–1230	<7	$0.3^{+0.4}_{-0.3}$	2	4.6 ± 0.3	4.2 ± 0.3
1100	>110	—	>800	370–1245	<7	$0.3^{+0.4}_{-0.3}$	2	4.1 ± 0.3	3.8 ± 0.3
1200	>110	—	>800	370–1690	<7	$0.3^{+0.4}_{-0.3}$	2	3.6 ± 0.2	3.4 ± 0.3
1300	>110	—	>800	370–1890	<7	$0.3^{+0.4}_{-0.3}$	2	3.2 ± 0.2	3.0 ± 0.2
1400	>110	—	>800	370–1940	<7	$0.3^{+0.4}_{-0.3}$	2	2.7 ± 0.2	2.7 ± 0.2
1500	>110	—	>800	370–2220	<7	$0.3^{+0.4}_{-0.3}$	2	2.5 ± 0.2	2.3 ± 0.2
$\mu\mu$ channel SR2									
85	>25	>10	—	—	<15	11.4 ± 3.5	13	0.001 ± 0.001	—
90	>25	>10	—	90–170	<15	4.1 ± 1.3	4	0.003 ± 0.003	—
100	>25	>15	—	98–145	<15	1.0 ± 0.3	0	0.006 ± 0.003	—
125	>60	>15	—	110–150	<15	0.8 ± 0.3	0	0.08 ± 0.01	—
150	>70	>15	—	145–175	<15	1.0 ± 0.4	2	0.28 ± 0.04	—
200	>100	>20	—	175–235	<15	1.3 ± 0.8	0	1.4 ± 0.1	—
250	>140	>25	—	226–280	<15	0.3 ± 0.2	0	3.0 ± 0.3	—
300	>140	>40	—	280–340	<15	0.4 ± 0.3	0	5.4 ± 0.5	0.7 ± 0.1
400	>140	>65	—	340–445	<15	0.5 ± 0.3	2	13.3 ± 1.3	2.7 ± 0.3
500	>140	>65	—	445–560	<15	0.8 ± 0.5	0	22.4 ± 2.2	6.8 ± 0.7
600	>140	—	—	560–685	<15	0.7 ± 0.4	0	30.2 ± 2.9	20.4 ± 1.8
700	>140	—	—	635–825	<15	0.8 ± 0.4	2	34.6 ± 3.4	24.7 ± 2.2
800	>140	—	—	755–960	<15	0.4 ± 0.3	0	34.8 ± 3.5	24.9 ± 2.3
900	>140	—	—	840–1055	<15	$0.2^{+0.2}_{-0.2}$	1	35.8 ± 3.6	26.9 ± 2.5
1000	>140	—	—	900–1205	<15	$0.1^{+0.2}_{-0.1}$	1	38.4 ± 3.9	28.9 ± 2.7
1100	>140	—	—	990–1250	<15	$0.1^{+0.2}_{-0.1}$	1	36.7 ± 3.7	29.2 ± 2.7
1200	>140	—	—	1035–1430	<15	$0.2^{+0.3}_{-0.2}$	1	38.5 ± 4.0	30.1 ± 2.8
1300	>140	—	—	1100–1595	<15	0.3 ± 0.3	1	38.5 ± 4.0	30.7 ± 3.0
1400	>140	—	—	1285–1700	<15	$0.1^{+0.2}_{-0.1}$	1	35.9 ± 3.8	29.4 ± 2.8
1500	>140	—	—	1330–1800	<15	$0.1^{+0.2}_{-0.1}$	1	36.4 ± 3.9	30.0 ± 2.9

High-Mss

m_N (GeV)	$p_T^{\ell_1}$ (GeV)	$p_T^{\ell_2}$ (GeV)	$m(\ell^\pm\ell^\pm W_{jet})$ (GeV)	$m(\ell W_{jet})$ (GeV)	$(p_T^{miss})^2/S_T$ (GeV)	Total bkgd.	N_{obs}	DY $A\epsilon$ (%)	VBF $A\epsilon$ (%)
$e\mu$ channel SR1									
85	>30	>10	>120	55–95	<7	26.1 ± 6.2	25	0.21 ± 0.03	—
90	>30	>10	>120	60–100	<7	37.4 ± 8.4	32	0.59 ± 0.07	—
100	>25	>20	>110	60–115	<7	23.6 ± 4.8	21	1.3 ± 0.1	—
125	>30	>30	>140	90–140	<7	25.5 ± 5.9	16	3.1 ± 0.2	—
150	>45	>35	>150	100–170	<7	34.1 ± 6.0	26	5.1 ± 0.3	—
200	>65	>35	>270	170–230	<7	11.1 ± 2.8	14	6.1 ± 0.4	—
250	>75	>60	>300	200–280	<7	11.1 ± 2.3	9	8.9 ± 0.5	—
300	>95	>60	>340	255–325	<7	5.8 ± 1.7	8	9.0 ± 0.6	3.4 ± 0.3
400	>120	>60	>530	325–450	<7	2.2 ± 1.0	7	7.4 ± 0.4	3.0 ± 0.3
500	>150	>60	>580	315–530	<7	1.8 ± 1.1	6	6.6 ± 0.5	3.0 ± 0.2
600	>175	—	>670	315–740	<7	1.2 ± 0.9	4	5.9 ± 0.4	3.5 ± 0.3
700	>180	—	>720	350–1030	<7	1.6 ± 1.1	3	5.2 ± 0.3	3.8 ± 0.2
800	>180	—	>720	400–1030	<7	1.6 ± 1.1	3	4.5 ± 0.3	3.7 ± 0.2
900	>185	—	>720	450–1040	<7	1.0 ± 0.7	2	3.8 ± 0.2	3.3 ± 0.2
1000	>185	—	>720	500–1415	<7	1.0 ± 0.7	2	3.4 ± 0.2	3.0 ± 0.2
1100	>185	—	>720	550–1640	<7	1.0 ± 0.7	1	2.8 ± 0.2	2.6 ± 0.2
1200	>185	—	>720	600–1780	<7	1.0 ± 0.7	1	2.4 ± 0.2	2.3 ± 0.2
1300	>185	—	>720	650–1880	<7	0.8 ± 0.7	1	2.1 ± 0.1	1.9 ± 0.2
1400	>185	—	>720	650–1885	<7	0.8 ± 0.7	1	1.8 ± 0.1	1.7 ± 0.2
1500	>185	—	>720	650–1885	<7	0.8 ± 0.7	1	1.5 ± 0.1	1.5 ± 0.1
1700	>185	—	>720	650–2085	<7	0.8 ± 0.7	1	1.2 ± 0.1	1.3 ± 0.1
$e\mu$ channel SR2									
85	>25	>10	—	—	<15	24.2 ± 6.4	31	0.001 ± 0.002	—
90	>25	>10	—	90–240	<15	13.4 ± 3.7	22	0.003 ± 0.002	—
100	>30	>15	—	100–335	<15	14.1 ± 4.1	21	0.009 ± 0.003	—
125	>35	>25	—	115–150	<15	0.6 ± 0.4	2	0.03 ± 0.01	—
150	>45	>30	—	132–180	<15	1.4 ± 0.5	2	0.14 ± 0.02	—
200	>70	>30	—	180–225	<15	1.5 ± 0.5	3	0.86 ± 0.09	—
250	>75	>55	—	225–280	<15	1.2 ± 0.4	2	1.7 ± 0.2	—
300	>95	>55	—	280–340	<15	1.2 ± 0.7	1	4.4 ± 0.4	0.8 ± 0.1
400	>125	>55	—	340–475	<15	2.0 ± 1.2	1	11.8 ± 1.1	2.7 ± 0.3
500	>145	>60	—	460–555	<15	0.7 ± 0.3	0	16.7 ± 1.6	5.2 ± 0.5
600	>160	—	—	555–645	<15	1.4 ± 0.9	1	20.2 ± 1.9	13.2 ± 1.2
700	>170	—	—	610–780	<15	2.0 ± 0.9	2	25.0 ± 2.4	17.6 ± 1.6
800	>170	—	—	730–895	<15	0.8 ± 0.4	2	26.1 ± 2.5	18.3 ± 1.6
900	>180	—	—	845–1015	<15	0.5 ± 0.2	0	25.6 ± 2.5	18.5 ± 1.7
1000	>180	—	—	930–1075	<15	0.2 ± 0.2	0	23.5 ± 2.3	17.6 ± 1.6
1100	>180	—	—	1020–1340	<15	0.3 ± 0.3	0	26.9 ± 2.7	19.6 ± 1.7
1200	>180	—	—	1080–1340	<15	$0.1^{+0.2}_{-0.1}$	0	25.9 ± 2.6	19.9 ± 1.8
1300	>180	—	—	1155–1595	<15	$0.2^{+0.2}_{-0.2}$	0	27.1 ± 2.7	20.7 ± 1.9
1400	>180	—	—	1155–1615	<15	$0.2^{+0.3}_{-0.2}$	0	26.7 ± 2.7	20.8 ± 2.0
1500	>180	—	—	1345–1615	<15	$0.0^{+0.1}_{-0.0}$	0	21.6 ± 2.2	18.0 ± 1.7
1700	>180	—	—	1400–1800	<15	0.7 ± 0.6	0	19.8 ± 2.1	17.0 ± 1.7

High-Mss

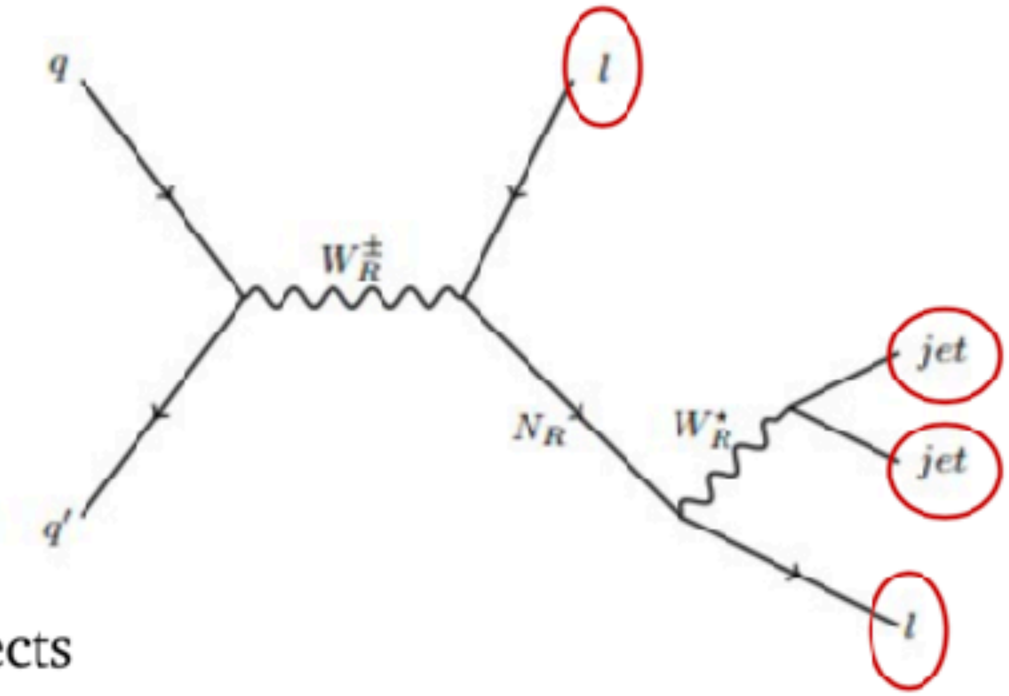
- SR1 600 GeV mm channel; 3 observed, 0.3 predicted, SR2 0 observed and 0.7 predicted.

RH neutrinos from W_R in lljj events

CMS-EXO-17-011

10.1007/JHEP05(2018)148

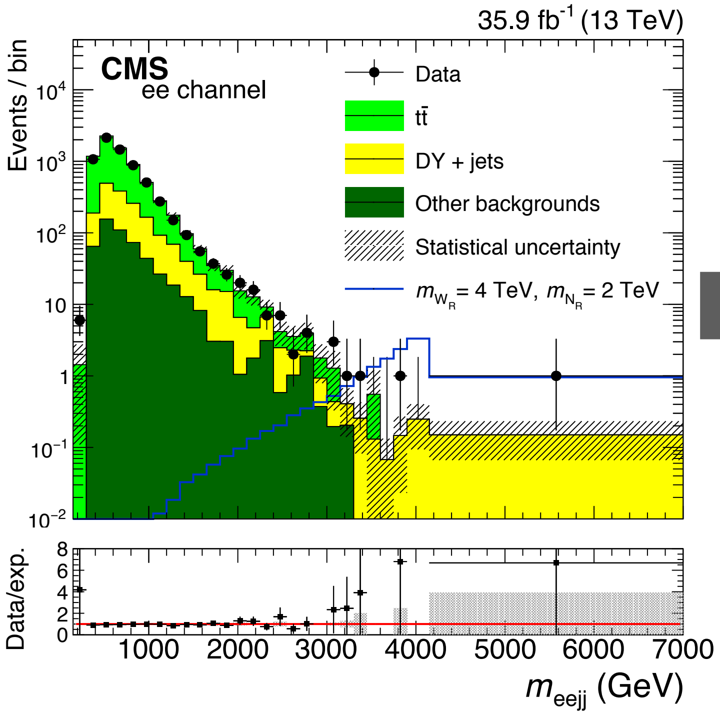
- LR symmetric model, no flavor changing
- Signatures : 2 electrons + 2 jets, 2 muons + 2 jets
- Selections :
  - 2 high-p_T leptons ($p_T^{leading}$>60 GeV, $p_T^{subleading}$>53 GeV) and |η|<2.4
  - 2 high-p_T jets (>40 GeV) and |η|<2.4
  - Δ_R>0.4 to ensure separation between final state objects

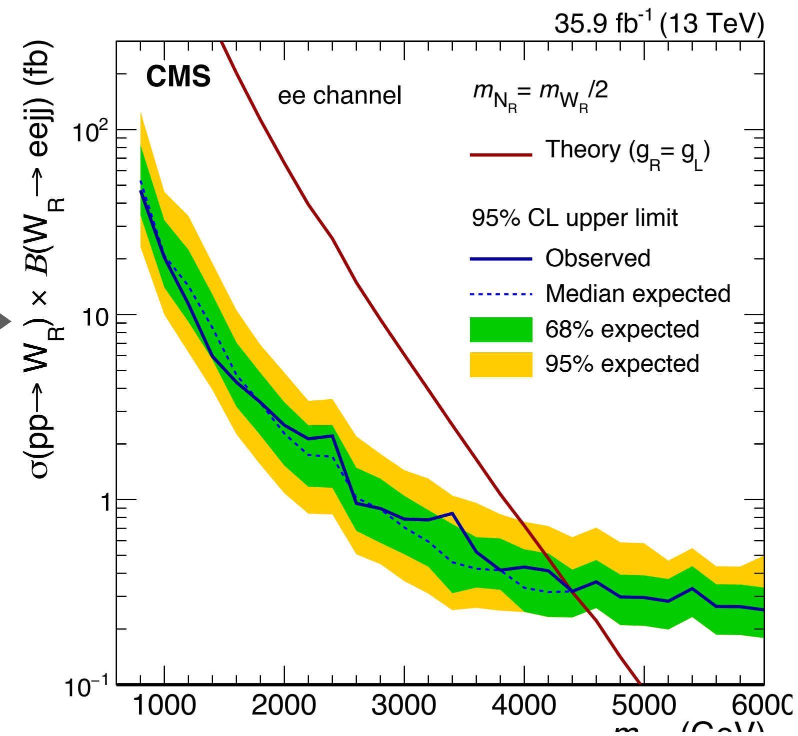


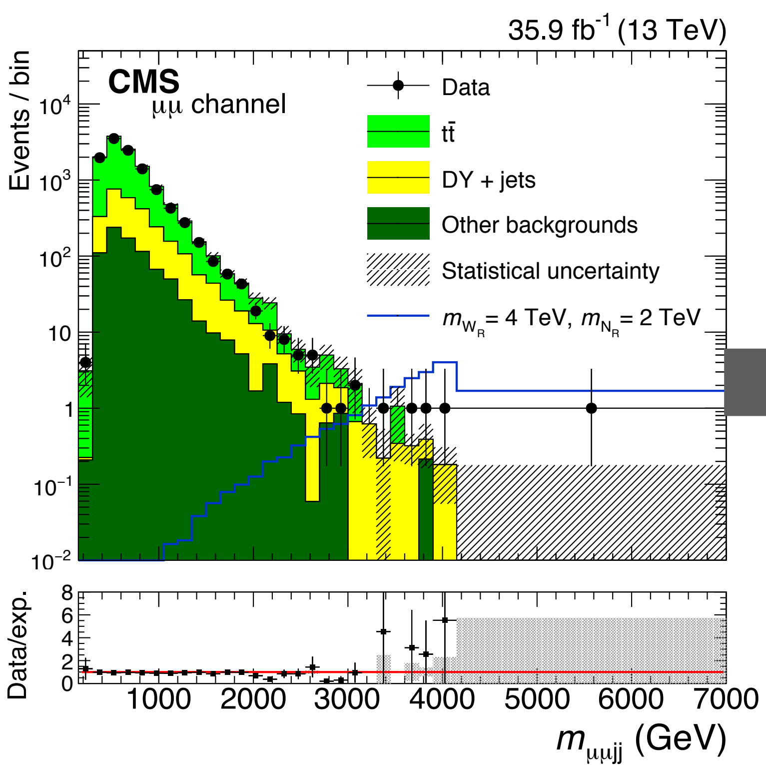
- Signal region requirements: $m_{\ell\ell}$>200 GeV, $m_{\ell\ell jj}$>600 GeV
- Background estimation :
  - $t\bar{t}$ (~75%) → data-driven estimate from e-μ CR
  - Drell-Yan+jets (~20%) → from simulation, normalized to data in Z peak region
  - W+jets, diboson, single top (~5%) → from simulation

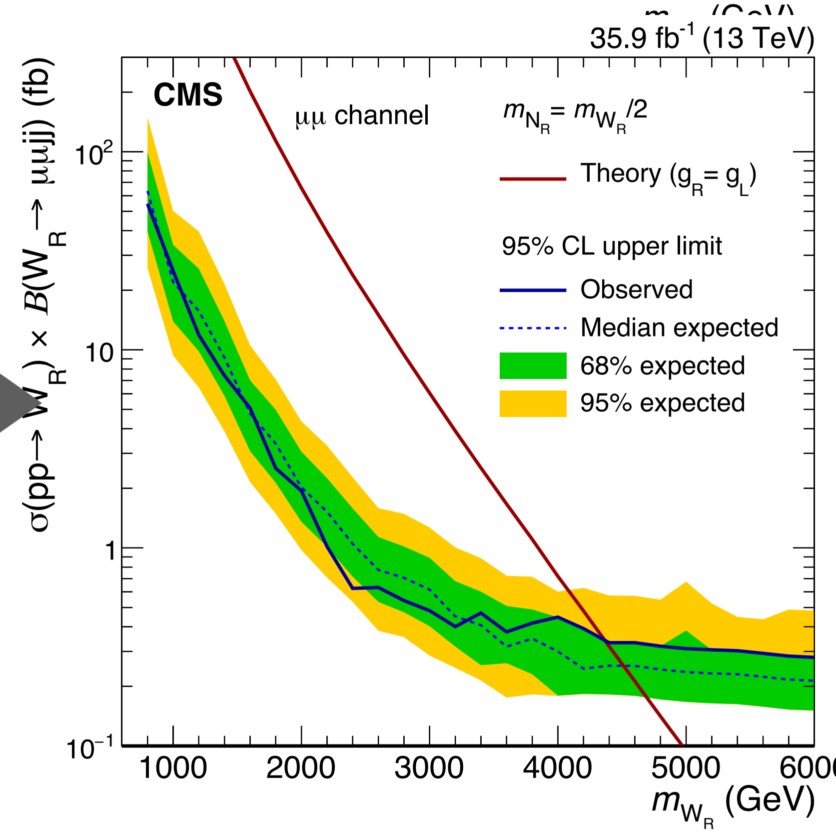
2016 data @ 13 TeV (lumi = 35.9 fb^{-1})

RH neutrinos from W_R in lljj events









- No significant excess observed ->Cut and count limit extraction.
- Limit set on m_{WR}. < 4.4 TeV.
  - Use m_N = 1/2 m_{WR}
- Improves limit by 1 TeV vs 2015 results.