Search for heavy neutral lepton at CMS

Martina Vit

On behalf of the CMS collaboration

30 July 2020

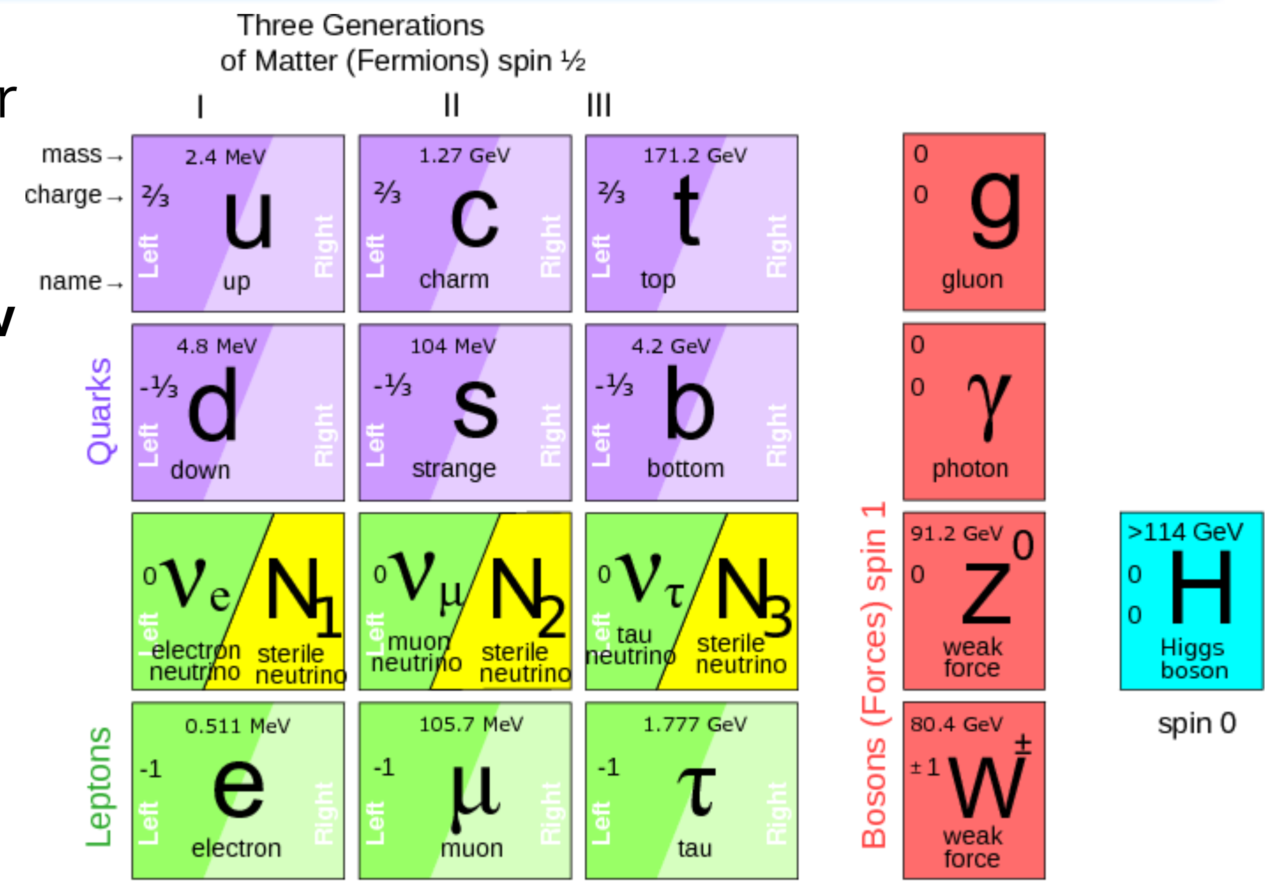
ICHEP2020: 40th International Conference on High Energy Physics, 28 Jul-6 Aug 2020

Heavy neutral leptons (HNL)

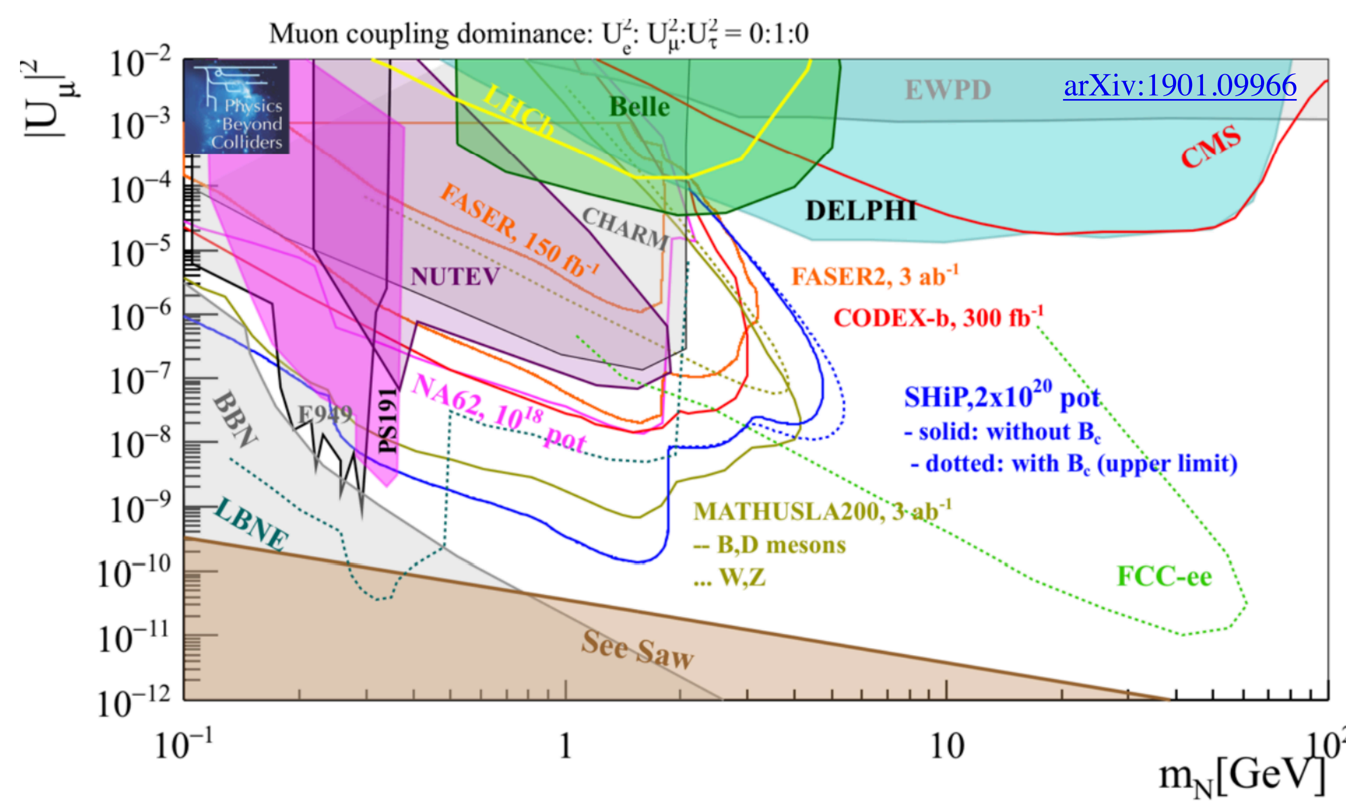
Right-handed **HNL** as potential solution for some of the outstanding problems of the SM.

- Origin of the **SM neutrino masses (seesaw mechanism)**;
- **dark matter candidate**;
- **matter-antimatter asymmetry.**

arXiv:hep-ph/0503065



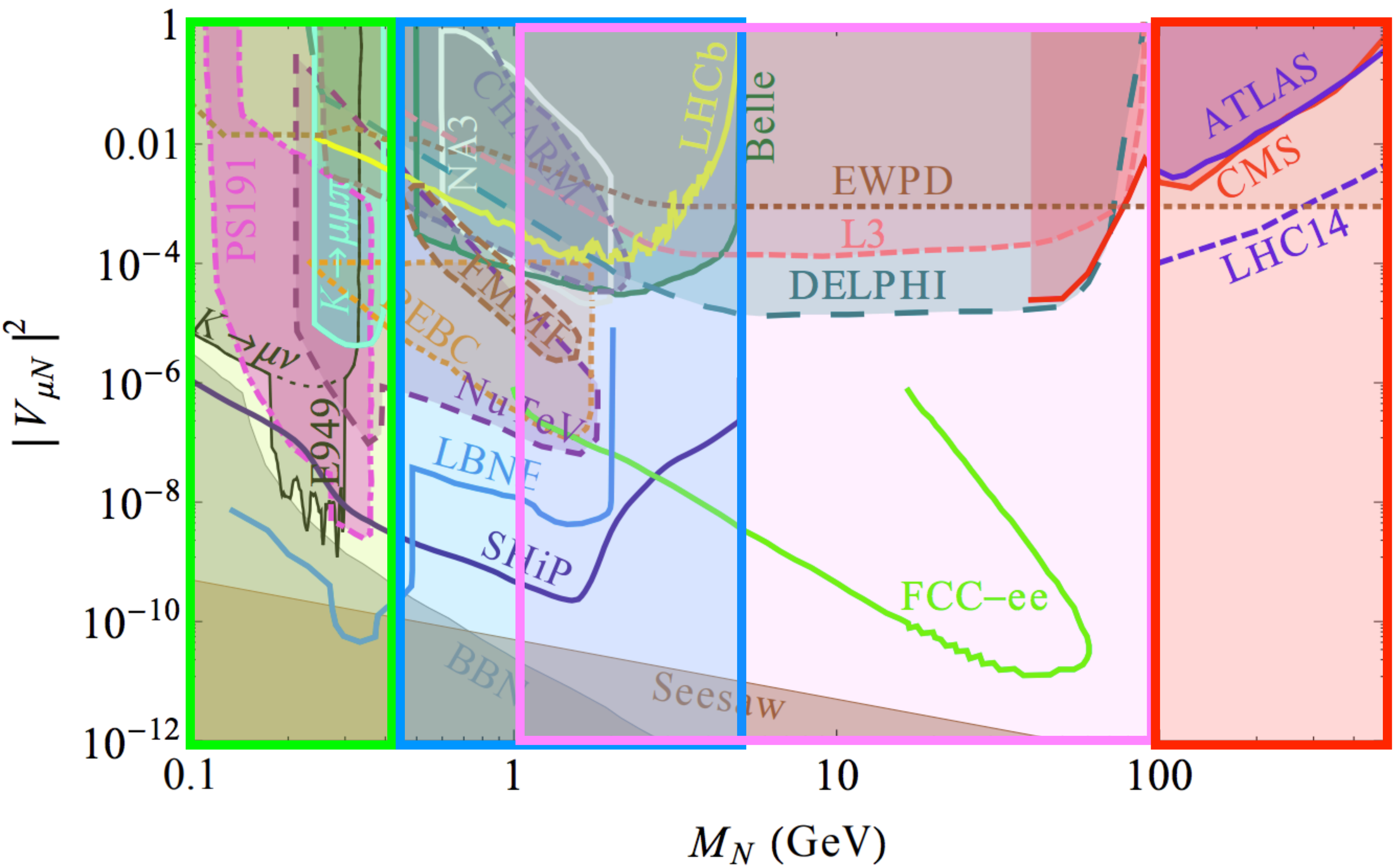
- N are sterile:
  - only interact with ν_{SM} through mixing: $\nu_{SM} \longrightarrow N$
- very low rate of $\nu \rightarrow N$: due to small mixing parameter $|V_{\ell N}|^2$ between ν_ℓ and N



Direct searches provide existing constraints and future projections on the mass and couplings with ν_{SM}

(filled areas - excluded; contours - projected experiments)

Direct searches: state and projections



- $m_N > m_Z$
- LHC can exceed the limits from electroweak precision data

- $m_N < m_Z$
- Results from LEP ($Z \to \nu N$)
- Currently explored at the LHC (ATLAS, CMS)

- $m_N < m_K$
- Using K decays, such as $K^\pm \to \ell N$, $K^\pm \to \mu\mu\pi$
- E.g. NA62

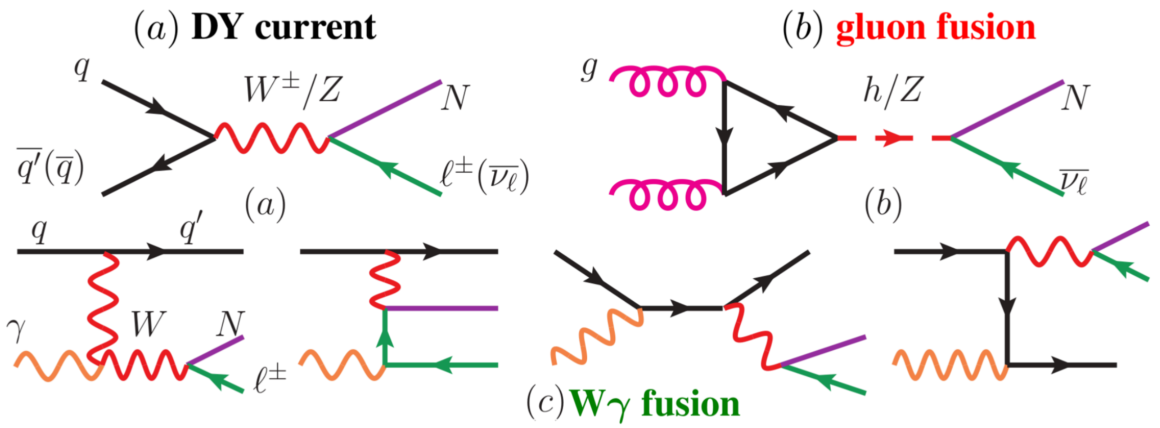
- $m_N < m_{D,B}$
- Explored at colliders (e.g. Belle, LHC*b*) or beam-dump experiments (e.g. SHiP)

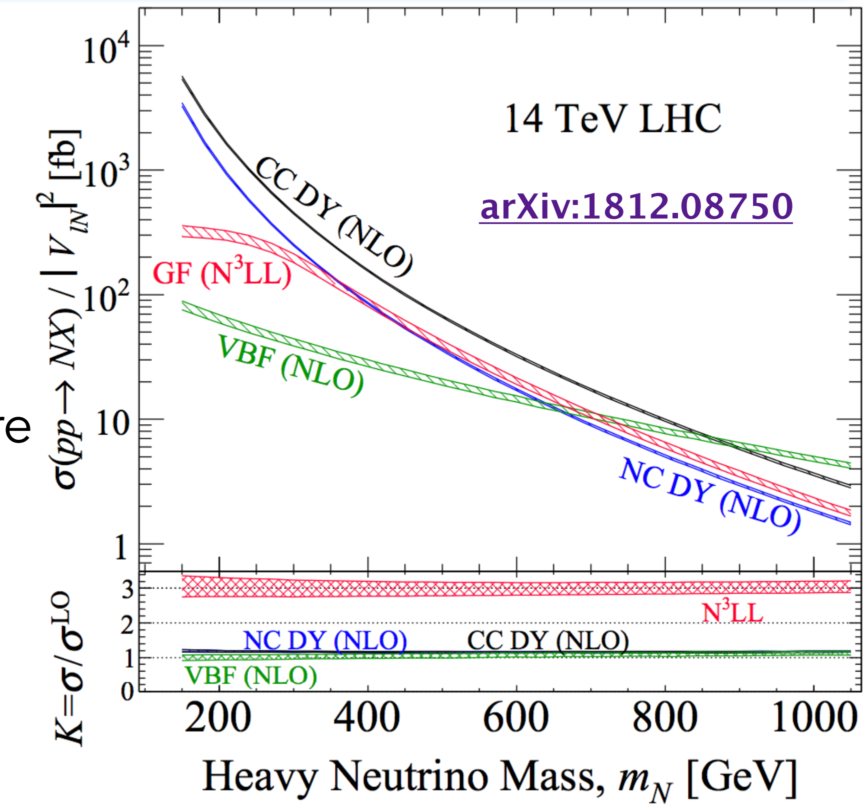
arXiv:1502.06541 [hep-ph]

By D. Trocino

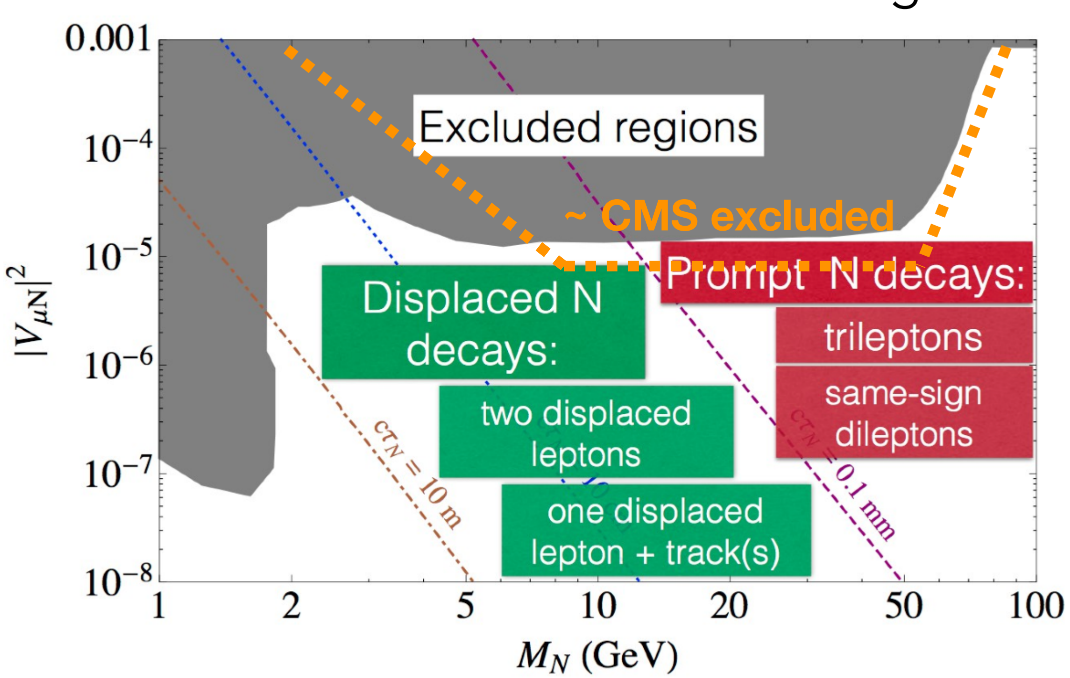
HNL production and decay at LHC

- $W^{\pm(*)}$ -> l+N (or Z/H -> vN)
  - Hight momentum lepton -> easy to trigger
  - Relatively large cross section
  - for high N masses VBF channel (Wγ fusion) becomes important
- Final states with multiple charged-leptons (Nl±) are experimentally more accessible





- HNL **decays**: $N \to W\ell$ $N \to Z\nu$ or $N \to H\nu$
- HNL **lifetime**: smaller is the mass or the N- mixing — longer N lives $\tau \propto \sum_i |V_{iN}|^{-2} m_N^{-5}$

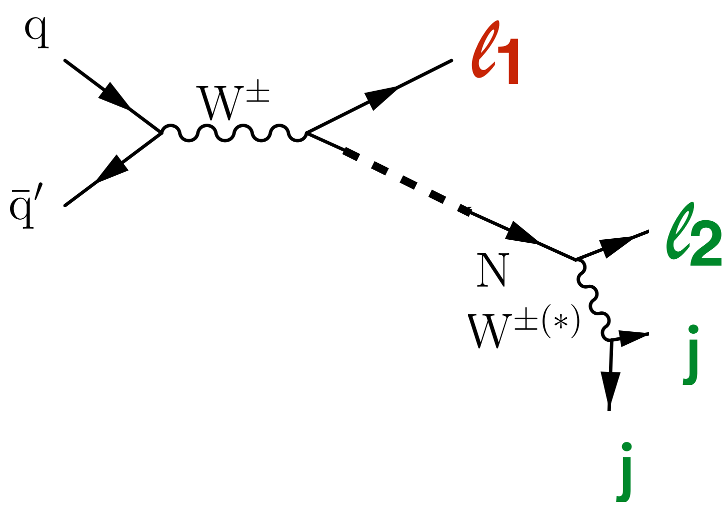


from very small (prompt decays) to macroscopic distances from production vertex (displaced decays) at very low mass and couplings.

Searches for prompt signatures

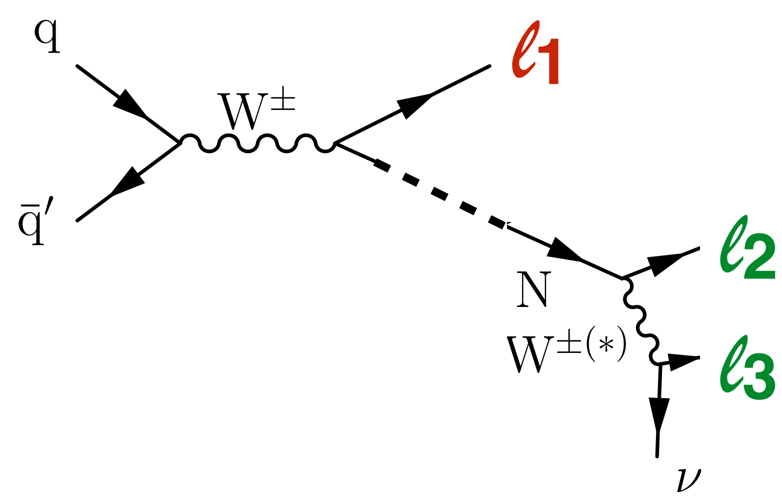
HNL from W decays: signal signatures

- Dilepton + 2 jets
  - fully reconstruct m_N peak
  - mostly sensitive to
    - high m_N (jet $p_T \gtrsim$ 30 GeV)



- Trilepton + missing energy (ν)
  - no clear m_N peak
  - can identify e and μ down to few GeV

  → low m_N



Depending on the nature of these *heavy neutral leptons* (HNL), decays can **conserve** or **violate** the lepton number

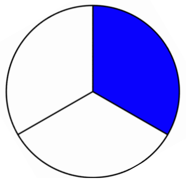
- **Dirac:** lepton number conserved (LNC) —> ℓ_1 and ℓ_2 OS
- **Majorana:** lepton number conserved (LNC) or violated (**LNV**) (LNV/LNC ratio is model dependent)
  - LNC: ℓ_1 and ℓ_2 **OS**
  - **LNV**: ℓ_1 and ℓ_2 **SS**

HNL in three leptons final state

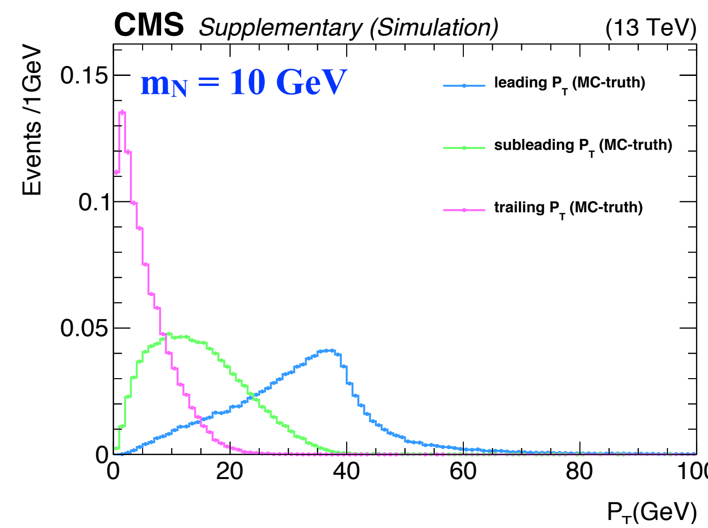
Trilepton final state

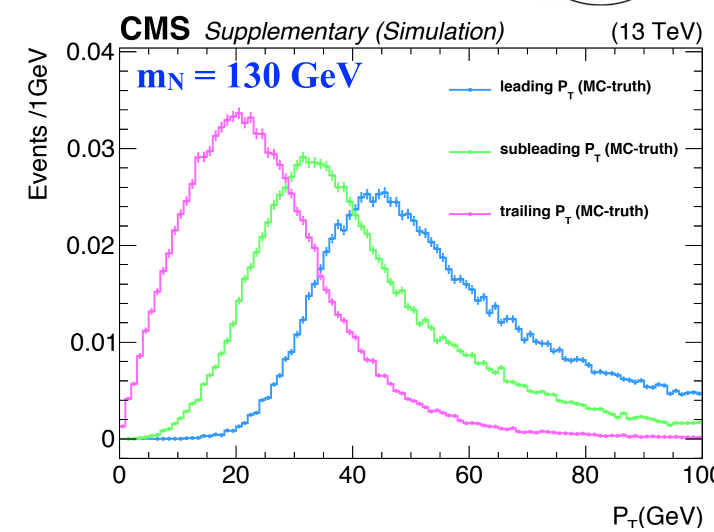
CMS-EXO-17-012

Run2 data



Search for a heavy neutral lepton N of Majorana nature decaying into a W boson and a charged lepton. The targeted signature consists of three prompt charged leptons in any flavor combination of electrons and muons.



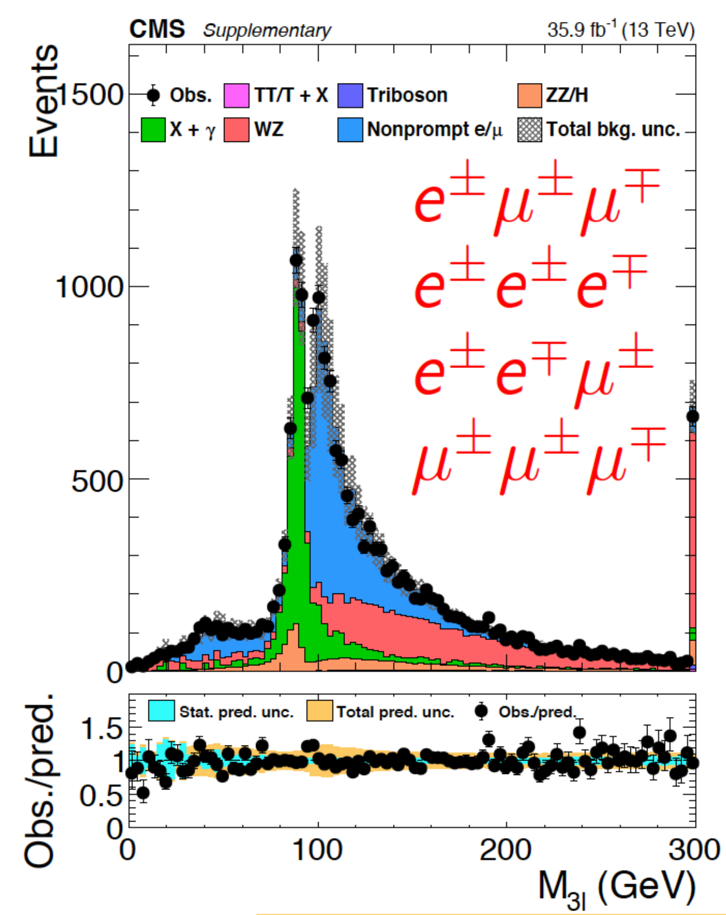


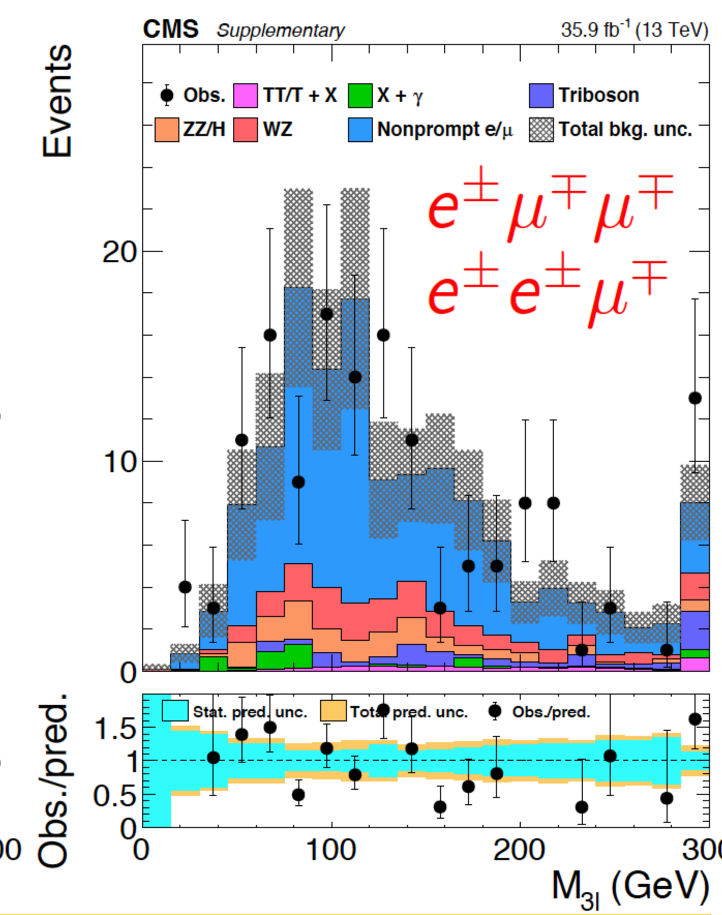
Signal features and identification

- Trilepton + missing energy (ν)
- lepton ***P_T* spectra are very soft** for low masses;
- leptons from HNL decay assumed to be prompt;
- moderate ETmiss, very small hadronic activity;

Background

- **non-prompt ℓ**
  - reducible background
  - mainly $t\bar{t} \to 2\ell$ and/or DY$\to 2\ell$ with a 3rd ℓ from jet fragmentation
- **rare processes**:
  - tribosons, ttX
- **WZ —> 3$\ell\nu$, ZZ —> 4ℓ**:
  - three signal-like leptons
  - almost always opposite-sign same flavor (OSSF) pair from Z —> 2ℓ
- **conversions:**
  - dominated by Zγ* with γ* —> 2ℓ
  - almost always with an OSSF pair





Two orders of magnitude background for events with an OSSF pair

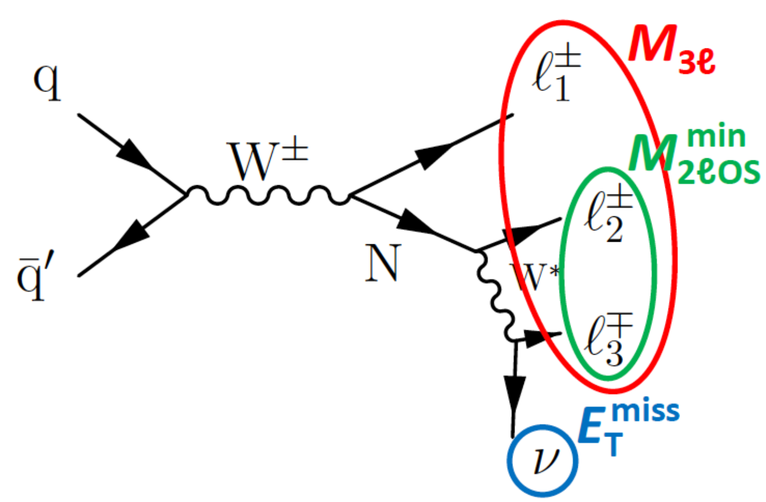
Trilepton final state

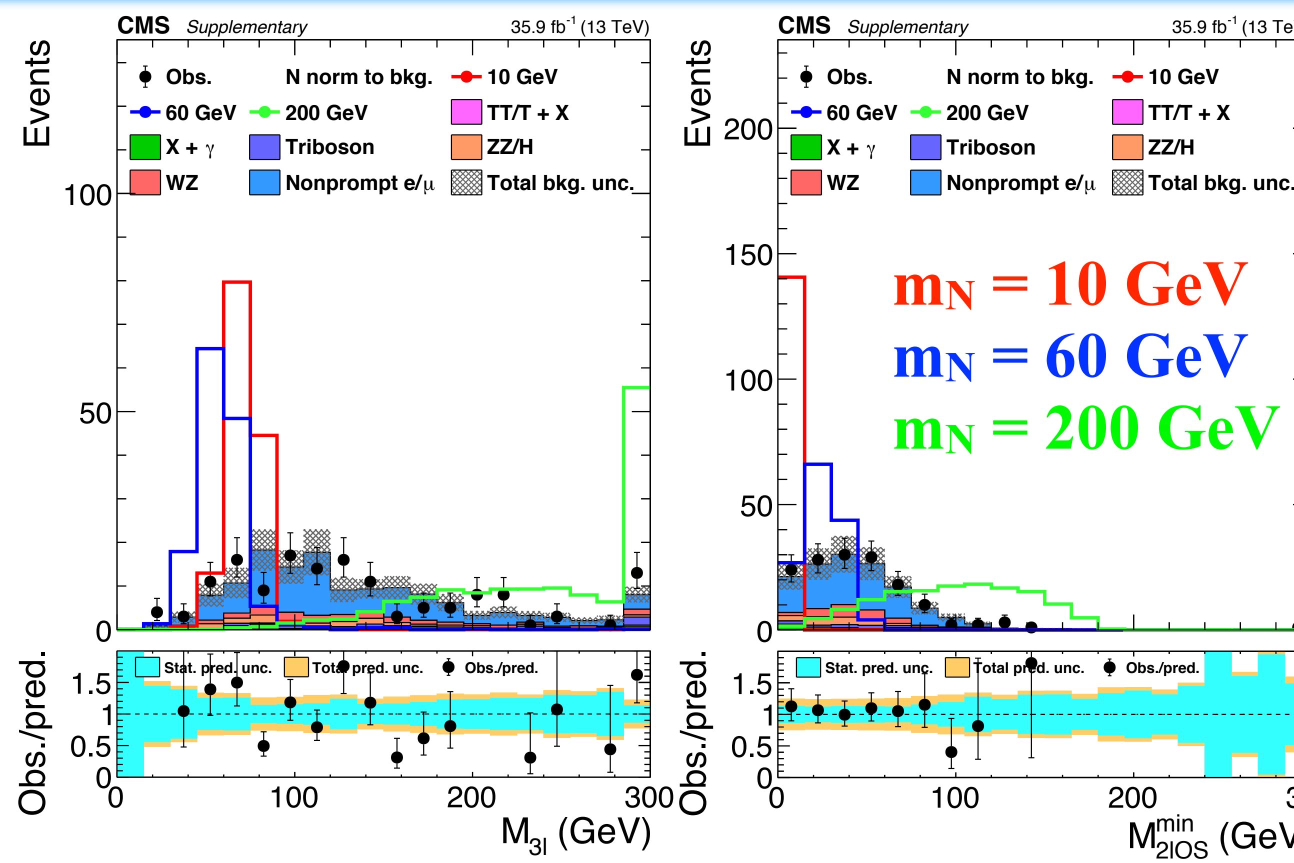
CMS-EXO-17-012

Search strategy

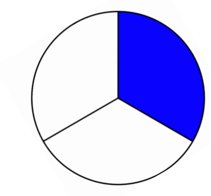
- 2 categories:
- low mass $m_N < m_W$:
  - categorize according to $P_{T(\text{leading})}$
  - Low pT threshold
  - Only use events without an OSSF pair
- High mass $m_N > m_W$:
  - Both OSSF and NO_OSSF
  - High pT threshold

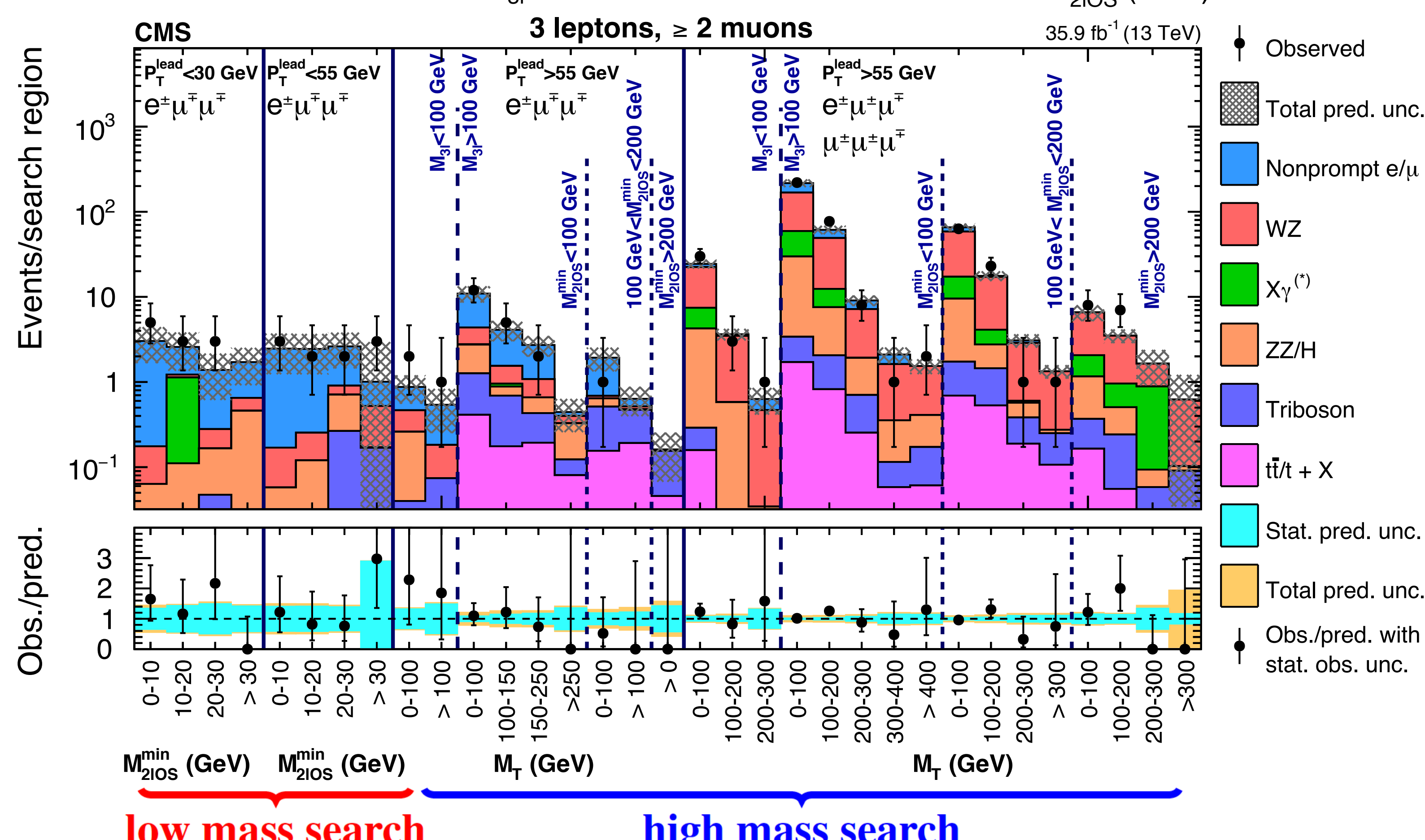
- Search variables:
  - M_{2lOS}, proxy for m_N
  - M_T, very high for high m_N
  - M_{3l}, for background rejection





Run2 data

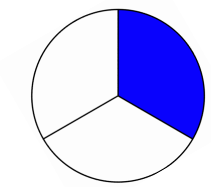




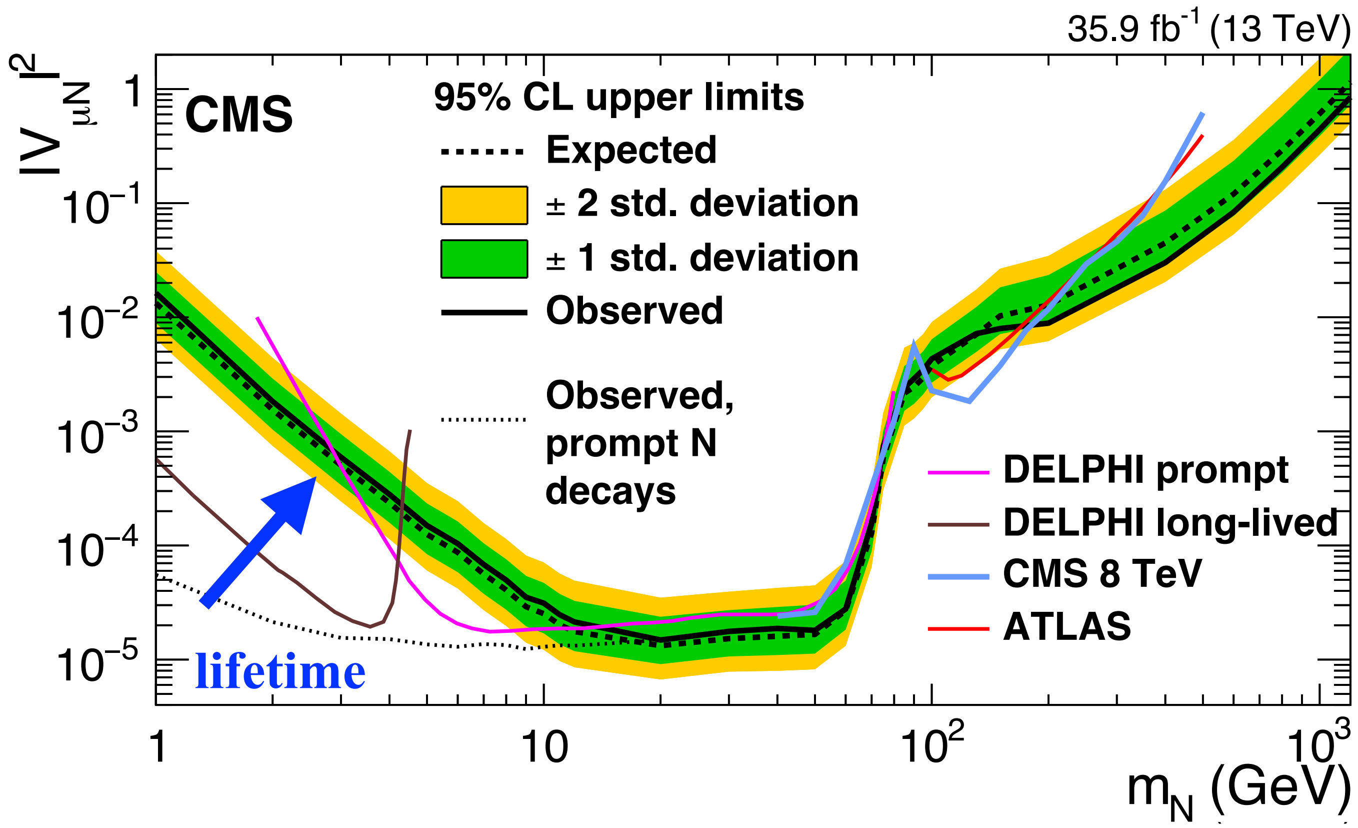
Trilepton final state

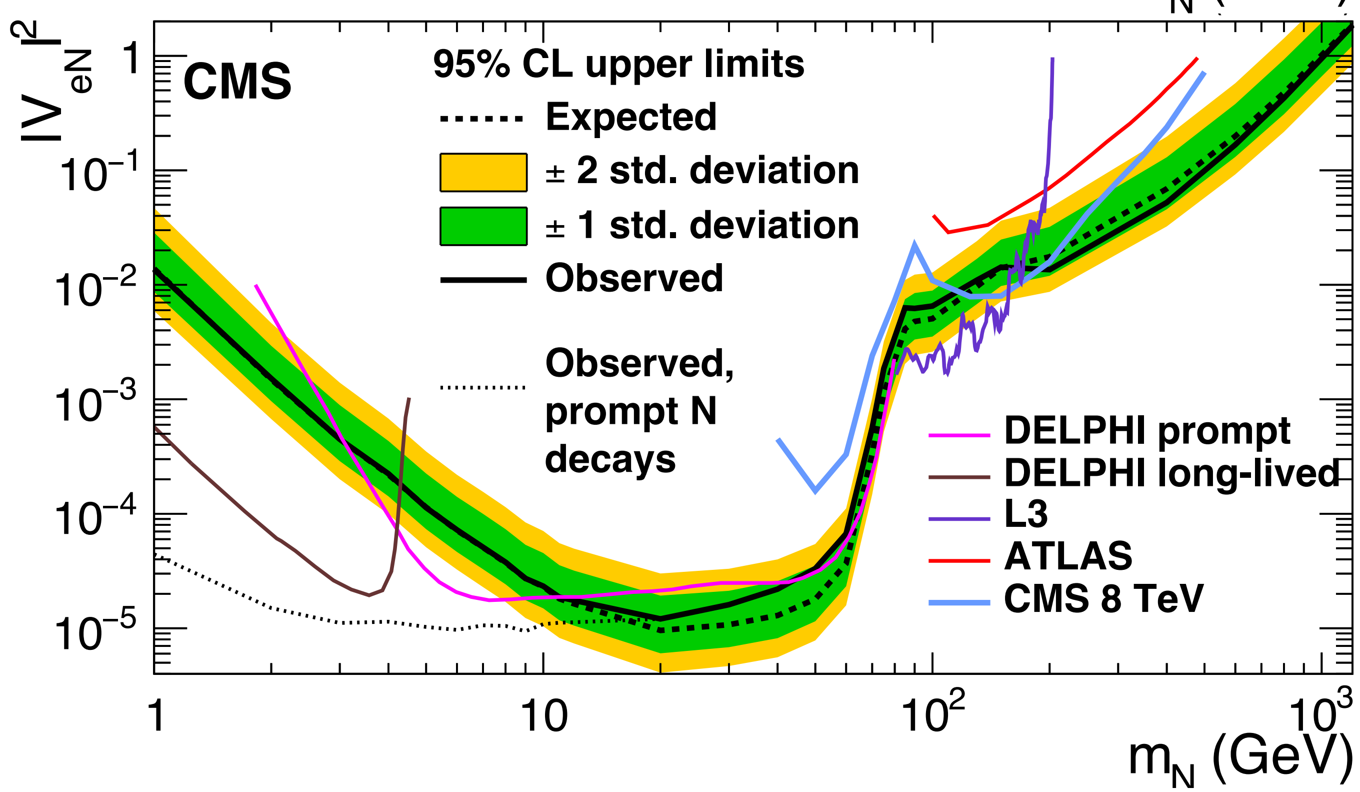
CMS-EXO-17-012

Run2 data



Final results





The data were collected in pp collisions at a $\sqrt{s}$ = 13 TeV, with an integrated luminosity of 35.9 fb^{-1} during 2016 Run.

No deviations from the SM are observed; upper limits set on ν_{SM}N coupling strengths V_{eN} and $V_{\mu N}$

New sensitivity

These are the **first direct limits** for N masses **above 500 GeV**

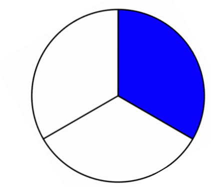
The first limits obtained at a hadron collider for **N masses below 40 GeV**

HNL in two same-sign leptons final state

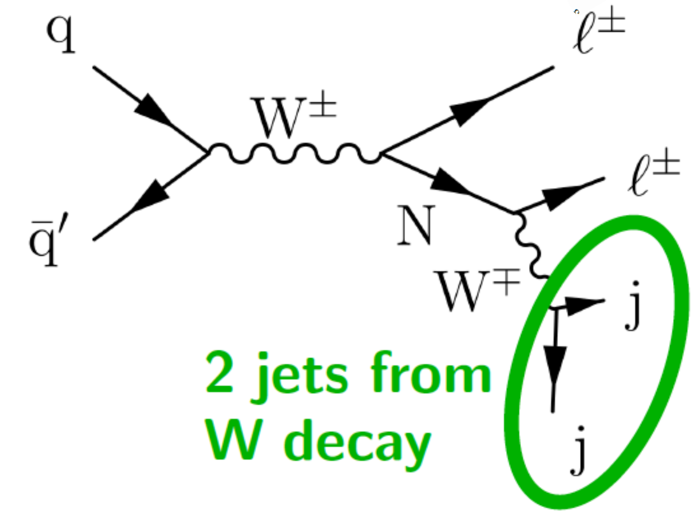
Dilepton-lljj final state

CMS-EXO-17-028

Run2 data



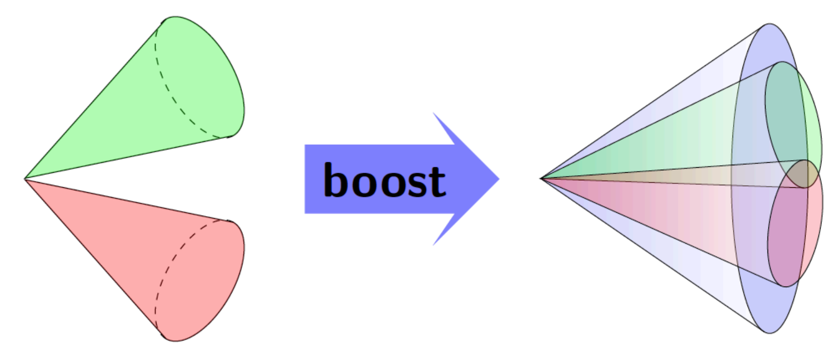
Search is performed for a heavy Majorana neutrino (N), produced by leptonic decay of a W boson propagator and decaying into a W boson and a lepton. The signature used in this search consists of two same-sign leptons, in any flavor combination of electrons and muons, and at least one jet.



Signal features and identification

- Signal contains **jets from hadronic W**
- Jet **reconstruction highly depends on m_N**
    - **Low m_N**: jet may fail to be reconstructed → **1 jet**;
    - **Intermediate m_N**: both jets reconstructed → **2 jets**;
    - **Very high m_N**: due to boost jets might merge → **1 fat jet**

- Search split into **several jet-content categories**:
    - ≥ 2 jets (anti-k_T 0.4): target low and high-mass N
    - = 1 jet (anti-k_T 0.4): low mass N
    - ≥ 1 fat-jet (anti-k_T 0.8): high mass N



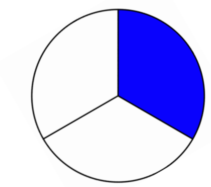
Background

- **non-prompt *l***
    - Dominated by W + hets and tt →1l
    - Second lelpton from jet-fragmentation
- **WZ, ZZ**:
    - Multiple prompt leptons
    - One or several leptons fail selection
- **conversions:**
    - dominated by Wγ* with γ* → 2l
- **Mismeasured charge:**
    - Charge of lepton wrongly measured
    - Negligible for μ
    - Dominated by DY → ee

Dilepton-lljj final state

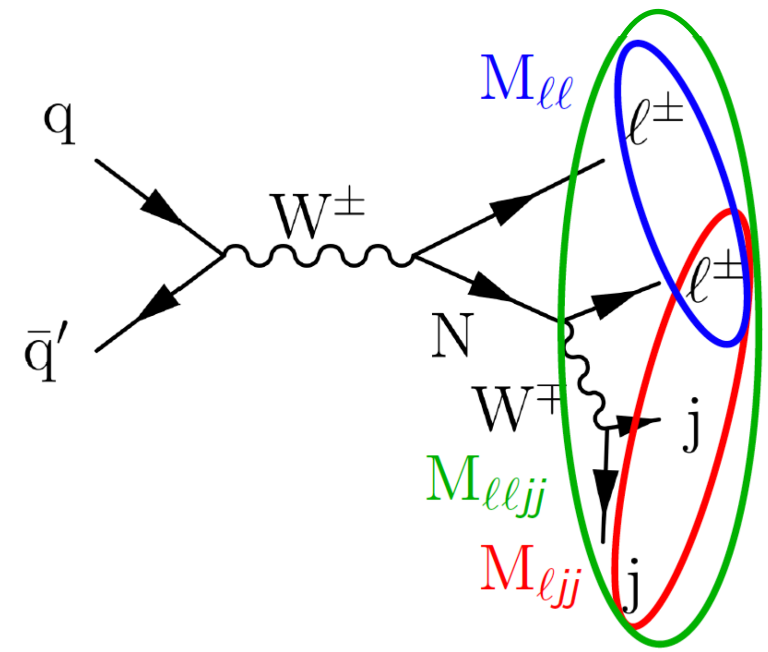
CMS-EXO-17-028

Run2 data

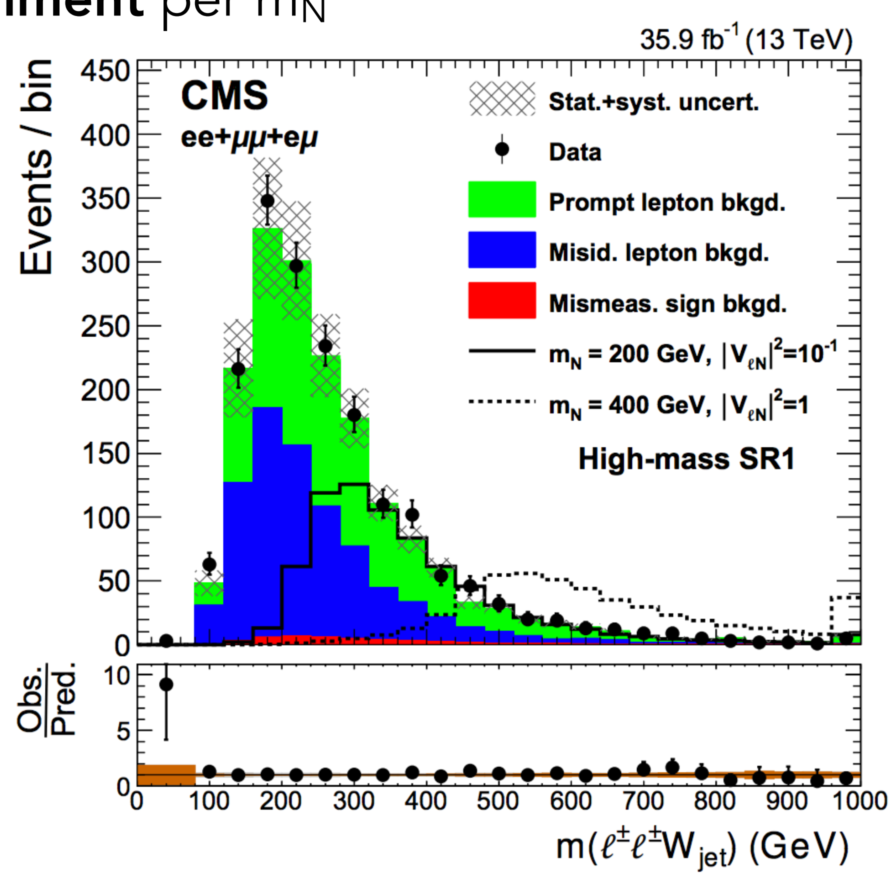


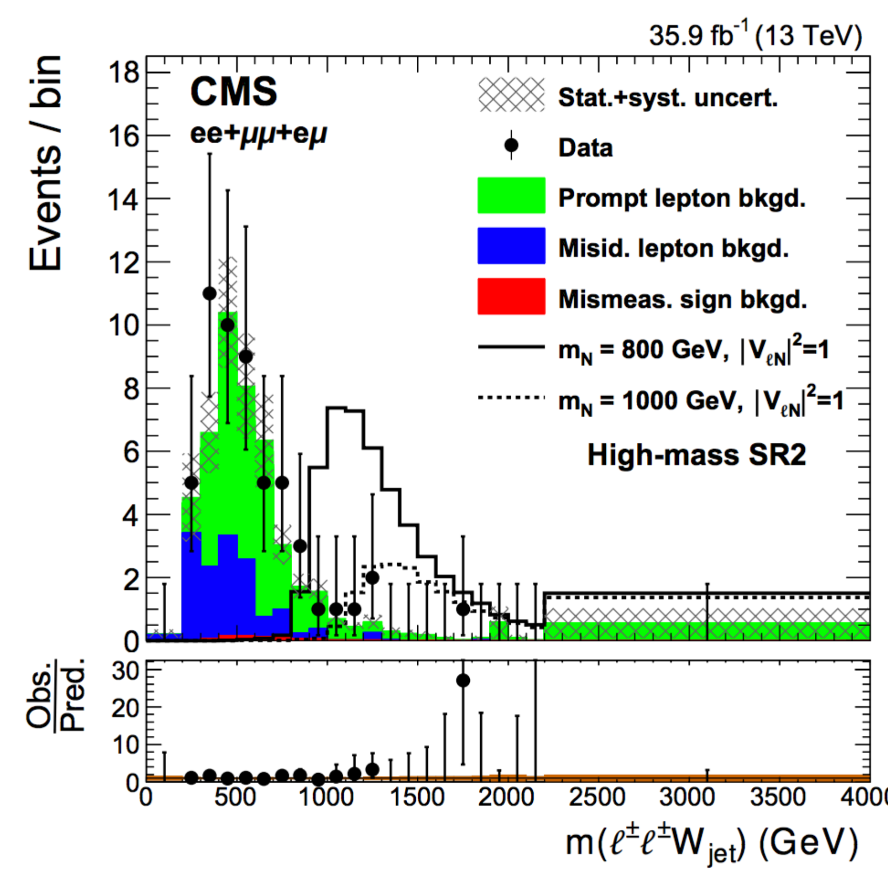
Search strategy

- Search variables:
  - **M_{lljj}**, peaks at m_W for light N, very large for heavy N
  - **M_{ll}**, good at rejecting backgrounds
  - **M_{ljj}**, peaks at m_N
  - P_T^{ℓ}
  - $\left|E_T^{miss}\right|^2 / S_T$: no ν in signal
    $\left(S_T = \sum_{leptons, jets, E_T^{miss}} |P_T|\right)$



- optimization strategy:
  - Construct bin with **optimal significance** for every m_N
  - **Single-bin counting experiment** per m_N



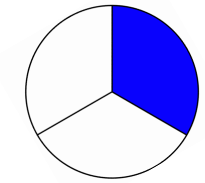


Dilepton-lljj final state

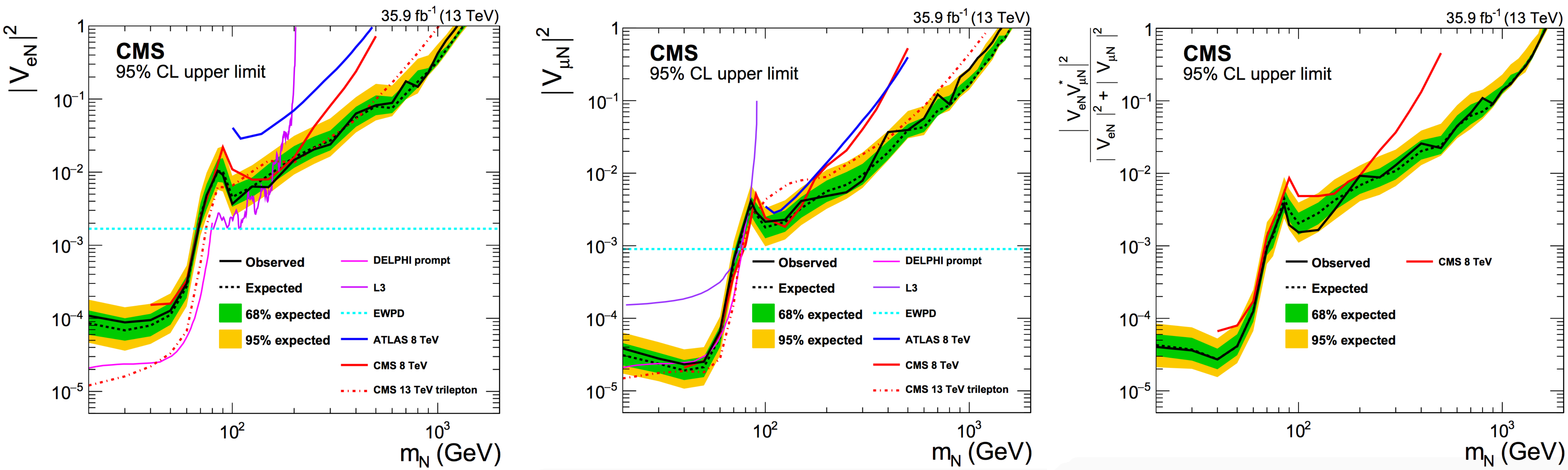
CMS-EXO-17-028

Run2 data

Final results



No deviations from the SM are observed; upper limits set on $\nu_{SM}N$ coupling strengths V_{eN} and $V_{\mu N}$ and mixed coupling



New sensitivity

First direct limits for **m_N > 1.2 TeV**

Most stringent limits for **m_N > 430 GeV**

Improve upon trilepton limits for high m_N

Lose sensitivity at low m_N due to jet P_T thresholds

Mixed coupling

It **can not be unambiguously probed in trilepton events** (ambiguity whether the lepton originates from N decay or not)

Use **dilepton (eμ) events to set limits**

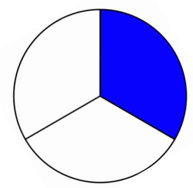
Significant improvement upon 8 TeV CMS results

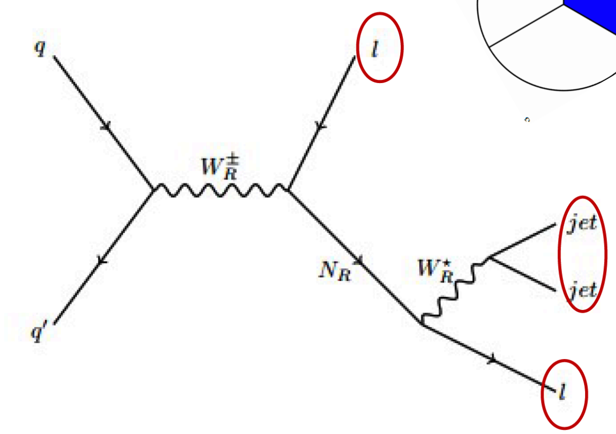
W_R - 2 SS leptons and 2 jets

CMS-EXO-17-011

Run2 data

Search for a heavy right-handed W boson (W_R) decaying to a heavy right-handed neutrino and a charged lepton in events with two same-flavor leptons (e or μ) and two jets.





Signal features and identification

- **Left-right symmetric model extension of the SM**:
  - Coupling of right-handed W are the same as left-handed W;
  - Intermediate heavy neutrino N_R
  - No flavor changing → final state has **2 same flavor leptons and 2 jets**
- Analysis designed to minimize model dependencies → not optimizing the selection on a specific signal model
- Select events with at least 2 leptons and at least 2 jets
- Reconstruct the **4-objects mass m_{lljj}**
- 2 signal regions, 1 for **μ channel** and 1 for **e channel**

Background

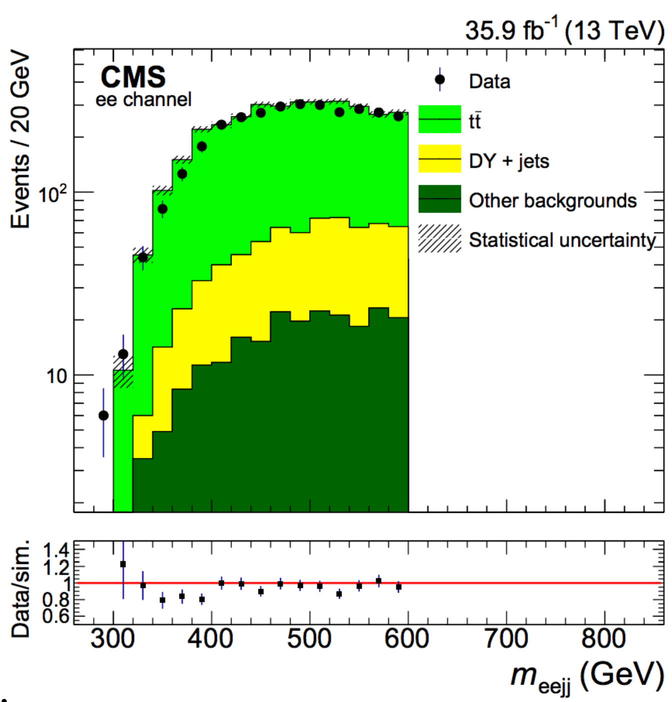
3 control regions

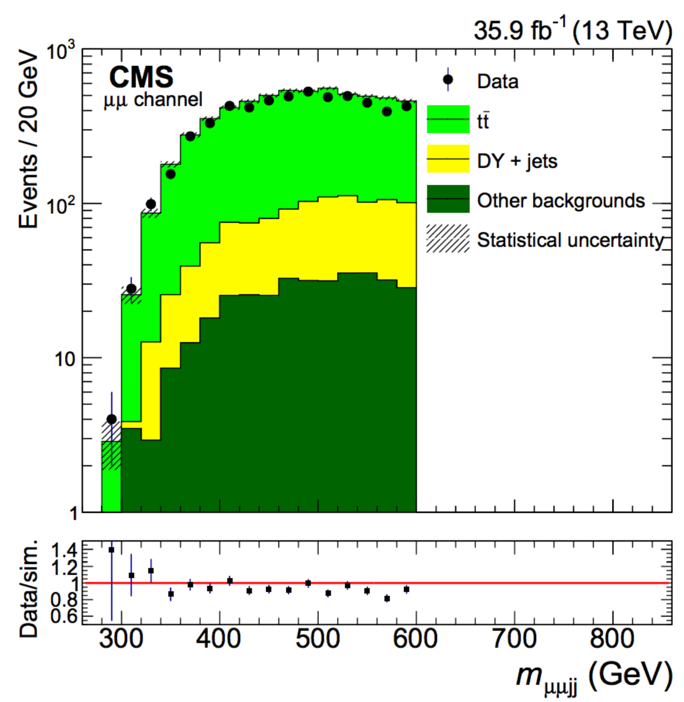
Two main (irreducible) backgrounds:

- TTbar (~ 75 %):
  - from data → in flavor sideband
- DY + jets (20%):
  - from simulation + normalization to data in control region

Additional (reducible) background (5%)

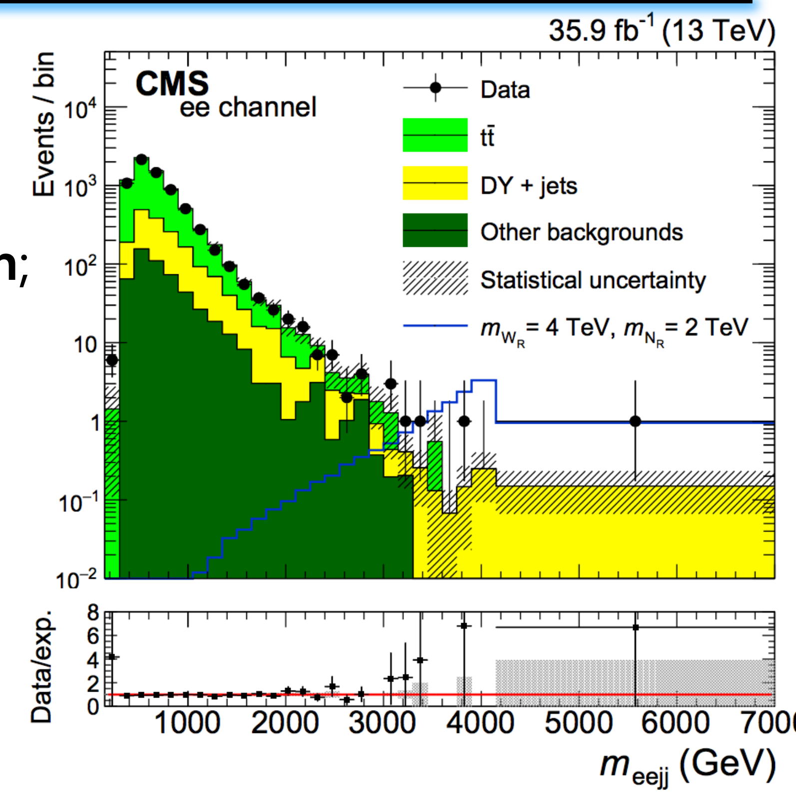
- W+jets, diboson, singleTop → from simulation





W_R - 2 SS leptons and 2 jets

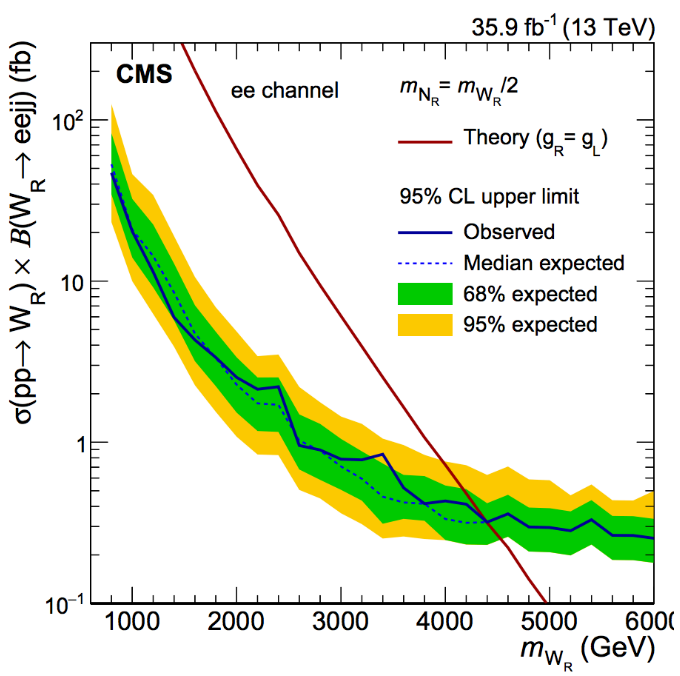
CMS-EXO-17-011

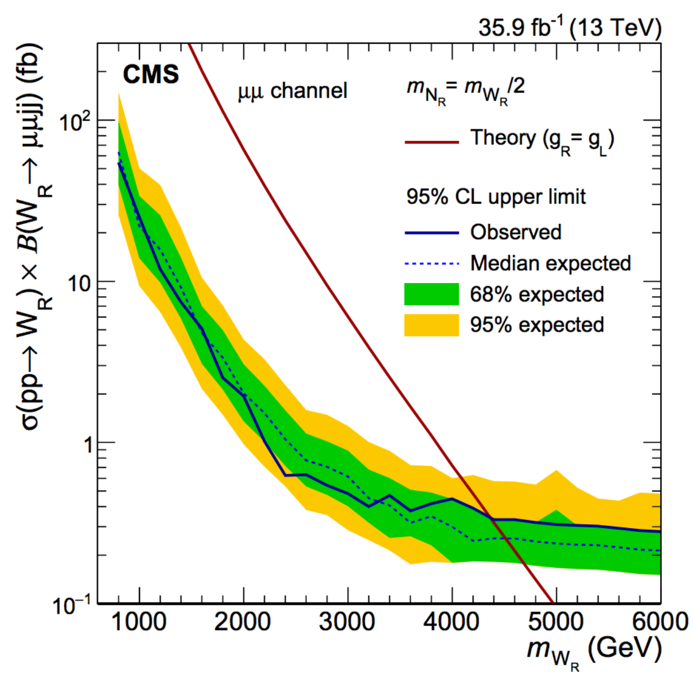


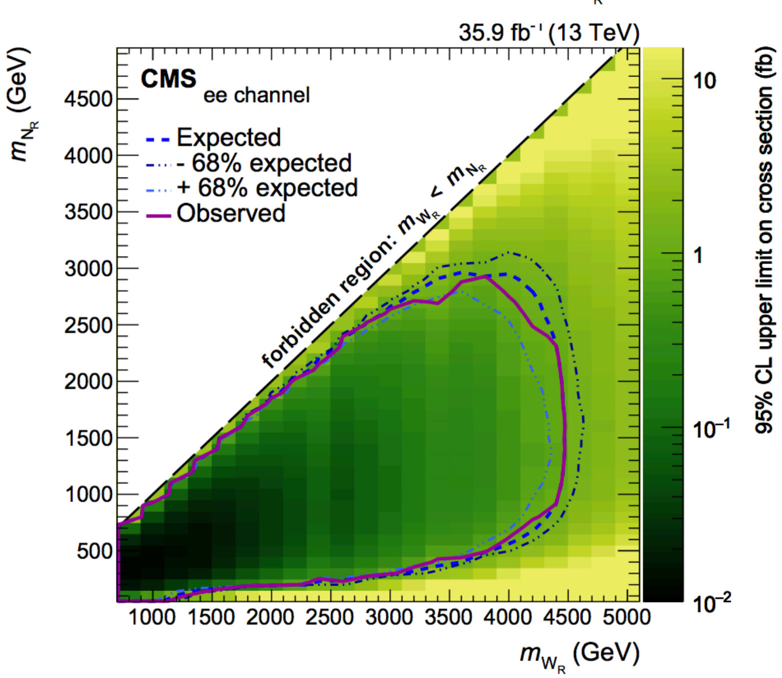
Analysis strategy

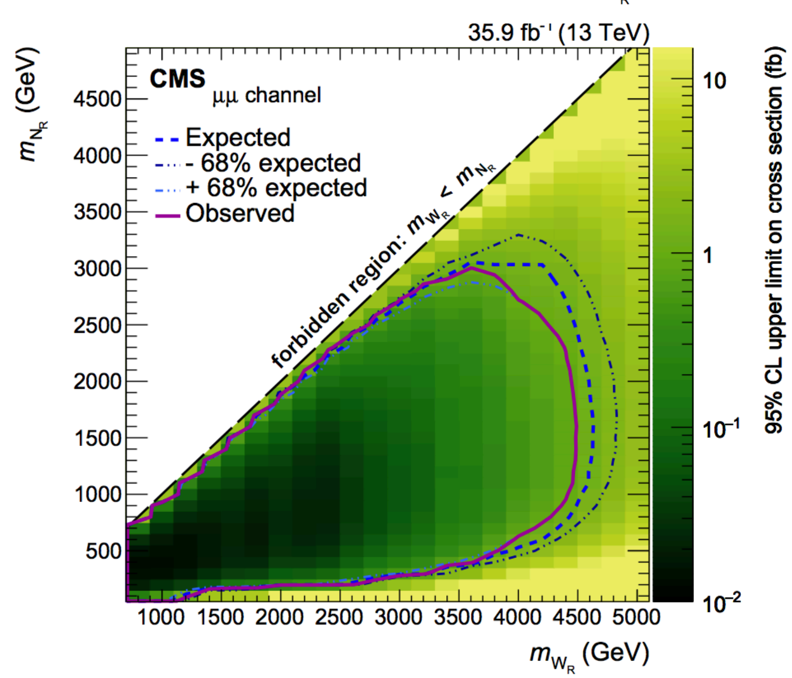
- **cut&count approach** in windows of m_{lljj} distribution:
  - windows of m_{lljj} → **minimizing the expected upper limit on the W_R x-section;**

Final results







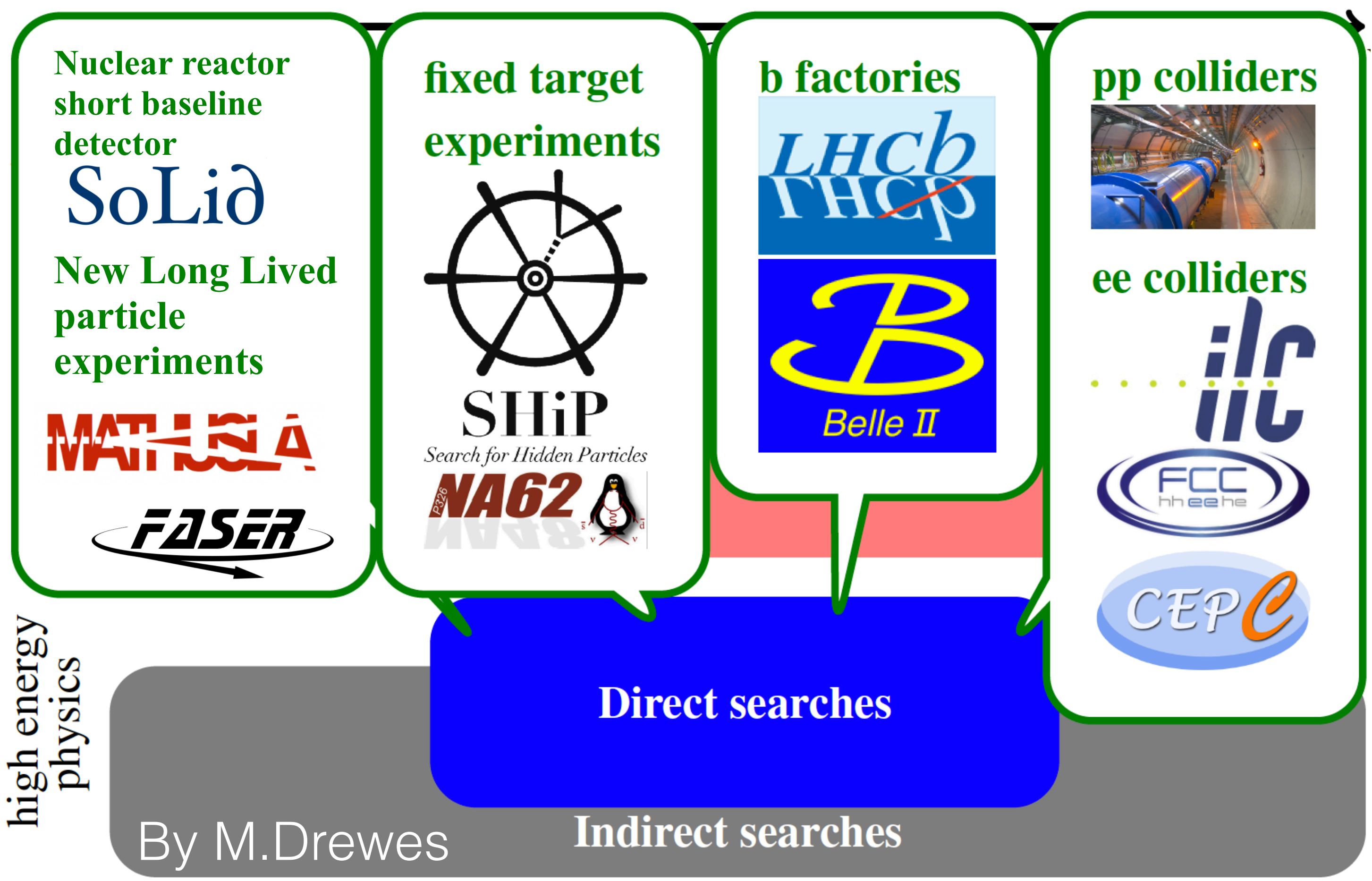


No significant excess are observed

- Limits on the W_R cross section are set **as function of the m_{W_R} and m_{W_R} vs m_{N_R}**
- m_{N_R} **excluded up to 4.4 TeV** when **m_{N_R} = 1/2 m_{W_R}**

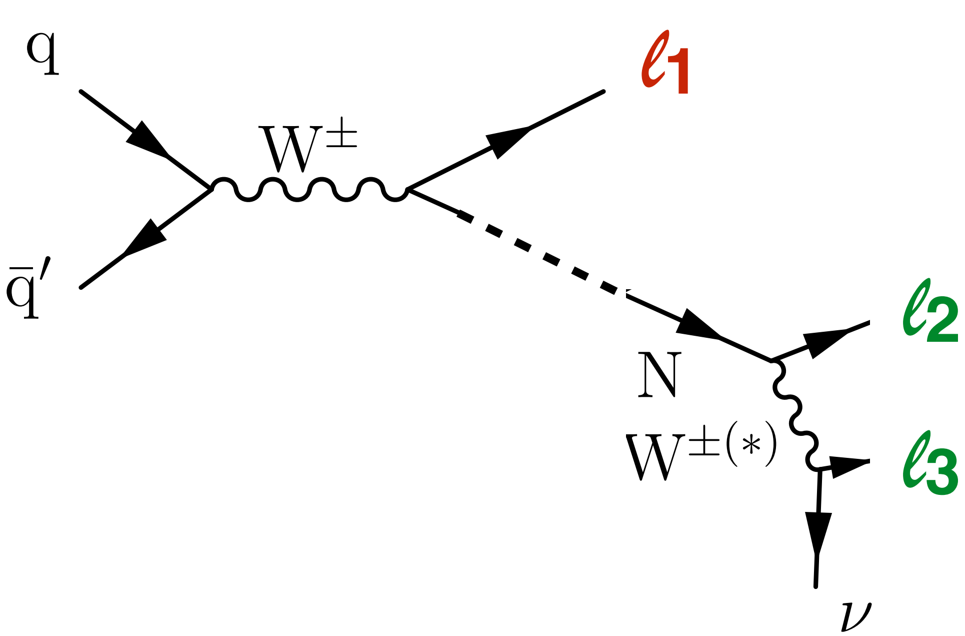
Summary and outlook

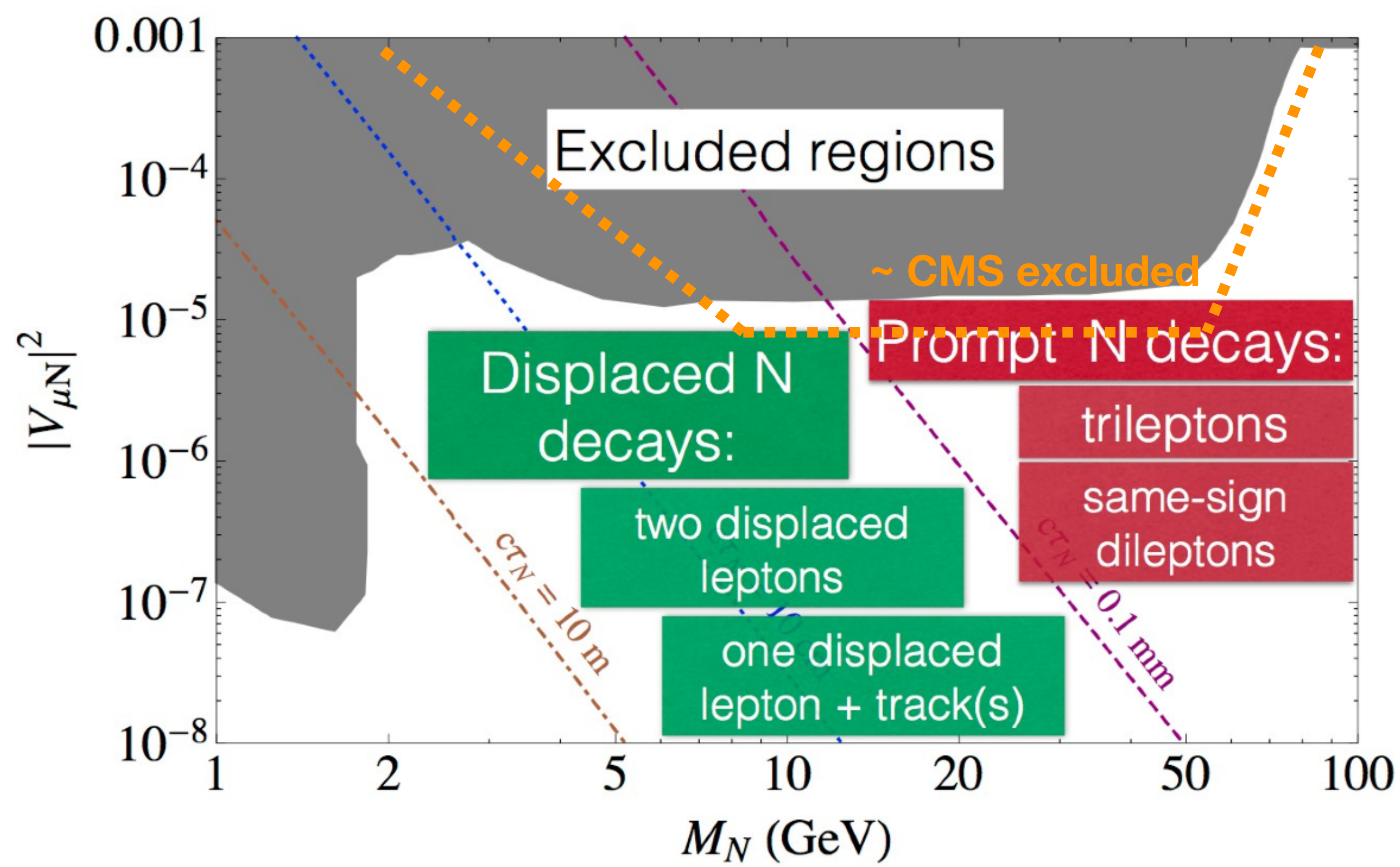
- The CMS experiment participates actively in the HNL hunting
  - extend the search to ~TeV masses
- Several searches already carried out with 2016 data, new results with full Run2 data are coming out
  - HNL from decay of B hadrons and W bosons
- New developments are underway
  - already tackling long-lived HNLs



Future steps

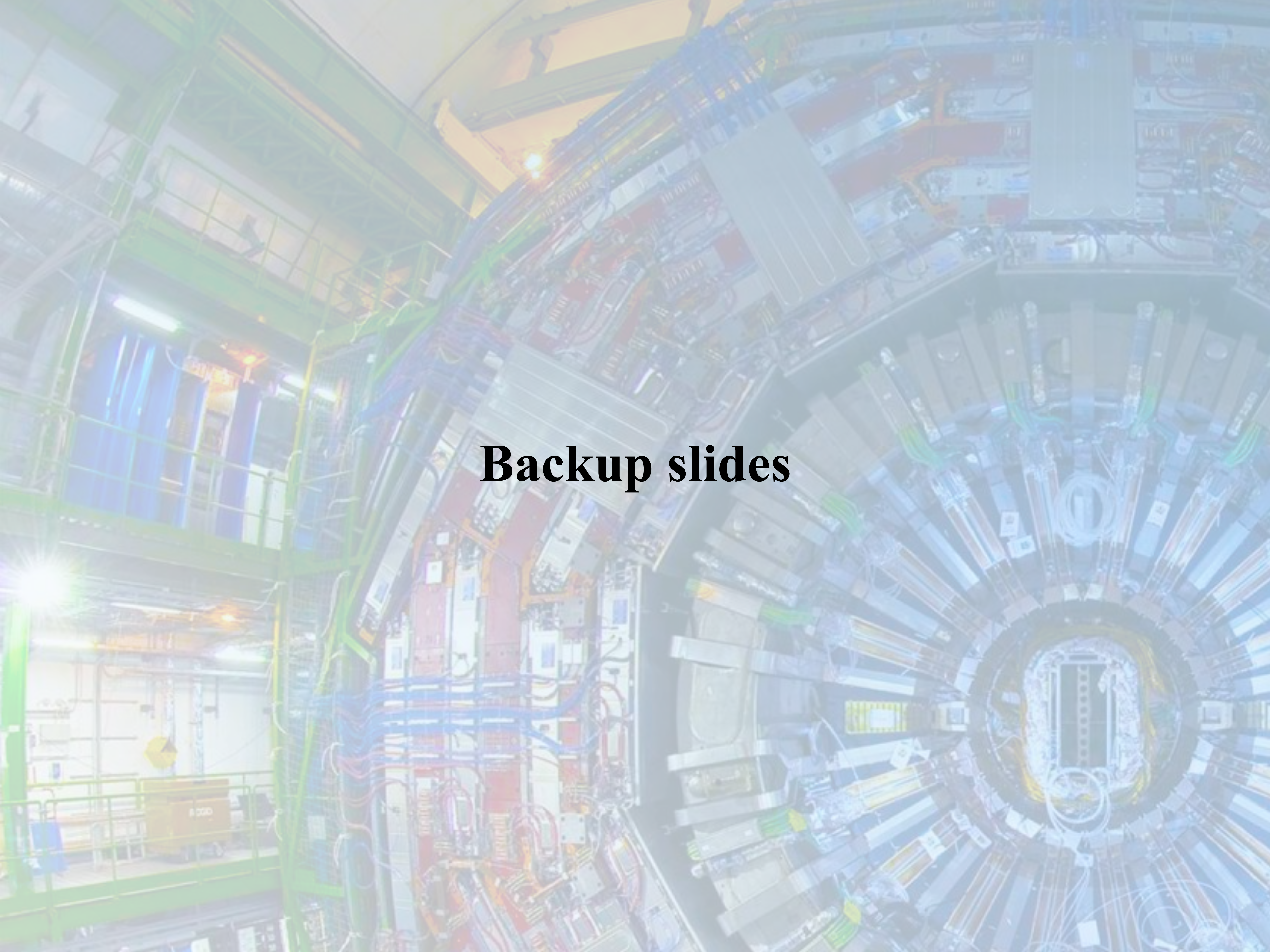
To increase our sensitivity to lower HNL masses and couplings, signatures with **displaced vertices** will have to be considered





to be continued…

HNL hunting is open!



Backup slides

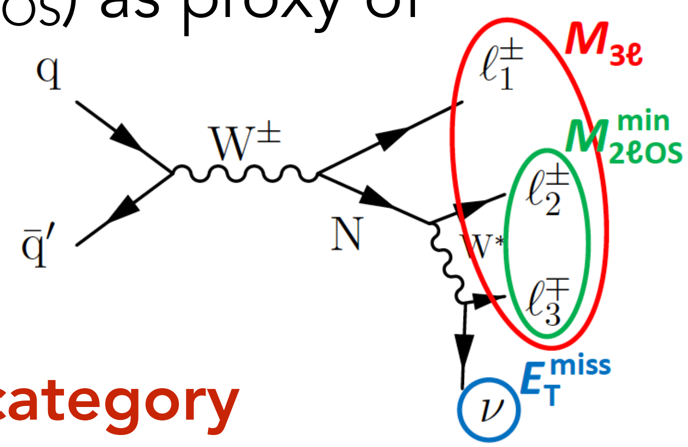
Search variables and strategy

arXiv:1802.02965

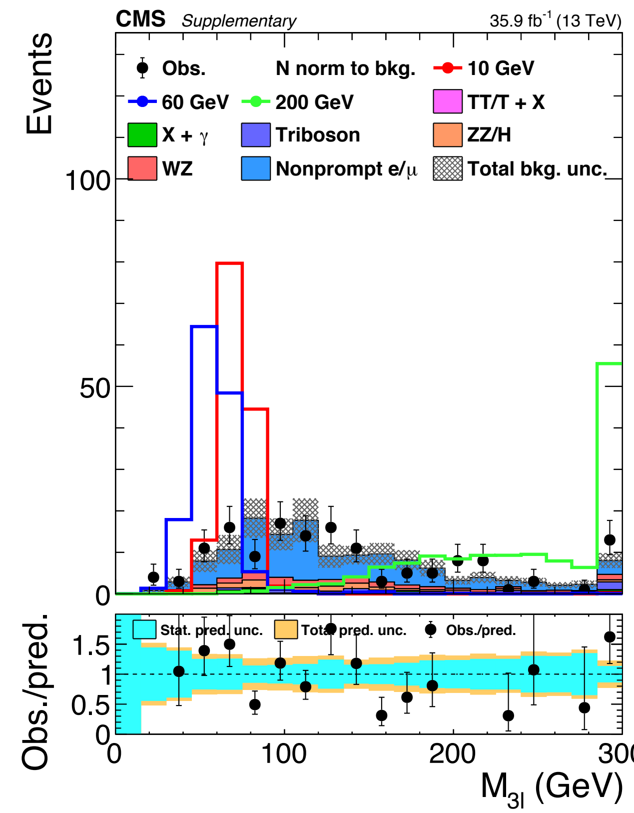
Low mass $m_N < m_W$

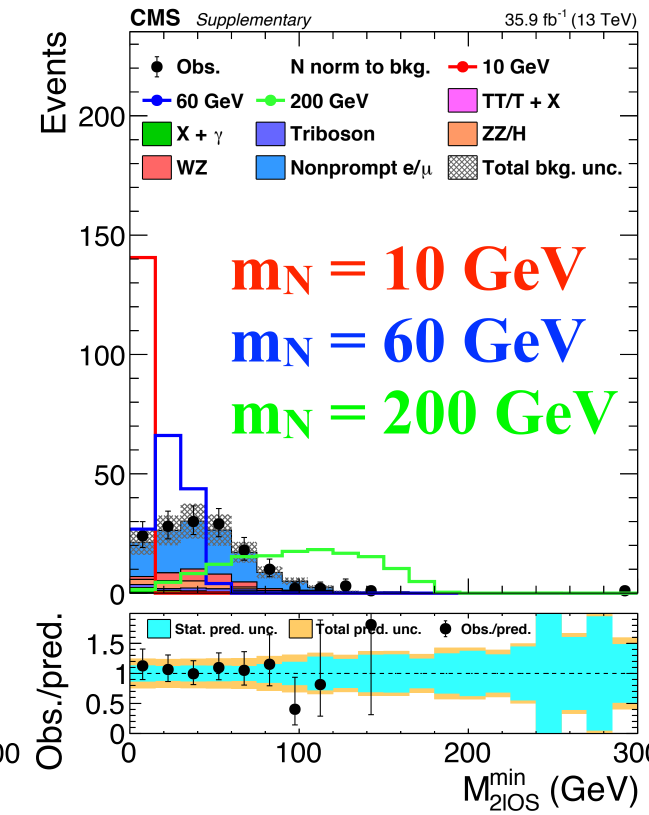
- ☑ categorize according to $P_{T(leading)}$

  < 30; 30 – 55 *GeV*
- ☑ binning in $\min(M_{2lOS})$ as proxy of M_N



only without OSSF category

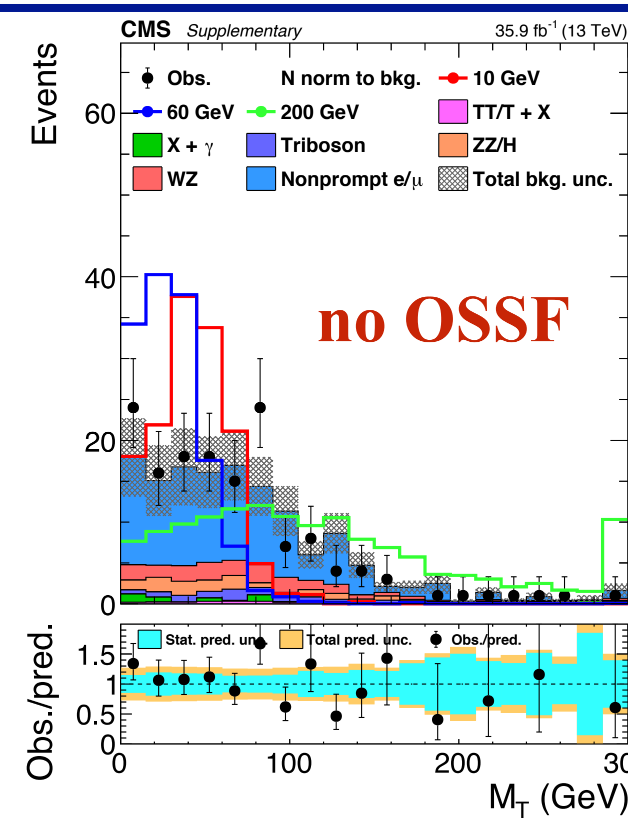


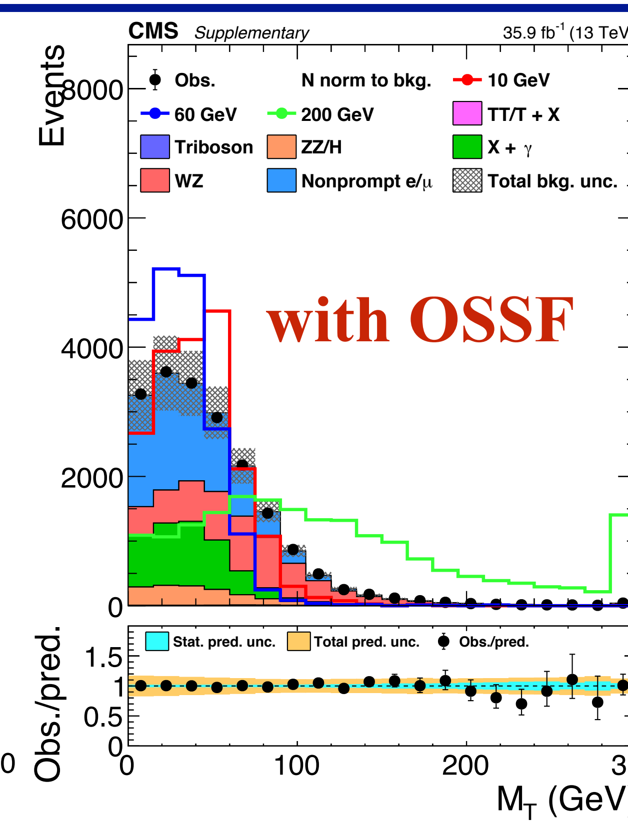


High mass $m_N > m_W$

- relatively soft trailing lepton, very hard leading lepton
- ☑ P_T > 55, 15, 10 *GeV*
- ☑ binning in $\min(M_{2lOS})$ and M_T(third)

with and without OSSF categories





Systematics

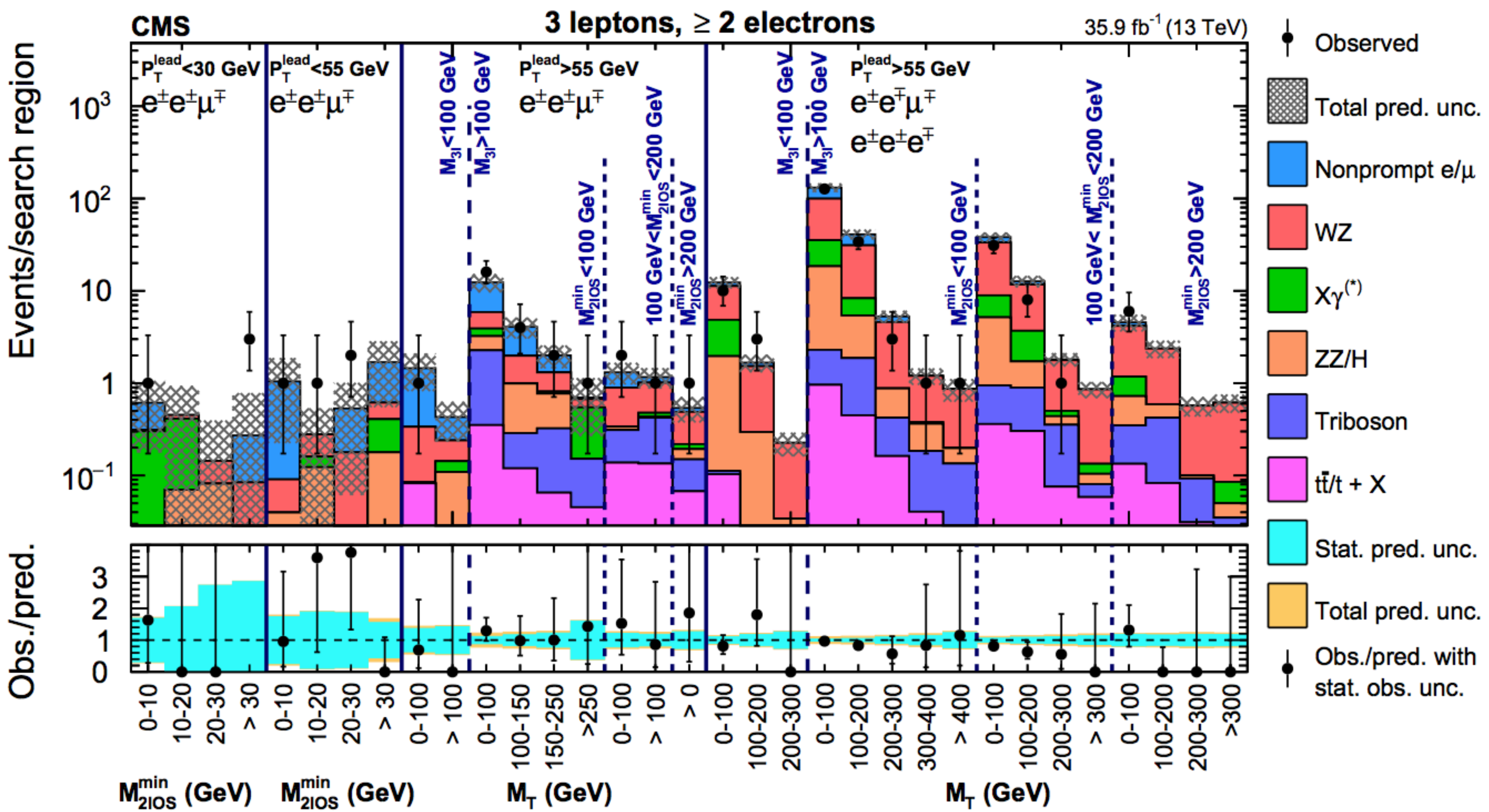
arXiv:1802.02965

Total SM background uncertainty is dominated by stat. uncertainty. Following sources of systematic uncertainties are considered:

Source	Estimated uncertainty (%)	Treatment
e/μ selection	2 per lepton	normalization
Trigger efficiency	2–5	normalization
Jet energy scale	0–3	shape
b tag veto	1–5	shape
Pileup	1–5	shape
Integrated luminosity	2.5	normalization
Scale variations	1–15	shape & normalization
PDF variations	0.1–1	shape
Other backgrounds	50	normalization
MC samples statistical precision	1–30	normalization
Nonprompt leptons (normalization)	30	normalization
Nonprompt leptons (W, Z bkg. subtraction)	5–20	shape
Conversions normalization	15	normalization
WZ normalization	8.5	normalization
ZZ normalization	10	normalization
ZZ normalization for $M_{\mathrm{T}} > 75$ GeV	25	normalization
Scale variations for signal processes	1–2	shape

VeN results

arXiv:1802.02965



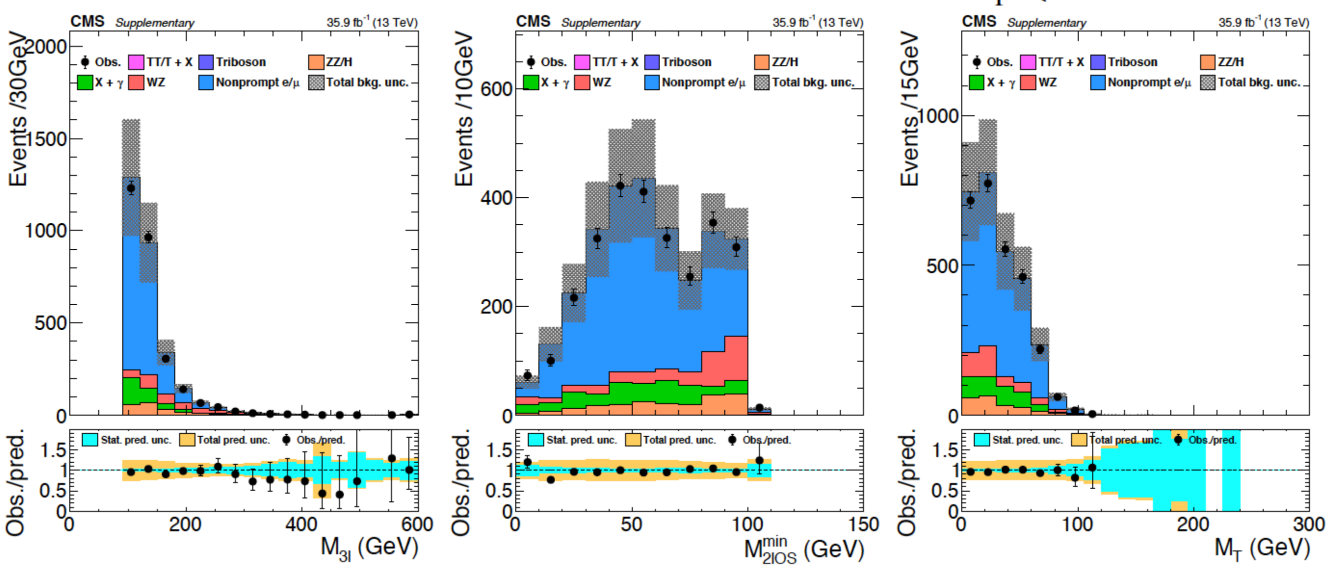
Validation nonprompt

arXiv:1802.02965

GHENT UNIVERSITY

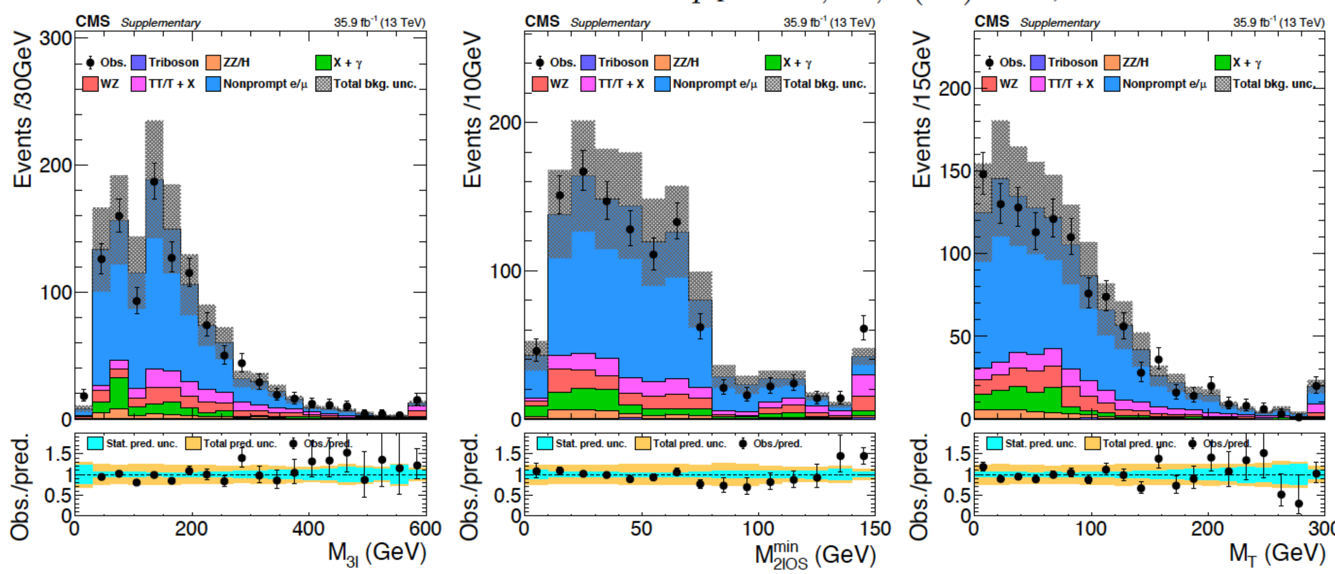
- enriched with misidentified electrons
- check the same f for this source
- systematic uncertainty of the method 30%

- OSSF pair present;
- $|M_{\ell\ell} - m_Z| < 15$ GeV;
- $|M_{3\ell} - m_Z| > 15$ GeV;
- 0 b-jets;
- $p_T > 15, 10, 5(10)$ GeV;
- $E_T^{miss} < 30$ GeV;
- $M_T < 30$ GeV



- enriched with $b \to X\ell\nu$
- check f performance
- validate all analysis kinematical variables

- if OSSF pair present;
  - $|M_{\ell\ell} - m_Z| > 15$ GeV (suppress Z)
  - $|M_{3\ell} - m_Z| > 15$ GeV (suppress conversions)
  - $\min M(\text{OSSF}) > 12$ GeV (suppress conversions)
- ≥ 1 b-jet;
- $p_T > 15, 10, 5(10)$ GeV;



Lesya Shchutska

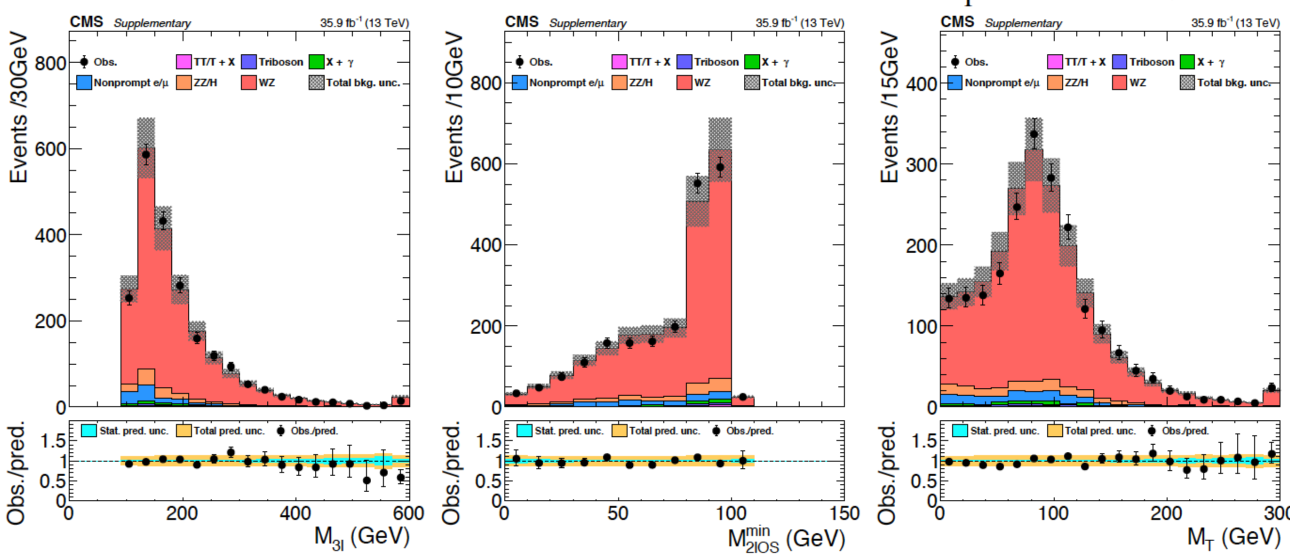
Validation WZ-ZZ

arXiv:1802.02965

Subdominant background in most regions: important only in high-mass SR with OSSF.

- derive process normalization
- measured SF = 1.08 ± 0.09

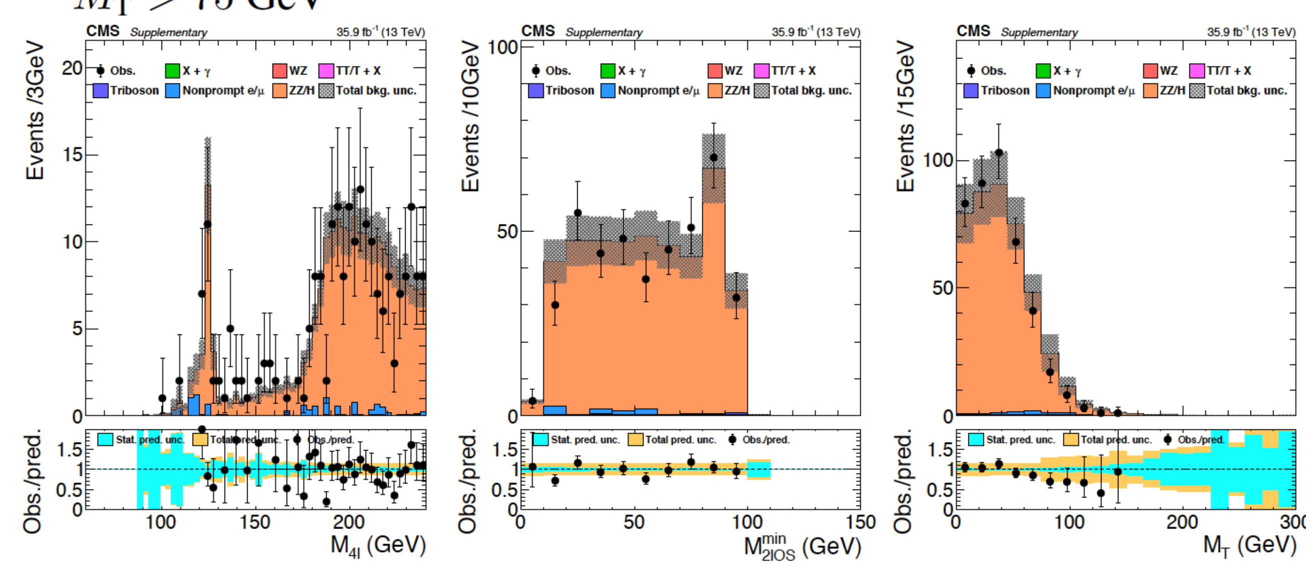
- OSSF pair present;
- $|M_{\ell\ell} - m_Z| < 15$ GeV;
- $|M_{3\ell} - m_Z| > 15$ GeV;
- 0 b-jets;
- $p_T > 25, 15, 10$ GeV;
- $E_T^{miss} > 50$ GeV;



Subdominant background: contributes only when one of the leptons is lost.

- derive process normalization
- measured SF = 1.03 ± 0.10
- additional uncertainty for $M_T > 75$ GeV

- 2 OSSF pairs present;
- $|M_{\ell\ell} - m_Z| < 15$ GeV for both;
- 0 b-jets;
- $p_T > 15, 10, 5(10)$ GeV;



Lesya Shchutska

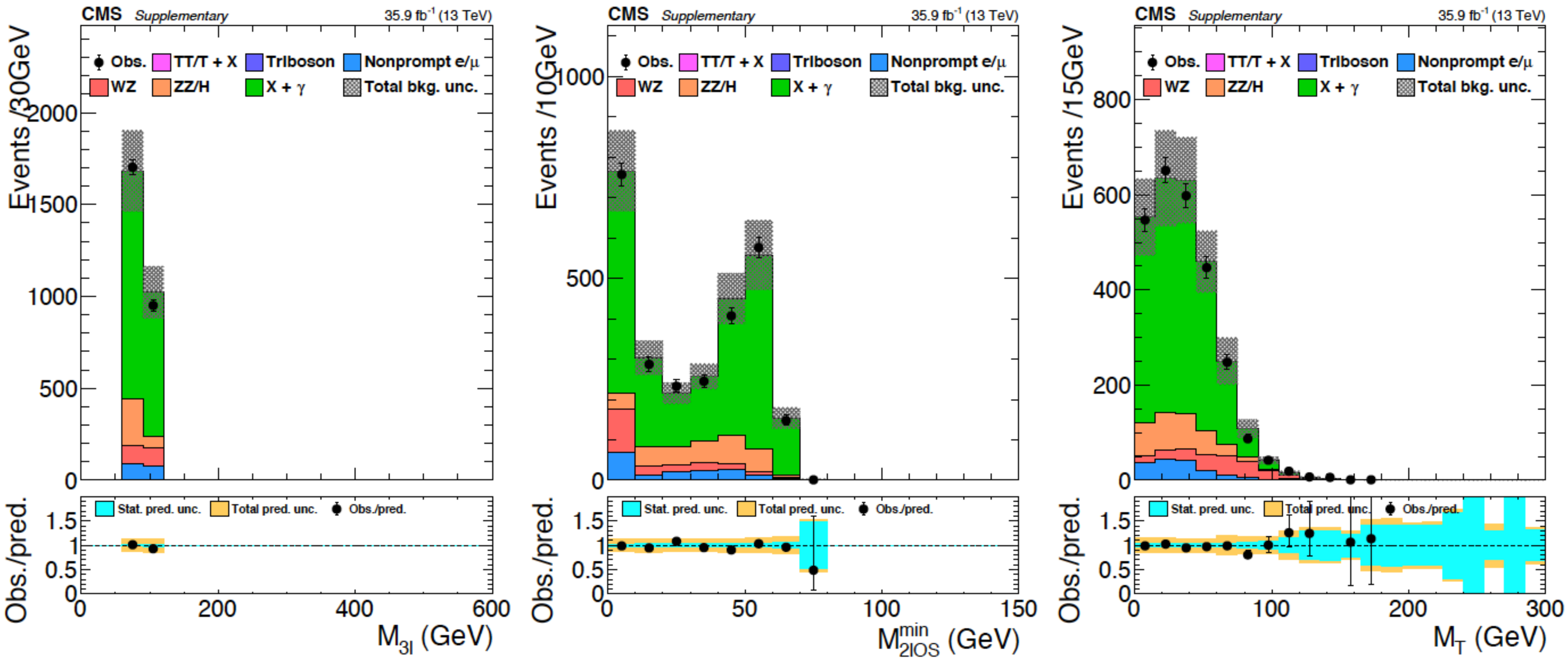
Validation conversion

arXiv:1802.02965

Subdominant background: more important for electron channel (external conversions).

- derive process normalization
- measured SF = 0.95 ± 0.08

- OSSF pair present;
- $|M_{\ell\ell} - m_Z| > 15$ GeV;
- $|M_{3\ell} - m_Z| < 15$ GeV;
- 0 b-jets;
- $p_T > 15, 10, 5(10)$ GeV;



Lesya Shchutska

CRs

arXiv:1806.10905

GHENT UNIVERSITY

- CR1: (SS2ℓ), at least one b-tagged AK4 jet,
- CR2: (SS2ℓ), $\Delta R(\ell_1, \ell_2) > 2.5$ and no b-tagged AK4 jet,
- CR3: (SS2ℓ), low-mass SR1 and either ≥ 1 b-tagged jet or $p_T^{miss} > 100\,GeV$,
- CR4: (SS2ℓ), low-mass SR2 and either ≥ 1 b-tagged jet or $p_T^{miss} > 100\,GeV$,
- CR5: (SS2ℓ), high-mass SR1 and either ≥ 1 b-tagged jet or $(p_T^{miss})^2/S_T > 20\,GeV$,
- CR6: (SS2ℓ), high-mass SR2 and either ≥ 1 b-tagged jet or $(p_T^{miss})^2/S_T > 20\,GeV$.

Table 2: Observed event yields and estimated background in the control regions. The uncertainties in the background yields are the sums in quadrature of the statistical and systematic components.

Channel	Control region	Estimated background	Observed
ee	CR1	366 ± 73	378
	CR2	690 ± 100	671
	CR3	222 ± 42	242
	CR4	48 ± 11	38
	CR5	334 ± 56	347
	CR6	25.7 ± 4.3	28
$\mu\mu$	CR1	880 ± 230	925
	CR2	890 ± 200	1013
	CR3	420 ± 100	439
	CR4	156 ± 42	174
	CR5	560 ± 120	568
	CR6	35.1 ± 7.0	38
eμ	CR1	1010 ± 240	1106
	CR2	1350 ± 230	1403
	CR3	650 ± 140	706
	CR4	143 ± 32	150
	CR5	920 ± 180	988
	CR6	62 ± 11	64

Systematics

arXiv:1806.10905

GHENT UNIVERSITY

Source / Channel	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)
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 variation	0–0.7 (0–0.2)	< 15 (< 20)	0–0.7 (0–0.1)	< 15 (< 20)	0–0.7 (0–0.2)	< 15 (< 20)
Scale variation	1–5 (0–0.1)	—	1–4 (0–0.3)	—	1–5 (0–0.2)	—
Estimated from data:						
Misidentified leptons	—	30 (30)	—	30 (30)	—	30 (30)
Mismeasured sign	—	29–41 (53–88)	—	—	—	

Table 4: Summary of the relative systematic uncertainties in heavy Majorana neutrino signal yields and in the background from prompt SS leptons, both estimated from simulation. The relative systematic uncertainties assigned to the misidentified-lepton and mismeasured-sign background estimated from control regions in data and simulation are also shown. The uncertainties are given for the low- (high-)mass selections. The range given for each systematic uncertainty source covers the variation across the mass range. Upper limits are presented for the uncertainty related to the PDF choice in the background estimates, however this source of uncertainty is considered to be accounted for via the normalization uncertainty and was not applied explicitly as an uncertainty in the background.

Table 3: Fractional contributions to the total background systematic uncertainties related to the uncertainties in the prompt SS lepton, misidentified-lepton, and mismeasured-sign background. The numbers are for the SR1 (SR2) in the case of m_N = 50 and 500 GeV.

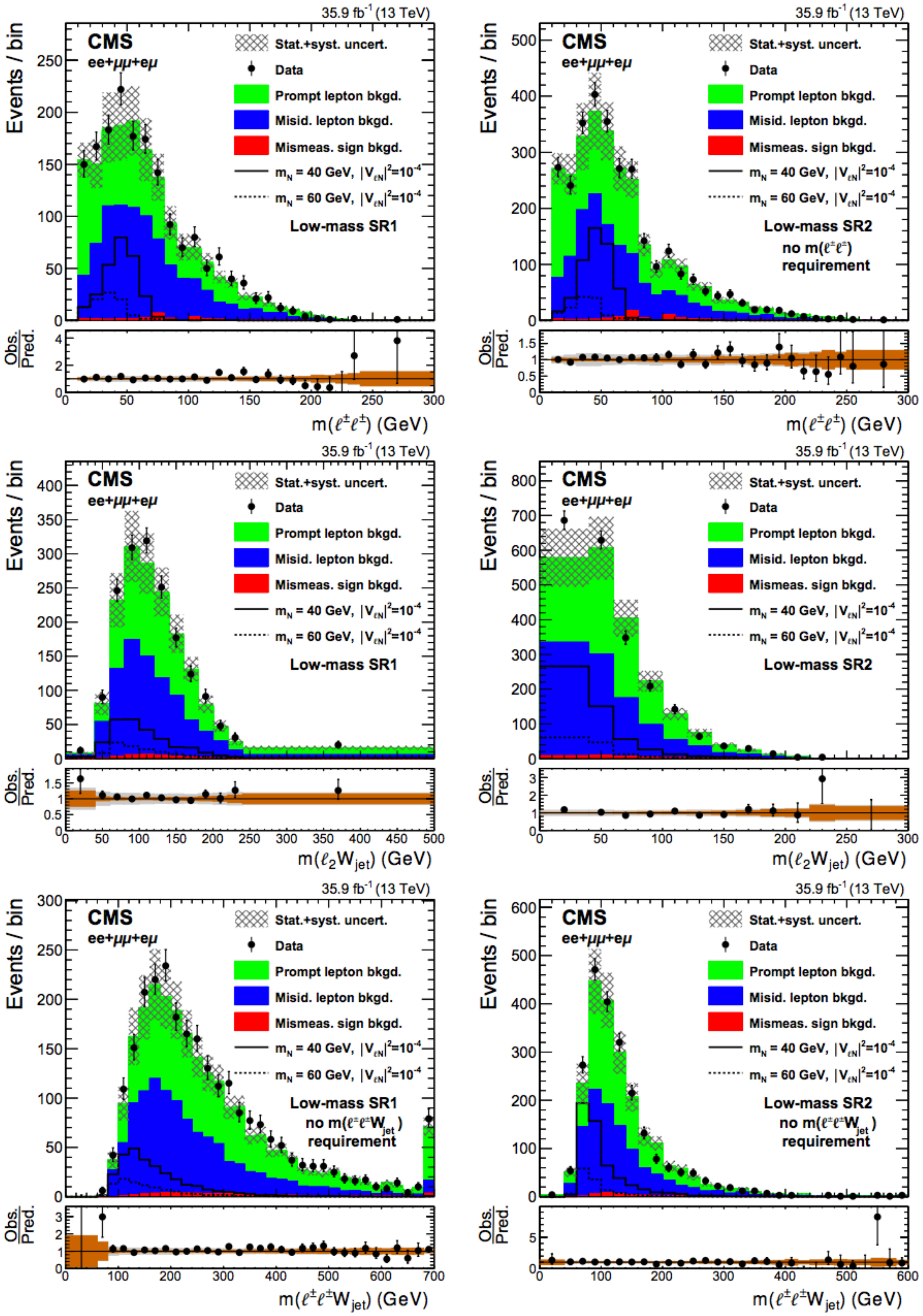
Channel	m_N (GeV)	Prompt-lepton (%)	Misidentified-lepton (%)	Mismeasured-sign (%)
ee	50	53 (49)	43 (46)	4.5 (4.9)
	500	60 (75)	3.6 (4.6)	37 (21)
$\mu\mu$	50	38 (42)	62 (58)	—
	500	100 (100)	0.0 (0.0)	—
$e\mu$	50	52 (45)	48 (55)	—
	500	99 (100)	1.3 (0.0)	—

SRs

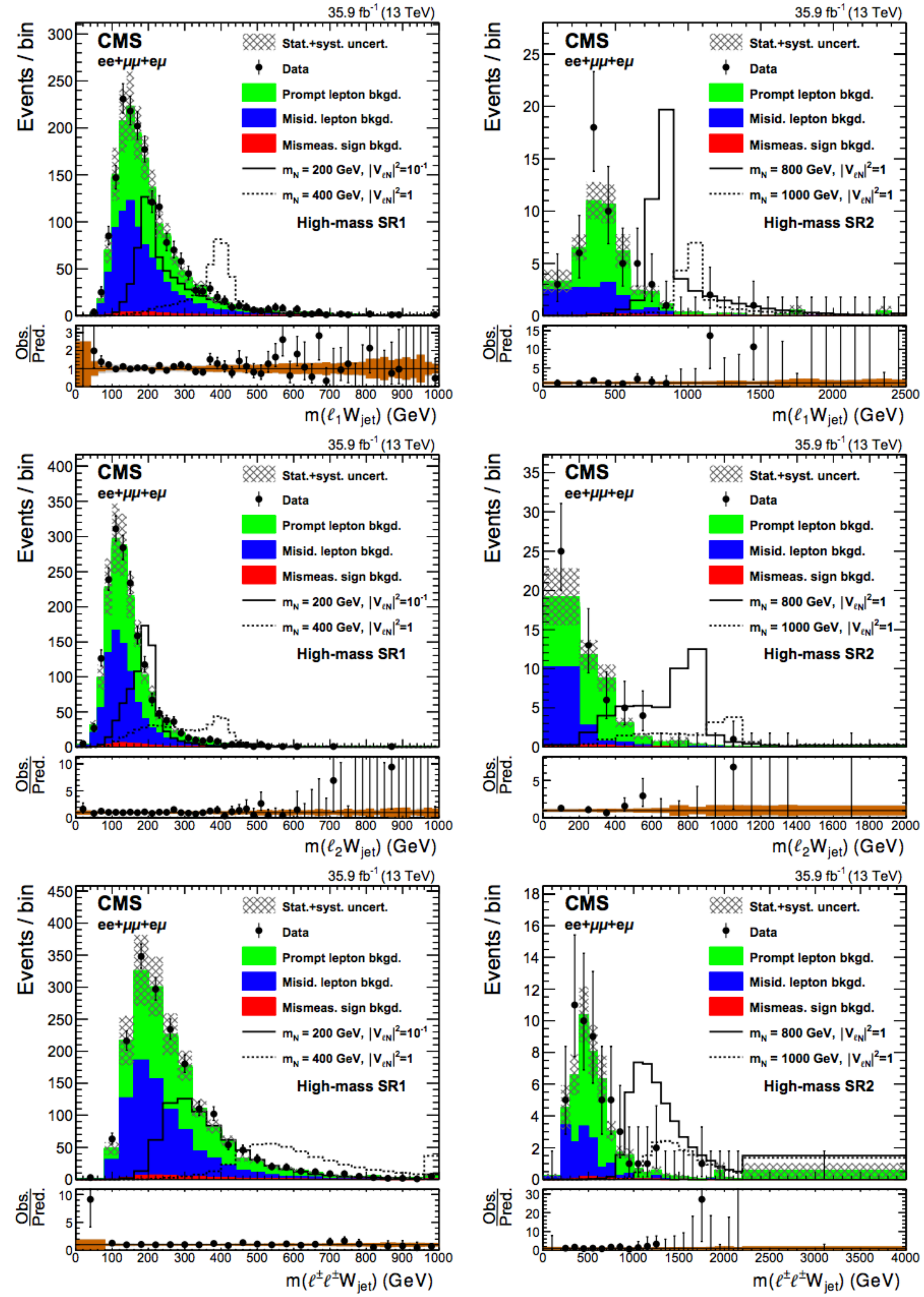
arXiv:1806.10905

GHENT UNIVERSITY

Low mass SR1-SR2



High mass SR1-SR2



CRs

arXiv:1803.11116

GHENT UNIVERSITY

Low dilepton mass CR

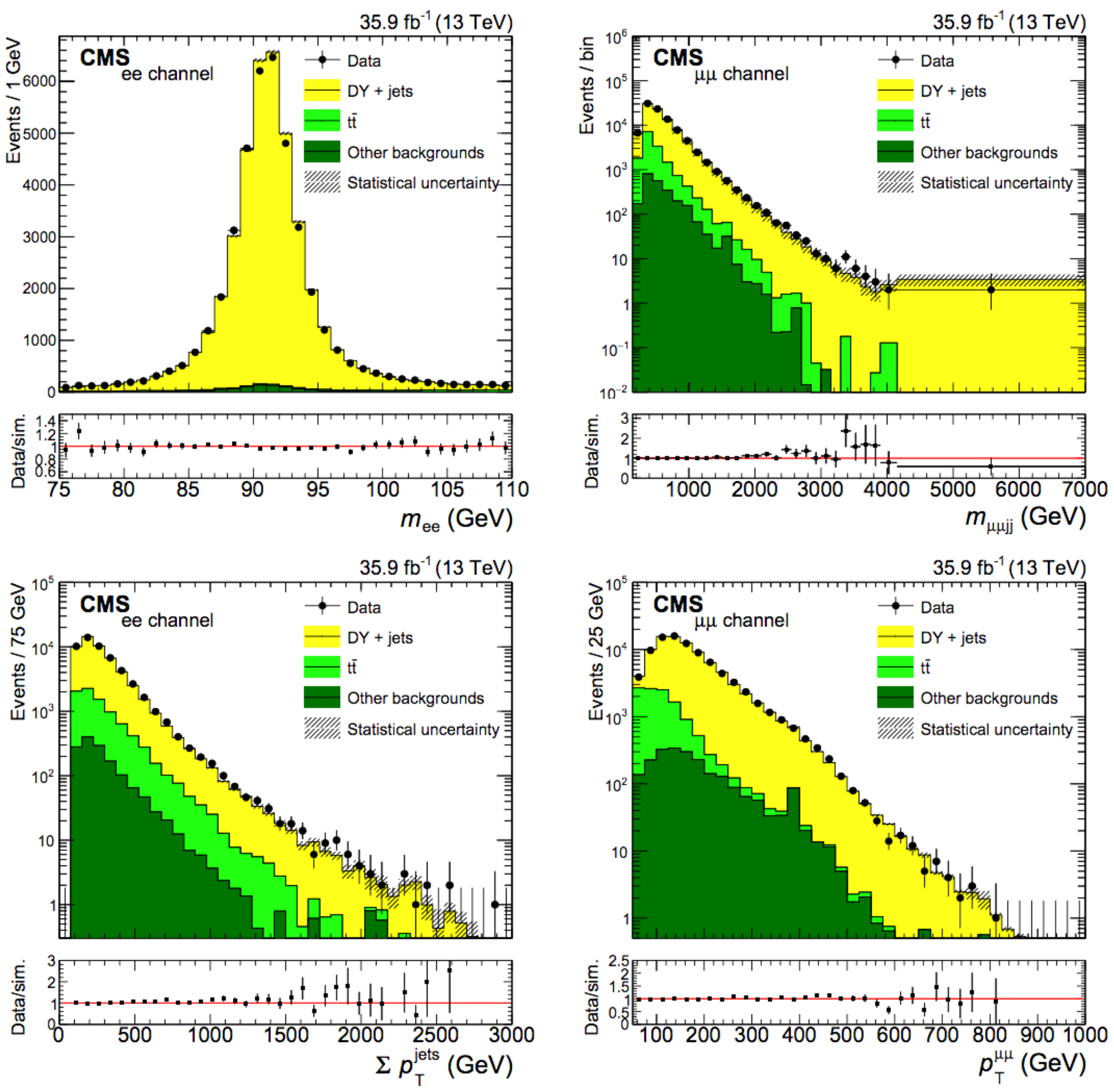


Figure 1: Kinematic distributions for events in the low dilepton mass control region with the DY SF applied. The dilepton mass (upper left) and the scalar sum of all jet transverse momenta (lower left) are shown for the ee DY plus two jets selection. The $m_{\ell\ell jj}$ (upper right) and the dilepton transverse momentum (lower right) are shown for the $\mu\mu$ DY plus two jets selection. The uncertainty bands on the simulated background histograms include only statistical uncertainties. The uncertainty bars in the ratio plots represent combined statistical uncertainties of data and simulation.

Flavor CR

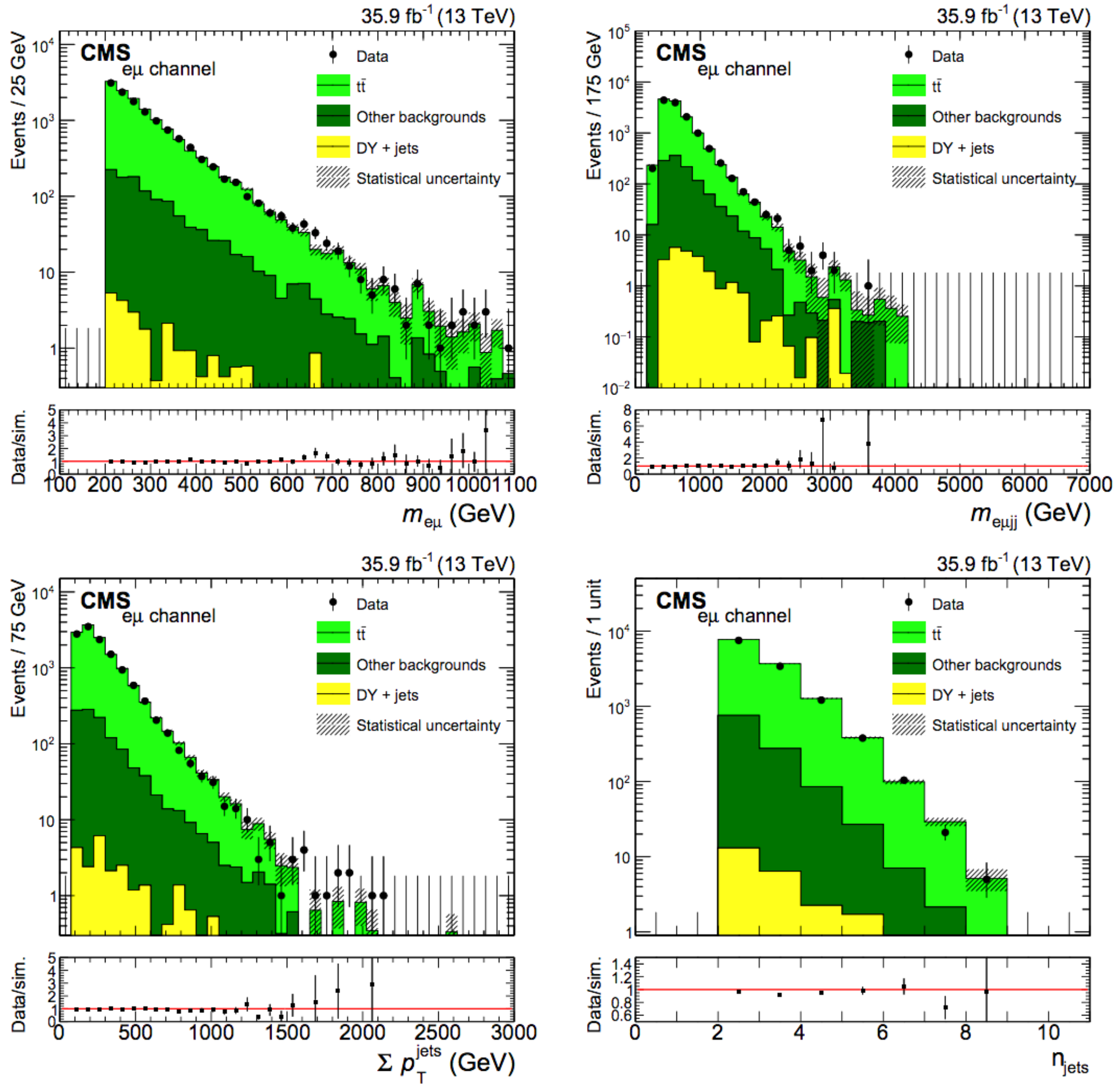


Figure 3: Kinematic distributions for events in the flavor control region with the DY SF applied. The dilepton mass (upper left), the $m_{\ell\ell jj}$ (upper right), the scalar sum of all jet transverse momenta (lower left), and the number of jets (lower right) are shown. The uncertainty bands on the simulated background histograms include only statistical uncertainties. The uncertainty bars in the ratio plots represent combined statistical uncertainties of data and simulation.

Systematics

arXiv:1803.11116

Table 2: Effect of systematic uncertainties in candidate reconstruction efficiencies, energy scale and resolutions on the signal and background yields. The Signal column shows the range of uncertainties computed at each of the W_R mass points. The Background column indicates the range of the uncertainties for the backgrounds.

Uncertainty	Signal (%)	Background (%)
Jet energy resolution	3.2–26	0.90–25
Jet energy scale	0.20–29	4.8–27
Electron energy resolution	3.7–4.8	2.7–4.5
Electron energy scale	3.7–6.4	4.9–5.9
Electron reco/trigger/ID	8.7–11	6.1–10
Muon energy resolution	4.7–10	6.9–12
Muon energy scale	4.7–10	6.2–12
Muon trigger/ID/iso	2.3–4.7	1.9–5.2

Table 3: Uncertainties affecting the $m_{\ell\ell jj}$ distribution shape and normalization. The uncertainties in the $t\bar{t}$ SFs affect the $t\bar{t}$ background, the uncertainties in the DY PDF and the DY factorization and renormalization scales affect the DY+jets background, and the uncertainty in the integrated luminosity affects both signal and backgrounds.

Uncertainty	Magnitude (%)
$t\bar{t}$ extrapolation ee/eμ SF	17 (stat+syst)
$t\bar{t}$ extrapolation $\mu\mu$/eμ SF	20 (stat+syst)
DY ee PDF	15–70 (syst)
DY ee renormalization/factorization	5.0–40 (syst)
DY $\mu\mu$ PDF	10–70 (syst)
DY $\mu\mu$ renormalization/factorization	10–50 (syst)
Integrated luminosity	2.5 (stat+syst)