# Searches for Lepton Number Violation at the LHC

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NIKHEF Amsterdam

ECT* Workshop on
Progress and Challenges in the Theory of Neutrinoless Double Beta Decay
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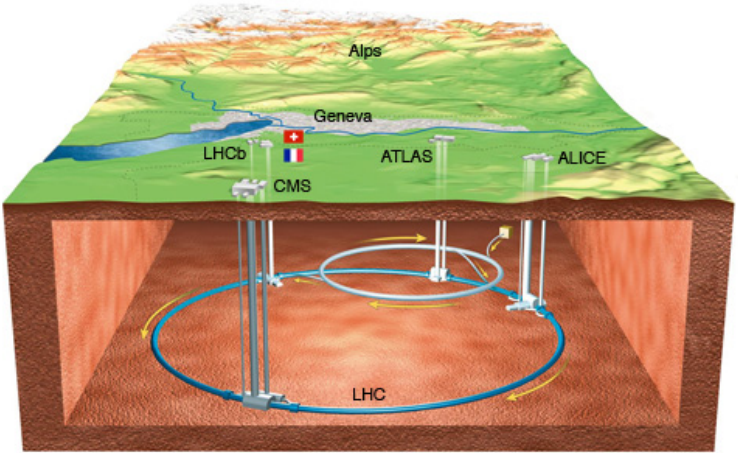
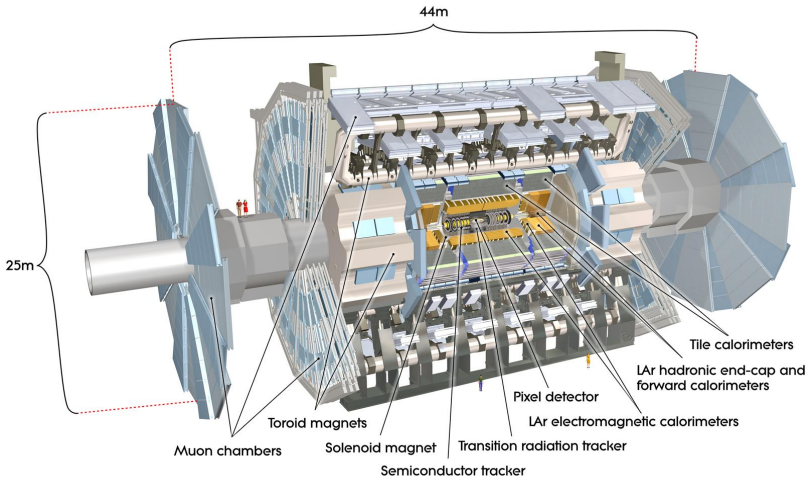
# The Large Hadron Collider (LHC)

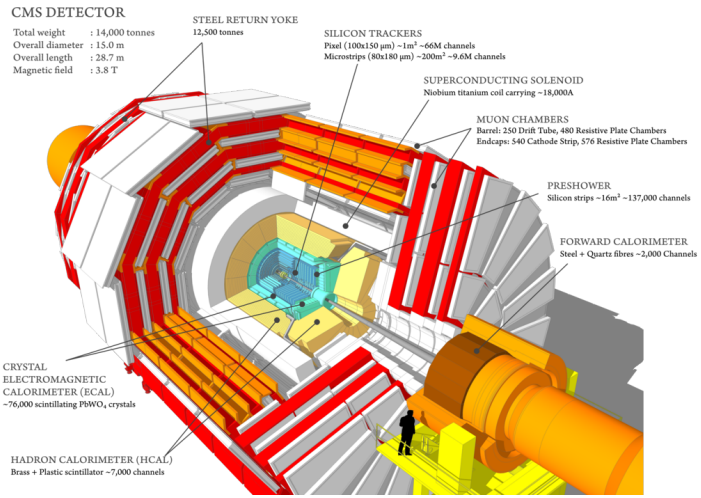
- 27 km long synchrotron at CERN
- $pp$ collisions at $\sqrt{s} = 13\,\text{TeV}$ (Run2; Run1: 7/8 TeV) up to every 25 ns at the experimental points
- Integrated luminosity in Run2 in ATLAS/CMS $\sim 140\,\text{fb}^{-1}$
- Expect around $300\,\text{fb}^{-1}$ in Run3 starting 2021



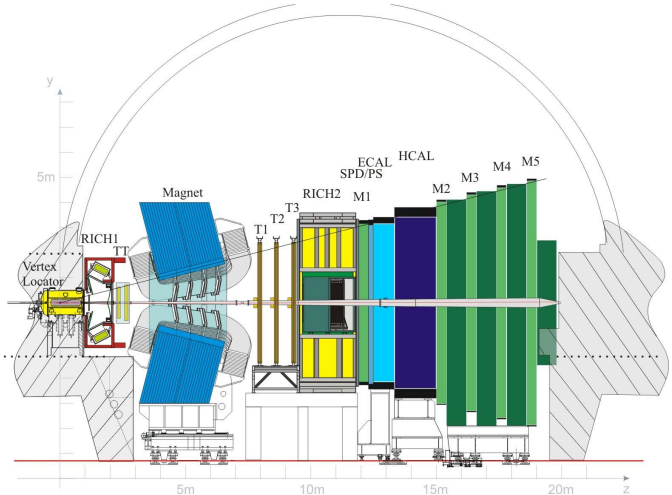
# ATLAS Experiment



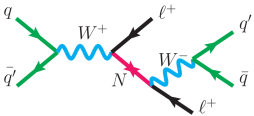
# Compact Muon Solenoid (CMS)

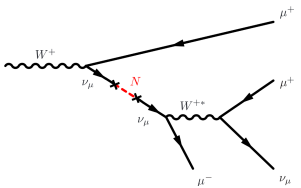


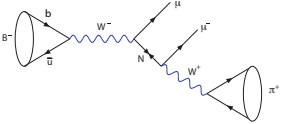
# LHCb Experiment

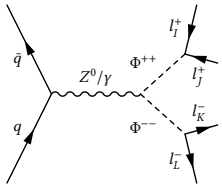


# Searches for Lepton Number Violation (LNV) at the LHC



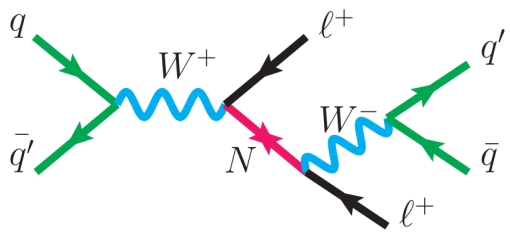




- Heavy Majorana neutrino $N$ in $W$ decays: $W^\pm \to N l^\pm \to W^\mp l'^\pm l^\pm$
  - Same-sign dilepton pair + jets (hadronic $W$ decay)
  - Tri-lepton (leptonic $W$ decay)
  - Decays of $B$ mesons

- Doubly-charged Higgs $\Phi^{\pm\pm}$: $\Phi^{++}\Phi^{--} \to l^+ l^+ l^- l^-$

# Same-Sign Dilepton + Jets




Search for a heavy Majorana neutrino $N$ in $W$ decays

$$W^{\pm} \to l^{\pm} N \qquad \text{with } l = e, \mu$$

LNV case: $\quad N \to W^{\mp} l'^{\pm}$

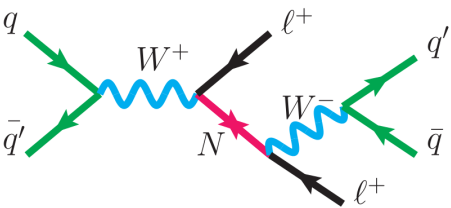
Signature in ATLAS/CMS: hadronic $W$ decay: same-sign dilepton plus jets ($llqq$)

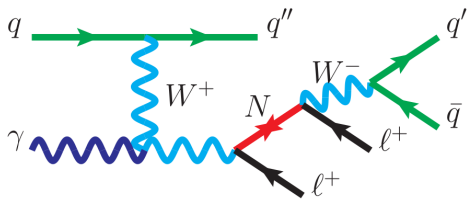
# CMS: Same-Sign Dilepton + Jets

- Data collected in 2016 in $pp$ collisions at $\sqrt{s} = 13\,\text{TeV}$ corresponding to $35.9\,\text{fb}^{-1}$

- Neutrino Minimal Standard Model ($\nu$MSM)
- Two prompt, same-sign (SS) leptons ($ee$, $\mu\mu$, $e\mu$) and at least one jet

- $N_{\text{jets}} \geq 1$: enhanced sensitivity at
  low $m_{\text{N}}$: final state leptons and jets are very soft
  high $m_{\text{N}}$: two jets are boosted and overlap
- Includes vector boson fusion channel
  $q\gamma \to Wq \to Nlq \to llqqq$ which enhances sensitivity at high $m_N \sim \mathcal{O}(100\,\text{GeV})$



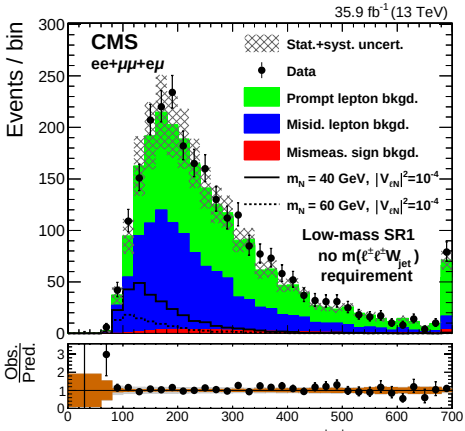




JHEP01 (2019) 122

# CMS: Same-Sign Dilepton + Jets

- $ee$: $p_T > 25(15)$ GeV
  $\mu\mu$: $p_T > 20(10)$ GeV
  $e\mu$: $p_T > 25(10)$ GeV
- $\geq 2$ 'standard' jets with $p_T > 20$ GeV, no 'wide' jet, or exactly 1 standard jet without a wide jet, or $\geq 1$ wide jet with $p_T > 200$ GeV
- Veto events with b-tagged jets ($t\bar{t}$ background)
- Signal regions:
  **Low mass** ($m_N < 80$ GeV): first $W$ on-shell, invariant mass of $ll$+jets should be $\sim m_W$
  **High mass** ($m_N > 80$ GeV): second $W$ on-shell, invariant mass of jets should be $\sim m_W$

Low mass region, $N_{\text{jets}} \geq 2$, no wide jet

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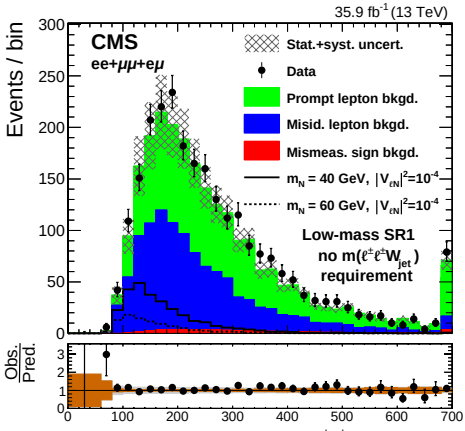
# CMS: Same-Sign Dilepton + Jets

- Background sources
  - SM processes with multiple prompt SS leptons: from $WW$, $WZ$, $ZZ$, $W/Z\gamma$, $\tau$ decays
  - Misidentified leptons: hadrons, heavy-flavour jets, light meson decays, ...
  - Opposite-sign (OS) $ll$ events with mismeasured sign of one lepton: $Z \to ll$, $WW \to l\nu l\nu$, Drell-Yan only relevant for electrons
- Estimated using simulation and control regions (prompt SS leptons and sign mismeasurement) or data-driven methods (mis-identification)

Low mass region, $N_{\text{jets}} \geq 2$, no wide jet

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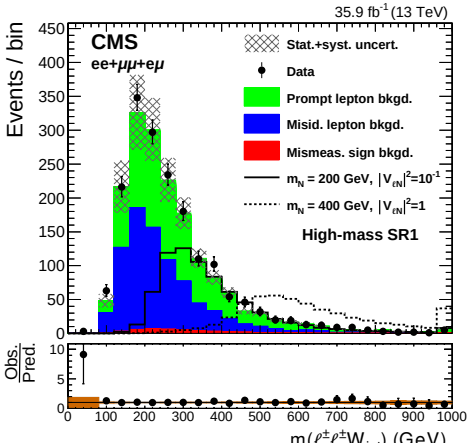


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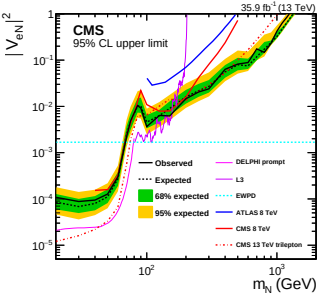
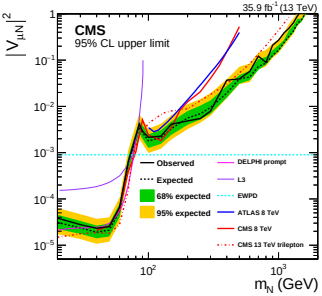
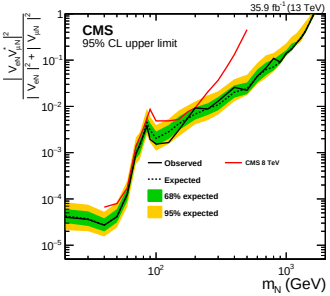
# CMS: Same-Sign Dilepton + Jets

Number of observed events consistent with Standard Model expectations

95 % CL exclusion limits on mixing matrix elements (νMSM) $|V_{eN}|^2$, $|V_{\mu N}|^2$ and $\frac{|V_{eN}V_{\mu N}^*|^2}{|V_{eN}|^2+|V_{\mu N}|^2}$ for $m_N$ between 20 GeV and 1200 GeV

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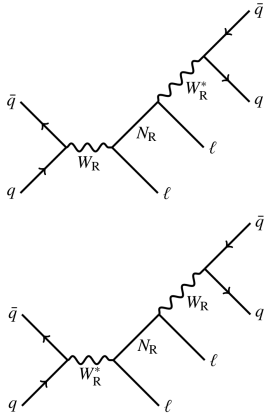
# ATLAS: Same-Sign Dilepton + Jets

- Data collected in 2015/2016 in $pp$ collisions at $\sqrt{s}$ = 13 TeV corresponding to 36.1 fb$^{-1}$
- Heavy right-handed Majorana or Dirac neutrinos $N_{\mathrm{R}}$ and right-handed $W_{\mathrm{R}}$ in the Keung-Senjanović process (PRL50 (1983) 1427)
- Dirac $N_{\mathrm{R}}$: only $l^{\pm}l^{\mp}$ pairs
  Majorana $N_{\mathrm{R}}$: $l^{\pm}l^{\mp}$ and $l^{\pm}l^{\pm}$ pairs
- $m_{W_{\mathrm{R}}} > m_{N_{\mathrm{R}}}$: $m_{W_{\mathrm{R}}}$ from $lljj$ system
  $m_{W_{\mathrm{R}}} < m_{N_{\mathrm{R}}}$: $m_{W_{\mathrm{R}}}$ from $jj$ system
- Signature: 2 prompt leptons $ee$ or $\mu\mu$ and two jets



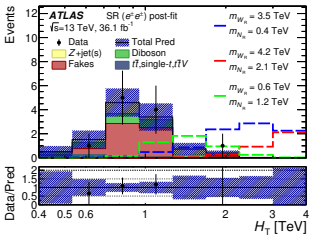

JHEP01 (2019) 016

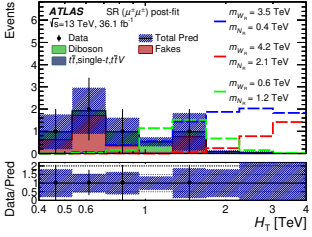
# ATLAS: Same-Sign Dilepton + Jets

- Selection:
  - OS: $p_{\mathrm{T}}(\mu) > 25\,\mathrm{GeV}$, $E_{\mathrm{T}}(e) > 25\,\mathrm{GeV}$
    SS: $p_{\mathrm{T}}(\mu) > 30\,\mathrm{GeV}$, $E_{\mathrm{T}}(e) > 30\,\mathrm{GeV}$
  - Two jets with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$,
    veto on events with $b$-tagged jets
  - Signal region:
    $m_{ll} > 400\,\mathrm{GeV}$, $m_{jj} > 110\,\mathrm{GeV}$, $H_{\mathrm{T}} > 400\,\mathrm{GeV}$

- Backgrounds:
  - Prompt leptons from $Z$, $W$, $H$, prompt $\tau$, diboson events, top quark events, $Z$+jets, $W$+jets
  - Mis-identified and non-prompt leptons
  - Charge mis-identification

- Binned Maximum likelihood fit to $m_{jj}$, $m_{lljj}$ or $H_{\mathrm{T}}$

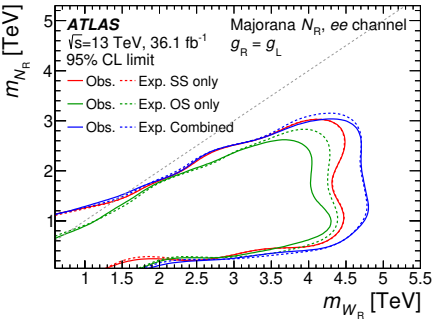


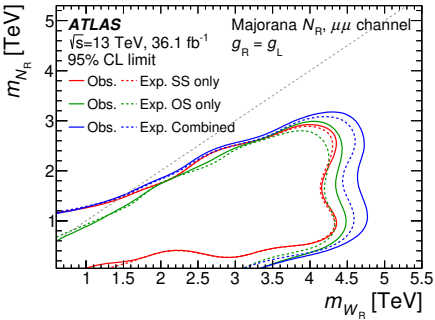




JHEP01 (2019) 016

# ATLAS: Same-Sign Dilepton + Jets

No significant deviations from the SM observed
95 % CL exclusion limits in $(m_{N_R}, m_{W_R})$ for $m_{W_R} < 4.7\,\text{TeV}$ for $0.5\,\text{TeV} < m_{N_R} < 3.0\,\text{TeV}$

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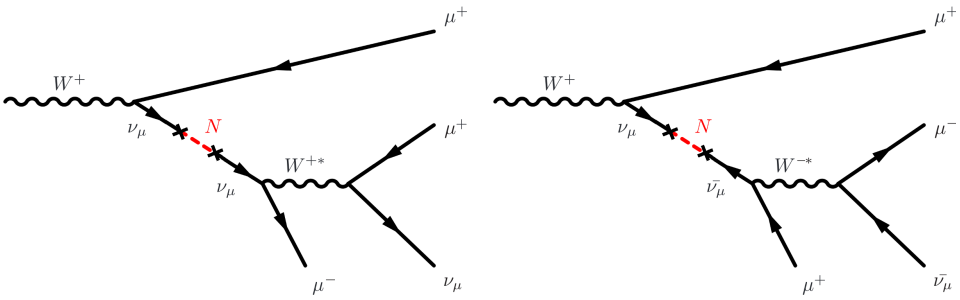
# Trilepton




Search for a heavy Majorana neutrino $N$ in $W$ decays

$$W^\pm \to l^\pm N \qquad \text{with } l = e, \mu$$

LNV case: $$N \to W^\mp l'^\pm$$

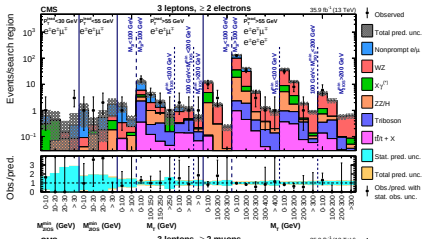
Signature in ATLAS/CMS: leptonic $W$ decay: tri-lepton plus $E_{\mathrm{T}}^{\mathrm{miss}}$ ($lll\nu$),
i.e. $m_N$ mass peak cannot be reconstructed

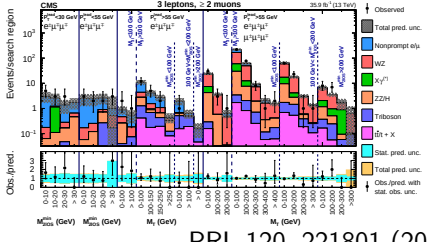
# CMS: Trilepton

- 35.9 $\text{fb}^{-1}$ of $pp$ collisions at $\sqrt{s}$ = 13 TeV
- $\nu$MSM

- Signature: 3 prompt leptons in any combination of $e$ and $\mu$, not all with the same charge
- **Low mass** ($m_N < m_W$, on-shell $W$) and **high mass** ($m_N > m_W$, off-shell $W$) region
- No OS same flavour pairs in low mass region

- Background: events with leptons from hadron decays and conversions, multiple leptons (e.g. diboson, top quark + boson), mis-identification, charge mis-identification

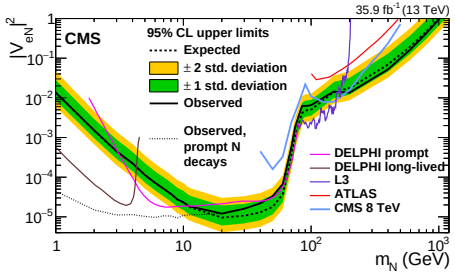


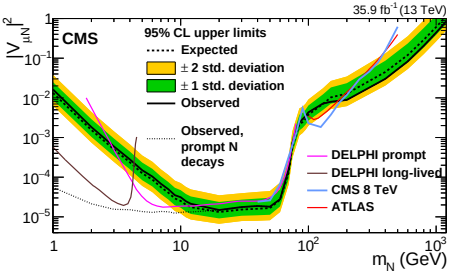




PRL 120, 221801 (2018)

# CMS: Trilepton

Observations consistent with the expected background
Upper limits at 95 % on $|V_{eN}|^2$ and $|V_{\mu N}|^2$ for 1 GeV < $m_N$ < 1.2 TeV



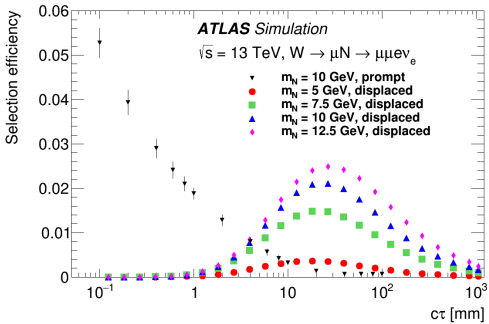

PRL 120, 221801 (2018)

# ATLAS: Trilepton

- 36.1 fb$^{-1}$(prompt) / 32.9 fb$^{-1}$(displaced) of $pp$ collisions at $\sqrt{s}$ = 13 TeV
- Single $N_R$ that couples either to $\nu_e$ or $\nu_\mu$ with coupling strength $U_l$, LNC and LNV processes possible

- **Prompt**: $\mu^\pm\mu^\pm e^\mp$ or $e^\pm e^\pm \mu^\mp$ from primary vertex
- **Displaced**: $\mu$ from $W$ decay and $\mu\mu$ or $\mu e$ from a displaced vertex ((4-300) mm from beam)
  $\Rightarrow$ very low background

- Background: top quark events, $W/Z$+jets, diboson, triboson, $b/c$-hadron decays, $\tau$ decays, mis-identification, charge mis-identification




arXiv:1905.09787

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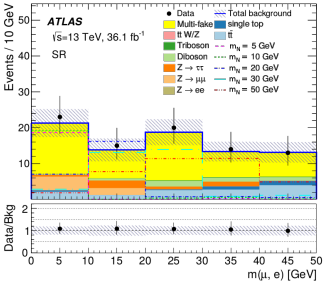
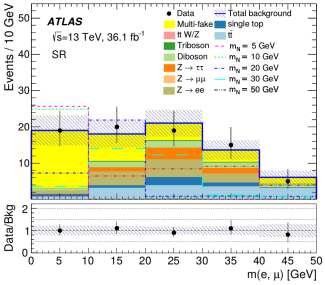


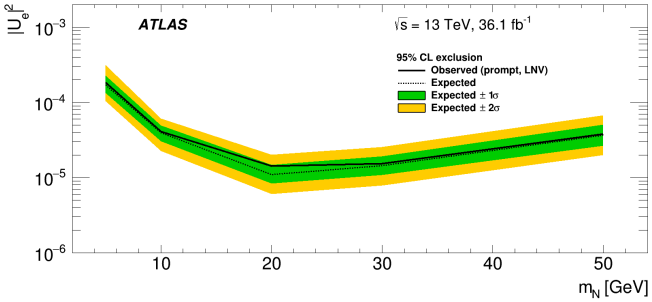




**Prompt**:

- Probe LNV $N$ with $5\,\text{GeV} < m_N < 50\,\text{GeV}$
- Observed $m_{e\mu}$ distribution consistent with background expectations
- Upper limits at $95\,\%$ CL on $|U_e|^2$ and $|U_\mu|^2$

arXiv:1905.09787

# ATLAS: Trilepton

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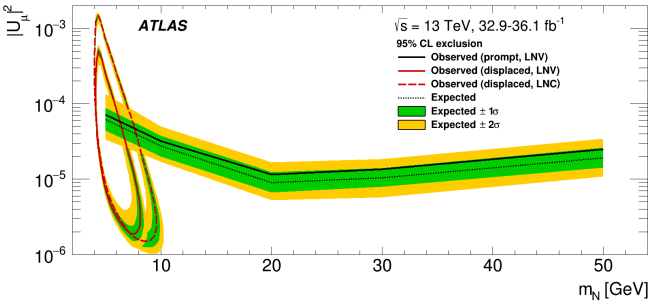
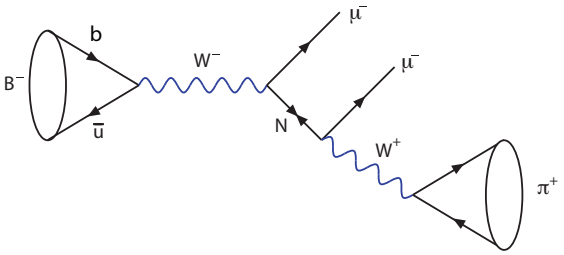



**Displaced**:

- Probe LNC and LNV $N$ with 4.5 GeV $< m_N <$ 10 GeV and 0.1 mm $< c\tau_N <$ 1000 mm
- Diplaced vertex with exactly $\mu\mu$ or $\mu e$ with opposite charge
- No events observed in signal regions
- Upper limits at 95 % CL on $|U_\mu|^2$

arXiv:1905.09787

# Majorana Neutrinos in B decays




Search for a heavy Majorana neutrino $N$ in $W$ decays

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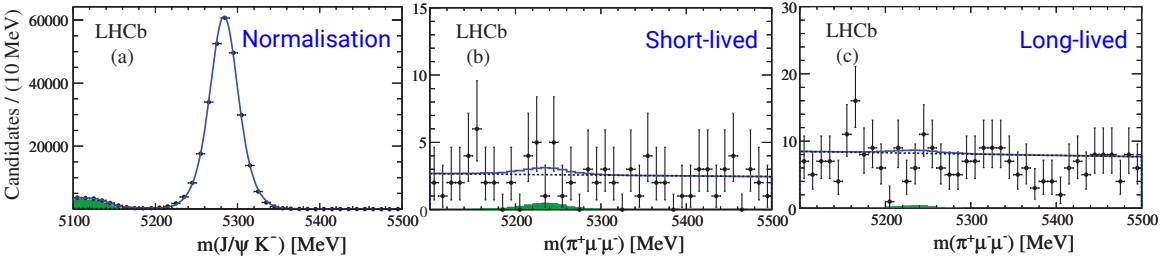
LNV case: $$N \to W^{\mp} l'^{\pm}$$

Signature in LHCb: $B^- \to N\mu^-$ and $N \to \pi^+\mu^-$

# LHCb: $B^- \to \pi^+\mu^-\mu^-$

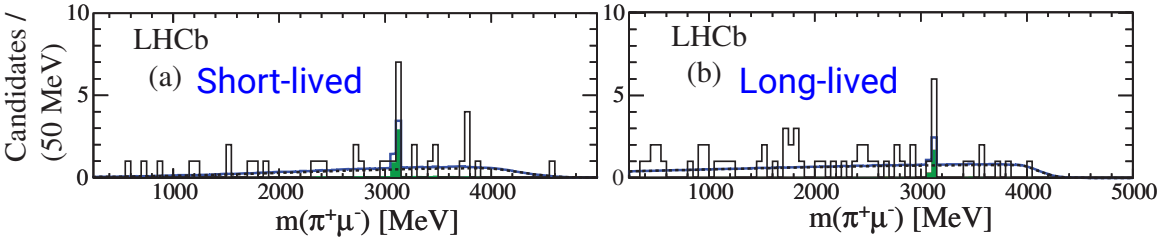



- $3\,\text{fb}^{-1}$ of $pp$ collisions at $\sqrt{s}$ of 7 TeV and 8 TeV
- Events with $\pi\mu\mu$ and $B$ vertex detached from primary $pp$ vertex
- Short-lived (S): $\tau_N \leq 1$ ps, $\pi\mu\mu$ from $B$ vertex
  Long-lived (L): $\tau_N \leq 1000$ ps, $\mu$ from $B$ vertex, $\pi\mu$ pair detached from $B$ vertex

- Normalisation channel $B^- \to J/\Psi K^-$ with $J/\Psi \to \mu^+\mu^-$
- Backgrounds: $B$ decays to charmonium states and combinatorics

PRL 112, 131802 (2014)

# LHCb: $B^- \to \pi^+\mu^-\mu^-$

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PRL 112, 131802 (2014)

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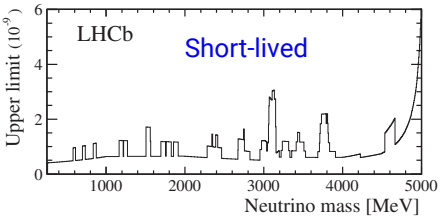


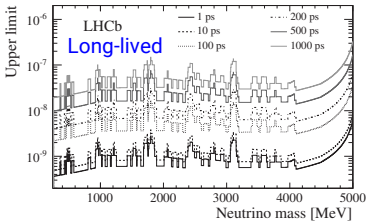


- Number of events in signal region around $m_B$ consistent with background expectation in (S)and (L)
- Exclusion limits at 95 % CL for $m_N$ in the range of (250-5000) MeV and $\tau_N$ of (0-1000) ps

- (S): $\mathrm{BR}(B^- \to \pi^+ \mu^- \mu^-) < 4.0 \cdot 10^{-9}$
- (L): detection efficiency differs with $\tau_N$ and thus BR limits, limits on coupling of muons to $N$ $|V_{\mu 4}|^2$

PRL 112, 131802 (2014)

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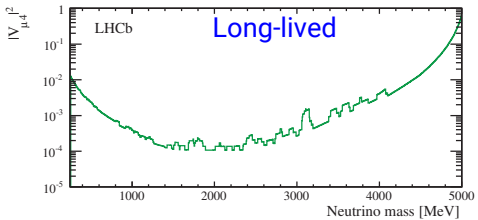


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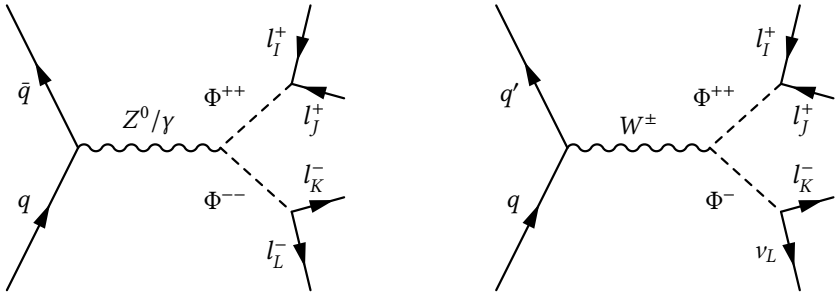
# Doubly-Charged Higgs




Scalar triplet $(\Phi^{++}, \Phi^+, \Phi)$ in Type-II seesaw $\Rightarrow$ Doubly-charged Higgs

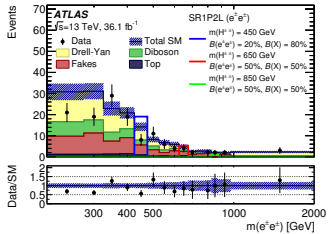
pair production $\quad Z/\gamma^* \to \Phi^{++}\Phi^{--} \to l^+l^+l^-l^-$

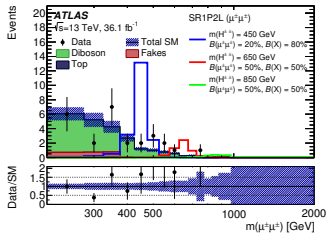
associative production $\quad W^\pm \to \Phi^{\pm\pm}\Phi^\mp \to l^\pm l^\pm l^\mp \nu$

Signature in ATLAS/CMS: 3 or 4 leptons with at least one SS pair

# ATLAS: Doubly-Charged Higgs

- 36.1 $\text{fb}^{-1}$ of $pp$ collisions at $\sqrt{s}$ = 13 TeV
- Pair production of $H^{\pm\pm}$ in Drell-Yan (PRD 68 (2003) 117701)
- Decays into either left-handed or right-handed leptons, here $ee$, $e\mu$ and $\mu\mu$
- Signal regions with 2, 3 or 4 prompt leptons
- Background: prompt leptons from diboson and $t\bar{t}+W/Z/H$, non-prompt leptons, mis-identification, charge mis-identification

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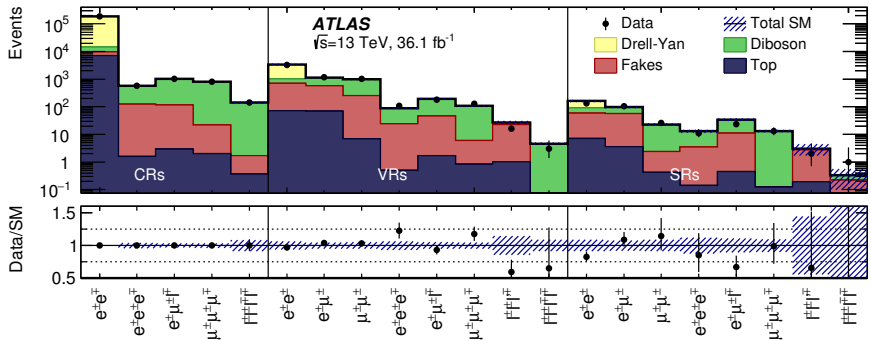
# ATLAS: Doubly-Charged Higgs

No significant excess observed in $m_{m_{l^\pm l^\pm}}$ distributions
Limits at 95 % CL on $m_{H^{\pm\pm}}$ in dependence on BR($H^{\pm\pm} \to l^\pm l^\pm$) for purely left- and right-handed couplings reaching up to 870 GeV (purely $e\mu$, left-handed) and 770 GeV (purely $e\mu$, right-handed)

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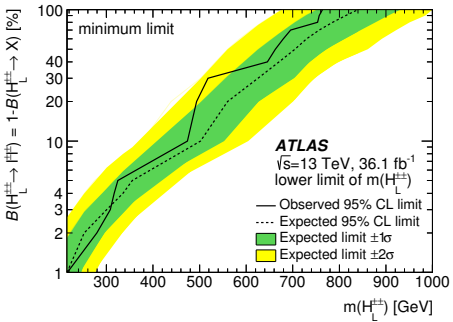


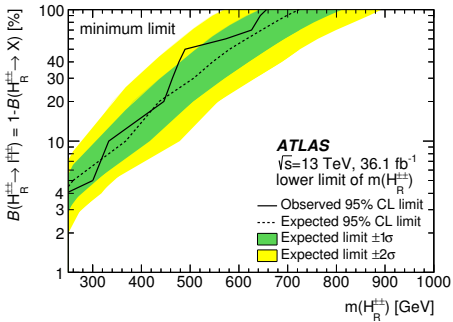


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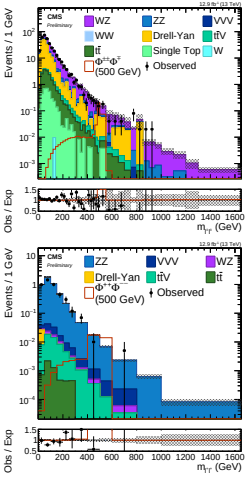
# CMS: Doubly-Charged Higgs

- 12.9 $\text{fb}^{-1}$ of $pp$ collisions at $\sqrt{s}$ = 13 TeV
- Search for left-handed $\Phi_L^{\pm\pm}$ from pair and associated production
- $\Phi^{\pm\pm}$ decays to $ee$, $e\mu$, $\mu\mu$, $e\tau$, $\mu\tau$, $\tau\tau$

- **3 leptons** ($W \to \Phi^{\pm\pm}\Phi^{\mp}$) and **4 leptons** ($Z/\gamma^* \to \Phi^{++}\Phi^{--}$) regions
- All leptons prompt
- $\tau$ with hadronic decay

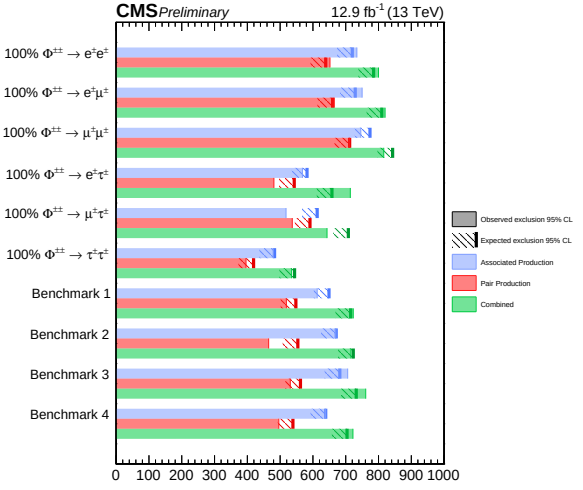
- Backgrounds: events with top quarks, diboson, triboson, Drell-Yan, $W$




CMS PAS HIG-16-036

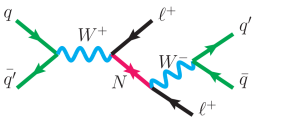
# CMS: Doubly-Charged Higgs

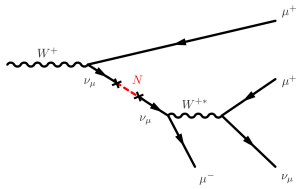
- No excess in $m_{l^\pm l^\pm}$ observed
- Upper limits on $m_{\Phi^{\pm\pm}}$ in dependence on BR($\Phi^{\pm\pm} \to l^\pm l^\pm$)
  ranging up to 535 GeV (purely $\tau\tau$)
  to 820 GeV (purely $e\mu$)

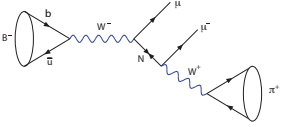


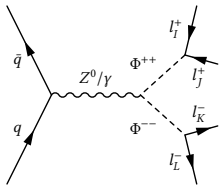

CMS PAS HIG-16-036

# Searches for Lepton Number Violation (LNV) at the LHC




- The LHC experiments have performed searches for heavy Majorana neutrinos and doubly-charged Higgs
- No excess was found and upper limits were set
- Prospects are promising:
  - Full Run2 data set increases statistics from $\sim 36\,\text{fb}^{-1}$ to $\sim 140\,\text{fb}^{-1}$ (ATLAS/CMS)
  - Run3 is expected to yield $\sim 300\,\text{fb}^{-1}$