# Heavy Neutrinos in displaced vertex searches at the LHC and HL-LHC

Based on `arXiv:1903.06100`

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Searching for long-lived particles at the LHC: Fifth workshop of the LHC LLP Community

# Framework

## Right handed neutrino $\nu_R$

$$\mathcal{L}_{\nu_R} = \frac{\mathrm{i}}{2}\overline{\nu_R}\partial\!\!\!/\nu_R - F_a\overline{\ell_L}_a\varepsilon\phi^*\nu_R - \frac{1}{2}\overline{\nu_R^c}M\nu_R + \text{h.c.} \ .$$

- $\phi$ SM Higgs doublet
- $\ell_{La}$ SM lepton doublets
- $F_a$ Yukawa coupling constants
- $\varepsilon$ antisymmetric SU(2) tensor

## One heavy neutrino mass eigenstate $N \simeq \nu_R + \theta_a\nu_{La}^c + \text{c.c.}$

$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}\theta_a^*\gamma^\mu e_{La}W_\mu^+ - \frac{m_Z}{\sqrt{2}v}\overline{N}\theta_a^*\gamma^\mu\nu_{La}Z_\mu - \frac{M}{v}\theta_a h\overline{\nu_L}_\alpha N + \text{h.c.} \ ,$$

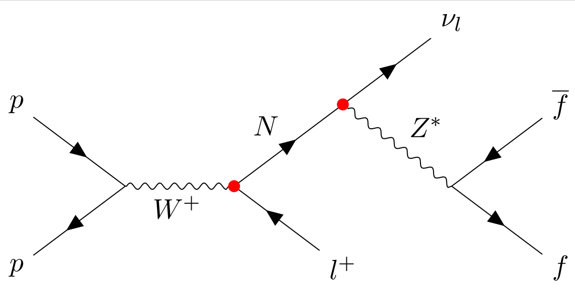
- $M$ mass of the heavy neutrino
- $v$ $= \langle\phi\rangle \simeq 174\,\text{GeV}$
- $\theta_a$ $= vF_a/M$ mixing angles to the SM flavours
- $h$ physical Higgs

## Restriction

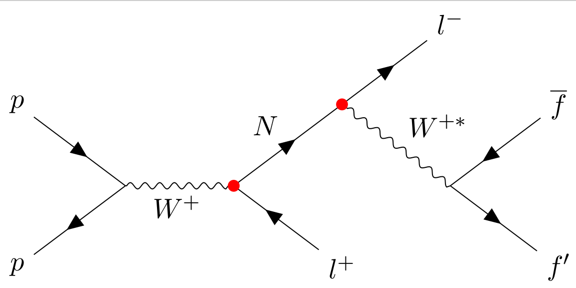
three extremal scenarios in which the heavy neutrinos exclusively mix with one SM generation

# Signature

## $Z$-decay




## $W$-decay




## Search strategy

- trigger on first lepton
- search for secondary vertex

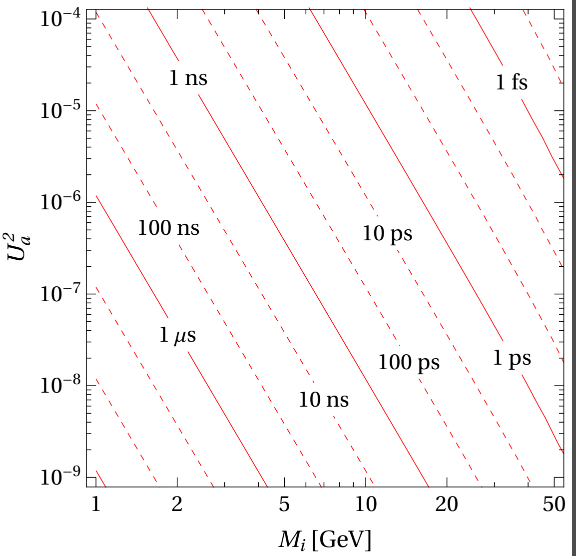
## Other production channels

$Z/h$ at leading order no lepton to trigger on

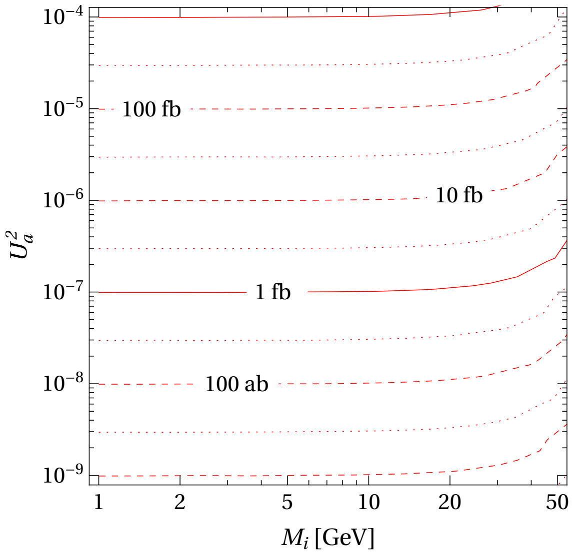
$B$ needs a different tool chain

# Properties

## Lifetime




## Crosssection




## Decay width for $M \gg 5\,\text{GeV}$

$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U_a^2 M^5 \;,$$

# One dimensional model

## Number of displaced vertex events

$$N_d \simeq L\sigma_\nu U_a^2 \left[\exp\left(-\frac{l_0}{\lambda_N}\right) - \exp\left(-\frac{l_1}{\lambda_N}\right)\right] f_{\text{cut}} \ .$$

$l_0$ minimal displacement

$l_1$ extension of the spherical detector

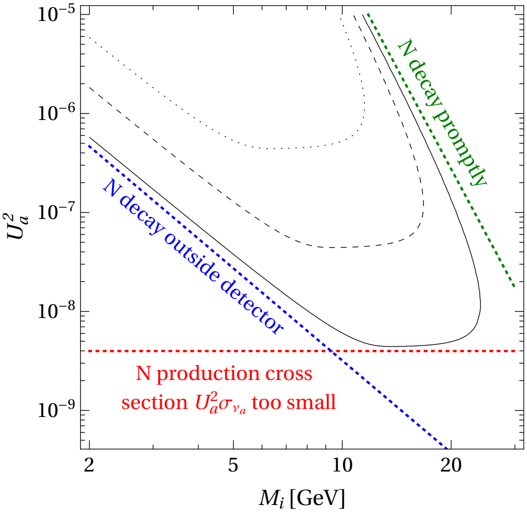
$\lambda_N = \beta\gamma/\Gamma_N$ decay length

$\beta\gamma = |\boldsymbol{p}|/M$ Lorentz factor

$f_{\text{cut}} \subset [0, 1]$ overall efficiency

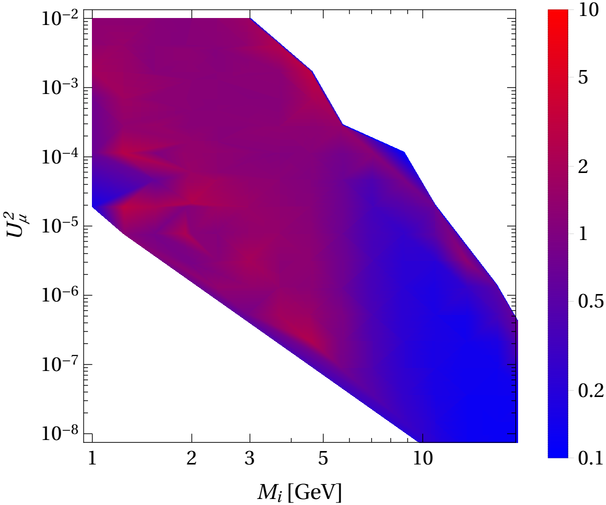
# Intuitive understanding

## Simplified model




- sensitivity curves correspond to 9 expected events for integrated luminosities of 3, 30, 300 $fb^{-1}$
- all efficiencies are 100 %

## Deviation from the full analysis



# Toolchain

## Public software

| | |
|---|---|
| `HeavyN_NLO` | Heavy neutrino model |
| `FeynRules` | UFO generation |
| `MadGraph5_aMC@NLO` | event generation |
| `MadWidth` | decay width |
| `MadSpin` | Heavy particle decays |
| `Pythia` | hadronisation and showering of coloured particles |

## Detector simulation

with private code based on public information of the detector geometry.

# Detector geometry

### ATLAS

| | |
|---|---|
| pseudo-rapidity | $\lvert\eta\rvert < 2.5.$ |
| tracker | (1.1 m, 3.4 m) |
| muon system | (5–10 m, 7–21 m) |

### CMS

| | | |
|---|---|---|
| pseudo-rapidity | $\lvert\eta\rvert < 2.5$ | (Up to Run 3) |
| | $\lvert\eta\rvert < 4$ | (HL-LHC) |
| tracker | (1.1 m, 2.8 m) | |
| muon system | (4–7 m, 7–11 m) | |

### LHCb

| | | |
|---|---|---|
| pseudo-rapidity | $2 < \eta < 5.$ | |
| VELO | (50 cm, 40 cm) | (vertex locator) |
| RICH 1 | at 1 m with (60 cm, 100 cm) | (ring imaging cherenkov) |
| RICH 2 | at 9 m with (4 m, 3 m) | |
| muon system | at 15 m with (5 m, 5 m) | |

inner tracker can provide veto info for appearing track candidates

# Trigger and tracker efficiencies

## Single lepton trigger

CMS $p_T(e,\ \mu,\ \tau) = 30,\ 25,\ 140\,\text{GeV}$
LHCb $p_T(e,\ \mu,\ \tau) = 10,\ 15,\ 50\,\text{GeV}$

## Single lepton and lepton pair triggers for ATLAS

[ATLAS 2017]

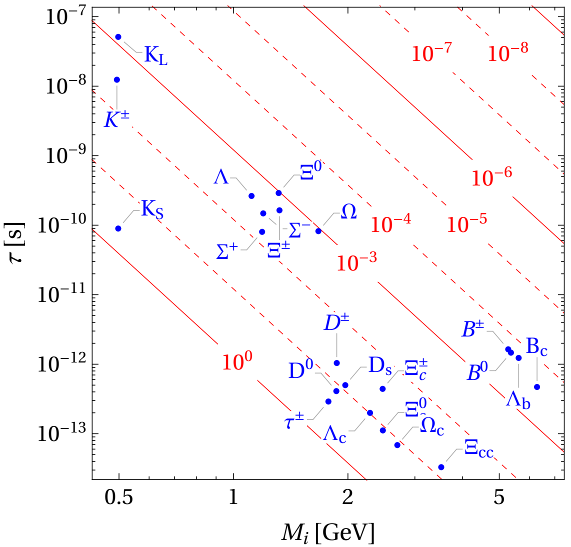
| | Single Lepton | | | Lepton Pair | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $e$ | $\mu$ | $\tau$ | $e,\ e$ | $e,\ \mu$ | $e,\ \tau$ | $\mu,\ \mu$ | $\mu,\ \tau$ | $\tau,\ \tau$ |
| $p_T^{\text{min}}$ [GeV] | 27 | 27 | 170 | 18, 18 | 8, 25<br>18, 15 | 30, 18 | 15, 15<br>23, 9 | 30, 15 | 40, 30 |

## Tracking and tagging efficiencies

Values from `DELPHES` detector cards

# Backgrounds

## SM particles vs. $U^2$




## SM background free region

$l_0 \gtrsim 5\,\text{mm}$ and $M \gtrsim 2\,\text{GeV}$

# Analysis

## Displaced vertex reconstruction

- at least 2 tracks
- invariant mass of 5 GeV
  (in order to suppress nuclear interactions backgrounds)

## Ray tracing

- reconstruction efficiency drops off linearly with remaining track
- particles must transverse at least half of the tracker
- consistent with ATLAS efficiency dependence [ATLAS 2018]

## Muon chamber [Bobrovskyi et al. 2011; CMS 2015]

- muon chamber covers more volume than the tracker
- long lived particles can be search for using only muon chambers
- we require reconstructed particle to transverses the whole muon chamber
- no invariant mass cut for purely muonic vertices

## Optimistic assumptions

- only two tracks for vertex reconstruction [vs. ATLAS 2018; Cottin et al. 2018]
- largest observable displacement by a factor of 2 better than current analyses [vs. ATLAS 2018]
- main problem: inability to simulate nuclear interactions and other detector effects

# Statistics

**Significance for $n$ observed events**

$$S(n|h) = \sqrt{-2\ln\frac{P(n|h)}{P(n|n)}}$$

**Poisson probability**

$$P(n|h) = \frac{h^n}{n!}e^{-h} ,$$

**$h$ is the number of events predicted by the**

- background with signal hypothesis $b+s$.
- background only hypothesis $b$

**Exclusion of model**

$S(n|b+s) \geq 2$

**Discovery of model**

$S(n|b) \geq 5$

**Projection to future searches**

estimation of $n$ with the prediction for the alternative hypothesis

**Exclusion**

$S(b|b+s) \geq 2$

$b = 1 \quad \rightarrow \quad n \geq 4$

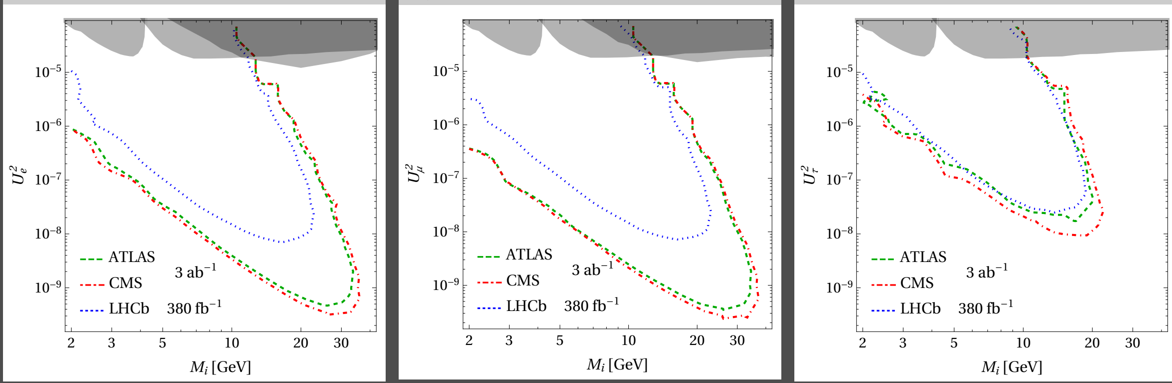
**Discovery**

$S(b+s|b) \geq 5$

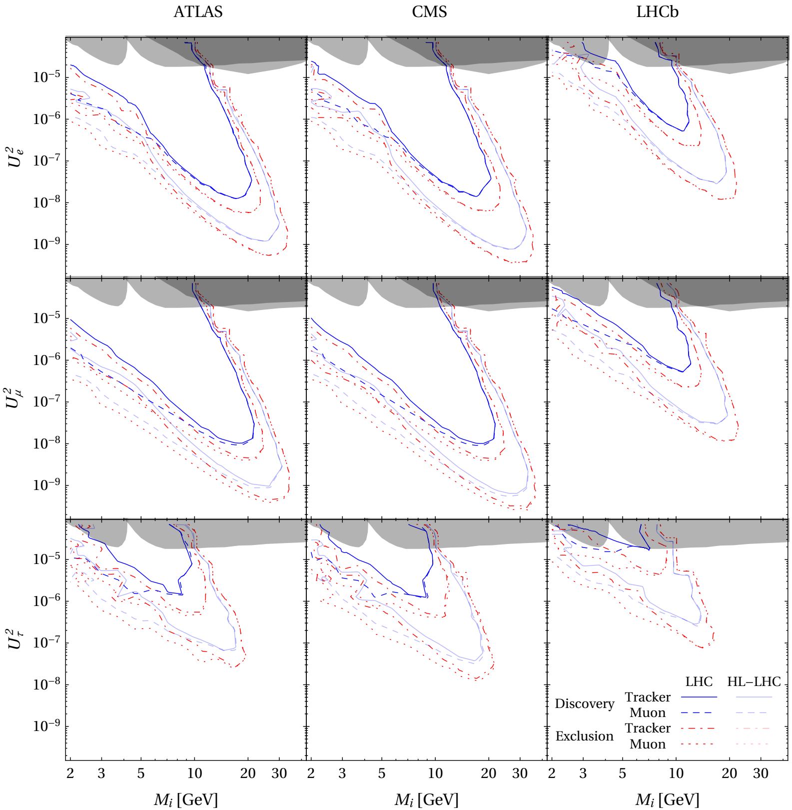
$b = 1 \quad \rightarrow \quad n \geq 9$

# Optimal exclusion reach

$U_e^2$ $U_\mu^2$ $U_\tau^2$

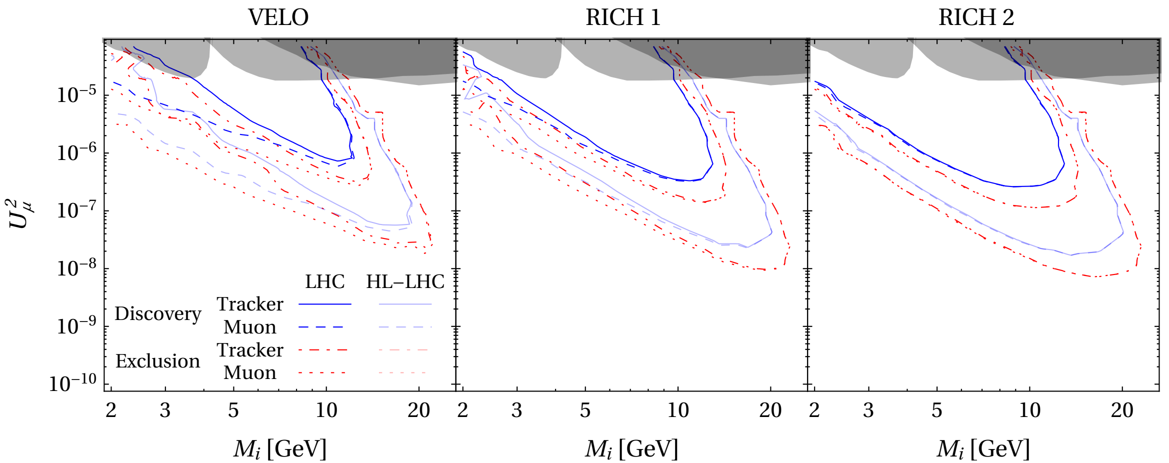


# Comparison


ATLAS
CMS
LHCb
$U_e^2$
$U_\mu^2$
$U_\tau^2$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
2 3 5 10 20 30
$M_i$ [GeV]
LHC
HL–LHC
Discovery
Tracker
Muon
Exclusion
Tracker
Muon

# Conclusion

- Increased luminosity will lead to significantly better bounds between $2\,\text{GeV} \lesssim M \lesssim 30\,\text{GeV}$
- muon chambers can provide valuable additional information about long-lived particles
- Optimized trigger are essential


VELO
RICH 1
RICH 2
$U_\mu^2$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
2
3
5
10
20
$M_i$ [GeV]
LHC
HL−LHC
Discovery
Exclusion
Tracker
Muon
Tracker
Muon

M. Drewes and J. Hajer. "Heavy Neutrinos in displaced vertex searches at the LHC and HL-LHC". arXiv: 1903.06100 [hep-ph]. №: CP3-19-11.

ATLAS. "Trigger Menu in 2016". ATL-DAQ-PUB-2017-001. URL: https://cds.cern.ch/record/2242069.

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