

Sterile Neutrinos at LHCb

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Motivation for sterile neutrinos

Three Generations of Matter (Fermions) spin $\frac{1}{2}$									
	I	II	III						
mass →	2.4 MeV	1.27 GeV	173.2 GeV						
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$						
name →	u up	c charm	t top						
Quarks	Left d down	Left s strange	Left b bottom	Right g gluon	Right γ photon	Right Z weak force	Right H Higgs boson	Right W weak force	
Leptons	Left e electron	Left μ muon	Left τ tau	Right Bosons (Forces) spin 1	Right Bosons (Forces) spin 0				

Credit: Shaposhnikov et. al

- ▶ Neutrino oscillations are evidence for new physics.
- ▶ Sterile neutrinos for type I seesaw mechanism.

The Seesaw Mechanism

- ▶ Naïve $(1 \nu_L, 1 \nu_R)$ version: $m_\nu = \frac{1}{2} \frac{v_{\text{EW}}^2 |y_\nu|^2}{M_R}$
- ▶ More realistic example, the $(2 \nu_L, 2 \nu_R)$ version:

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ 0 & \mathcal{O}(y_\nu) \end{pmatrix}, \quad M_N = \begin{pmatrix} M_R & 0 \\ 0 & M_R(1 + \varepsilon) \end{pmatrix}$$

$$\Rightarrow m_{\nu_i} = \frac{v_{\text{EW}}^2 \mathcal{O}(y_\nu^2)}{M_R} (1 - \delta_{i2} \varepsilon)$$

⇒ Knowledge of m_{ν_i} implies a relation between y_ν and M_R .

Lowscale Seesaw

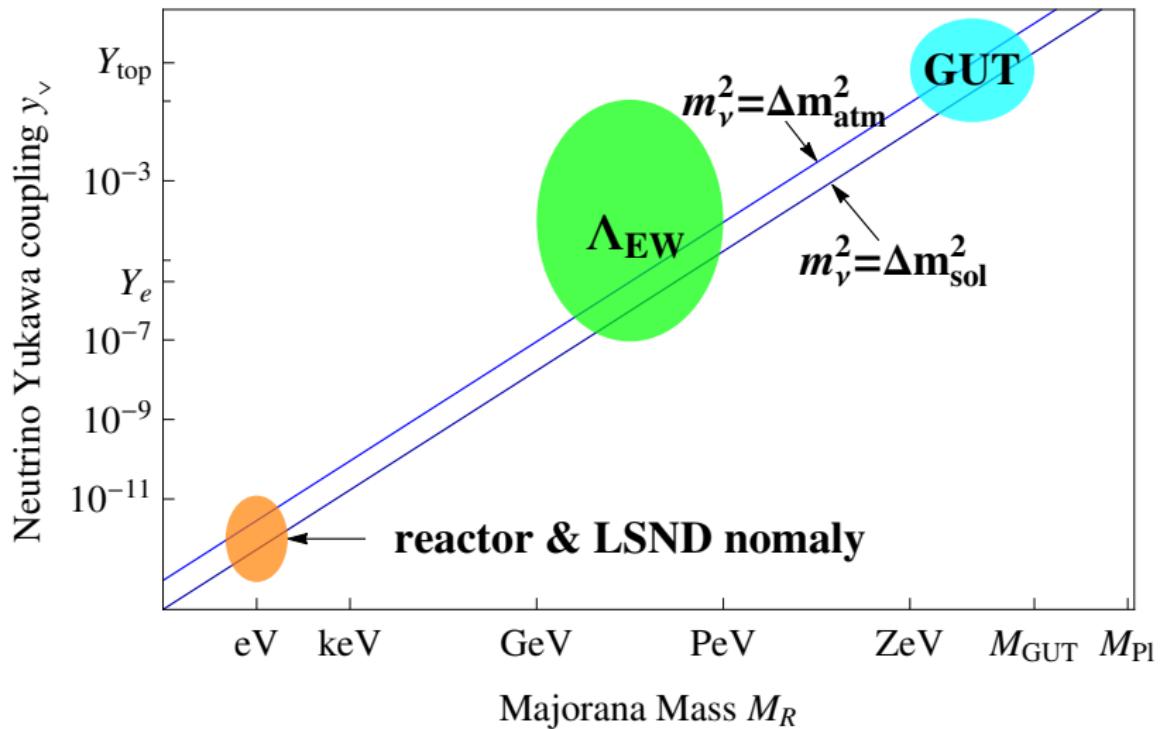
- ▶ Specific structures of the Yukawa and mass matrices can be realised by symmetries (no fine tuning).
- ▶ A $(2 \nu_L, 2 \nu_R)$ example:

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ \mathcal{O}(y_\nu) & 0 \end{pmatrix}, \quad \begin{pmatrix} 0 & M_R \\ M_R & \varepsilon \end{pmatrix}$$

$$\Rightarrow m_{\nu_i} = 0 + \varepsilon \frac{v_{\text{EW}}^2 \mathcal{O}(y_\nu^2)}{M_R^2}$$

$\Rightarrow y_\nu \sim \mathcal{O}(1)$ and $M_R \sim v_{\text{EW}}$ possible!

The Big Picture



The Symmetry Protected Seesaw Scenario

Benchmark model, defined in Antusch, OF; JHEP 1505 (2015) 053

Similar to: Mohapatra, Valle (1986); Malinsky, Romao, Valle (2005); Shaposhnikov (2007); Kersten, Smirnov (2007)

- ▶ Collider phenomenology dominated by two sterile neutrinos N_i with protective symmetry, such that

$$\mathcal{L}_N = -\frac{1}{2} \overline{N_R^1} M (N_R^2)^c - y_{\nu_\alpha} \overline{N_R^1} \tilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

- ▶ Further “decoupled” sterile neutrinos included.
- ▶ Active-sterile mixing: $\theta_\alpha = y_{\nu_\alpha} \frac{v_{\text{EW}}}{\sqrt{2}M}$, $\theta^2 \equiv \sum_\alpha |\theta_\alpha|^2$
- ▶ The mass matrix:

$$\mathcal{M}_\nu = -\frac{1}{2} \begin{pmatrix} 0 & \left(\frac{y_{\nu_\alpha} v_{\text{EW}}}{\sqrt{2}} \right) & 0 \\ \left(\frac{y_{\nu_\alpha} v_{\text{EW}}}{\sqrt{2}} \right)^T & 0 & M \\ 0 & M & 0 \end{pmatrix} + \text{H.c.}$$

**Many searches at the LHC exist.
In the following I focus on LHCb's.
Please ask later “why”!**



CERN-EP-2016-283
LHCb-PAPER-2016-047
April 25, 2017

Search for massive long-lived particles decaying semileptonically in the LHCb detector

The LHCb collaboration[†]

Abstract

A search is presented for massive long-lived particles decaying into a muon and two quarks. The dataset consists of proton-proton interactions at centre-of-mass energies of 7 and 8 TeV, corresponding to integrated luminosities of 1 and 2 fb^{-1} , respectively. The analysis is performed assuming a set of production mechanisms

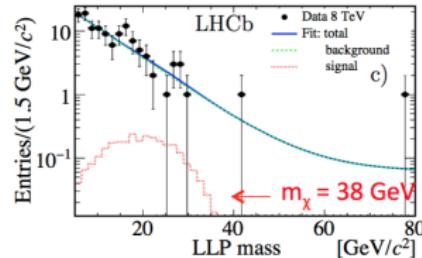
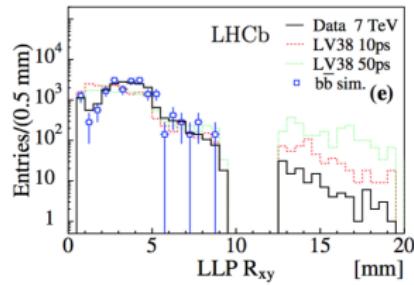


LLP to $\mu + \text{jets}$

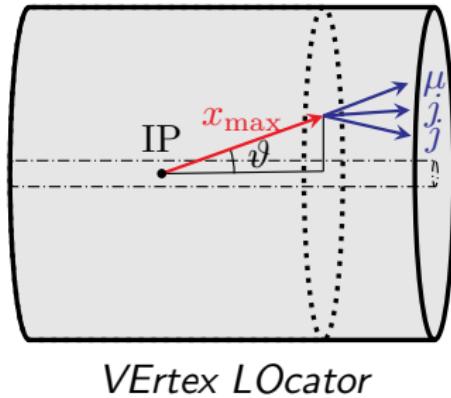
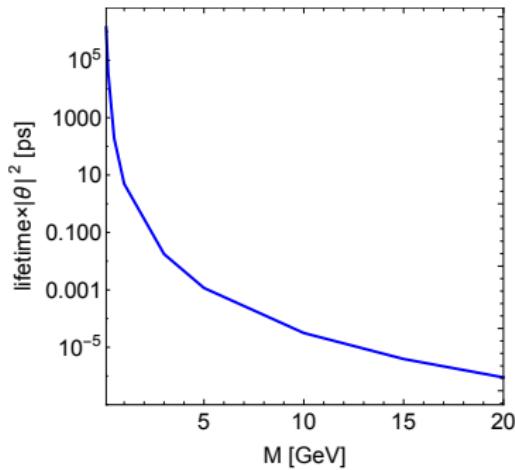
NEW

Eur. Phys. J. C (2017) 77:224

- ➊ **Signature:** single displaced vertex with several tracks and a high p_T muon
- ➋ Model: mSUGRA neutralino decaying to a lepton and two quarks
- ➌ Using 3 /fb at 7 and 8 TeV
- ➍ LLP $m=[20\text{-}80] \text{ GeV}/c^2$, $\tau=[5\text{-}100] \text{ ps}$
- ➎ Background dominated by bb
 - tight selection + MVA classifier
- ➏ Number of candidates from fit to LLP mass



Displaced vertex searches



VErtex LOCator

- ▶ $M < m_W$ and $|\theta|^2 < 10^{-5}$ leads to macroscopic lifetimes
- ▶ Consider N decaying into $\mu + j$
- ▶ Secondary vertex with “large” displacement in VELO
- ▶ “Large” means no SM background for displacements
 - > 2 cm (conservative)
 - > 5 mm (progressive, lepton isolation)

Analytic estimate of event numbers

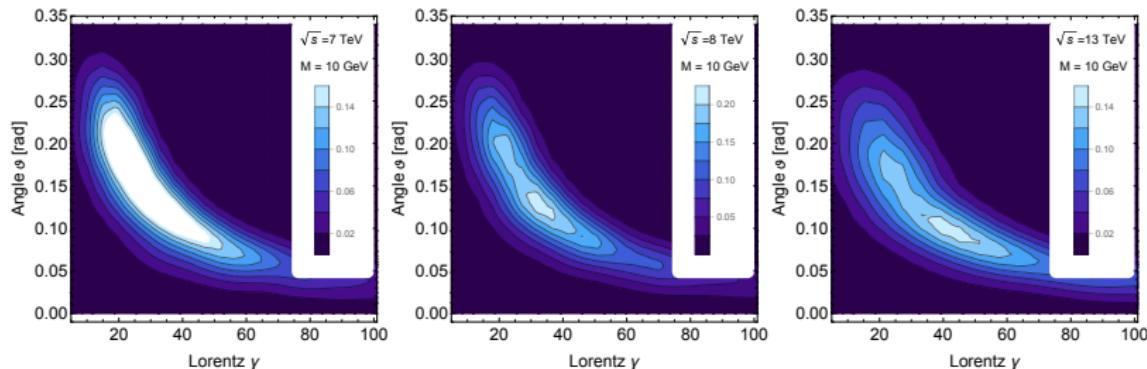
$$N_{\text{dv}}(\sqrt{s}, \mathcal{L}, M, |\theta|^2) = N_{xN} \times \int D_{xN}(\vartheta, \gamma) P_{\text{dv}}(x_{\min}, x_{\max}, \Delta x_{\text{lab}}) d\vartheta d\gamma$$

- ▶ $N_{xN} = \sum_{x=\nu, \ell^\pm} \sigma_{xN}(\sqrt{s}, M, |\theta|^2) \times \text{Br}_{\mu jj} \times \text{luminosity}$
 $\sigma_{xN} \sim \mathcal{O}(100 - 1000) \text{ pb} \times |\theta|^2$
- ▶ D_{xN} distribution of events in γ, ϑ
- ▶ P_{dv} distribution of events in a given (lab) volume
- ▶ ϑ angle wrt. beam axis
- ▶ γ Lorentz boost of N proper frame wrt. lab frame
- ▶ x_{\min}, x_{\max} are functions of ϑ

Kinematic distributions from MC simulation

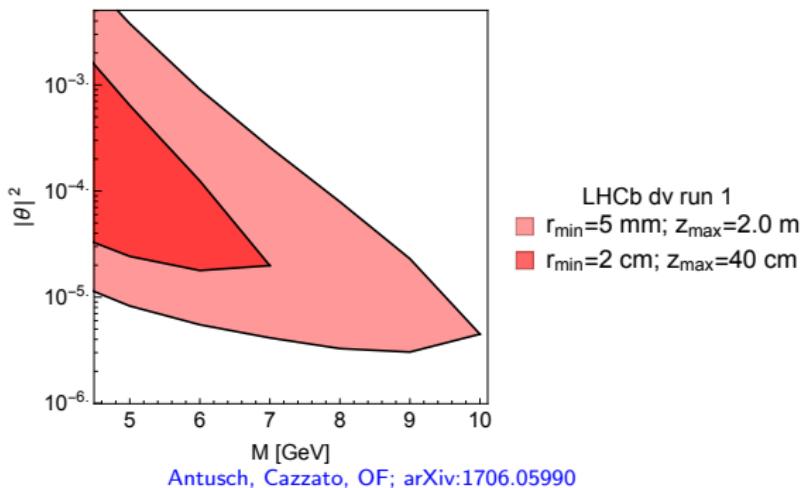
using WHIZARD

- Distributions for the process $pp \rightarrow \nu N$:



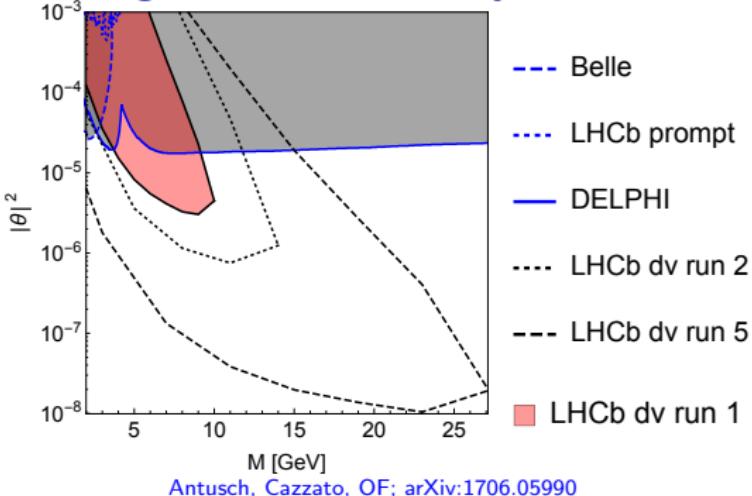
- Dist.s for $pp \rightarrow \ell^\pm N$ similar, but smaller values for ϑ
- Dist.s for $pp \rightarrow \ell^+ N$ get closest to the beam
- Consider for decay products:
 - $2 < \eta(f) < 5$, $f = \mu, j$
 - $P_t(\mu) > 12$ GeV

Present LHCb exclusion constraints



- ▶ Estimated exclusion limits at 95% C.L., $\Leftrightarrow N_{\text{obs}} \geq 3.09$.
- ▶ Dark red: conservative estimate.
- ▶ Light red: progressive estimate,
includes assumptions for the efficiency.
- ▶ All limits for $|\theta|^2 = |\theta_\mu|^2$ (i.e. $|\theta_e| = |\theta_\tau| = 0$).

Forecasts, assuming dedicated analyses



- ▶ Displaced muons plus jets at 13 TeV
- ▶ Assuming 100% efficiency and $\Delta r > 5$ mm, $\Delta z < 2$ m.
- ▶ black dotted: sensitivities for the present amount of data of 5 fb^{-1}
- ▶ black dashed: 380 fb^{-1} for the high-luminosity run.
- ▶ All limits for $|\theta|^2 = |\theta_\mu|^2$ (i.e. $|\theta_e| = |\theta_\tau| = 0$).

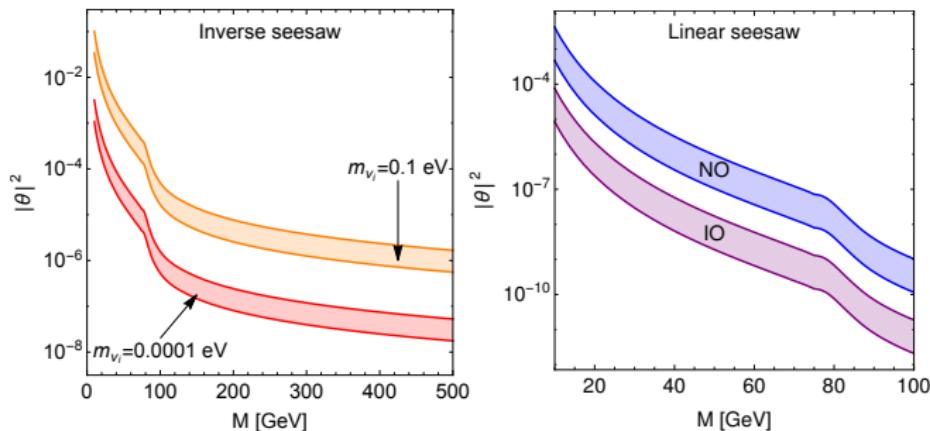
Heavy neutrino-antineutrino oscillations

- ▶ Neutrinos are Majorana, (their own antiparticle), both can decay into ℓ^+ and ℓ^- .
- ▶ Define:

antineutrino, $W^- \rightarrow \bar{N}\ell^-$, decay width $\Gamma_{\bar{N}}$, mass $M_{\bar{N}}$
neutrino, $W^+ \rightarrow N\ell^+$, Γ_N , M_N

- ▶ If $\Gamma_N \simeq \Gamma_{\bar{N}} > |M_N - M_{\bar{N}}| \equiv \Delta M$
 \Rightarrow interference cancels lepton number violation (LVN)
- ▶ In the symmetry protected seesaw scenario (SPSS) lepton number is conserved (LNC) due to $M_N = M_{\bar{N}} \equiv M$
- ▶ In the SPSS, and at LHC we expect...
 - ... $pp \rightarrow \ell_\alpha^+ \ell_\beta^- jj$ (LNC) ✓
 - ... $pp \rightarrow \ell_\alpha^\pm \ell_\beta^\pm jj$ (LVN) ✗

Generating light neutrino masses



Antusch, Cazzato, OF; arXiv:1709.03797

Perturbations of the mass matrix: $M_\nu = \begin{pmatrix} 0 & m_D & \varepsilon \\ (m_D)^T & \varepsilon^T & M \\ \varepsilon & M & \varepsilon \end{pmatrix}$

- ε linear seesaw
- ε inverse seesaw
- ε inverse seesaw, no contribution to light neutrino masses
- $\Rightarrow \Delta M$ fixed by light neutrino masses \Rightarrow LNV

A very unique signature

- ▶ Drell-Yan: $W^+ \rightarrow \ell^+ N \xrightarrow{\text{oscillation}} \ell^+ \bar{N}$
Oscillation governed by: $g_-(t) \simeq -ie^{-iMt} e^{-\frac{\Gamma}{2}t} \sin\left(\frac{\Delta M}{2}t\right)$
- ▶ ΔM yields oscillation frequency:

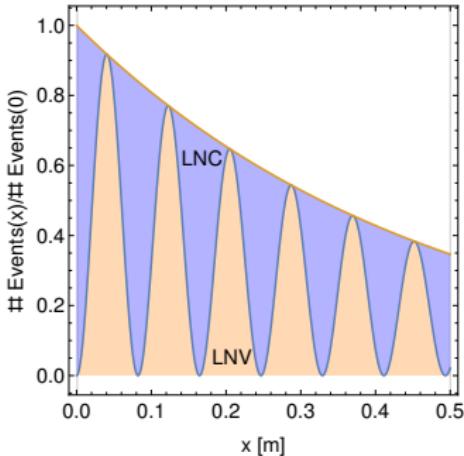
$$\lambda_{\text{osc}}^{\text{lin,NO}} = 5.96 \cdot 10^{-5} \sqrt{\gamma^2 - 1} \text{ m ,}$$

$$\lambda_{\text{osc}}^{\text{lin,IO}} = 3.29 \cdot 10^{-3} \sqrt{\gamma^2 - 1} \text{ m ,}$$

$$\lambda_{\text{osc}}^{\text{inv}} \approx 2.48 \cdot 10^{-6} \left(\frac{|\theta|^2}{10^{-4}} \right) \left(\frac{10^{-4} \text{ eV}}{m_{\nu_i}} \right) \sqrt{\gamma^2 - 1} \text{ m .}$$

- ▶ Decay: $\ell^+ \bar{N} \longrightarrow \ell^+ (\ell^+ jj)_{\text{displaced}}$
- ⇒ Prompt lepton, displaced vertex & same-sign (SS) leptons

Heavy neutrino-antineutrino oscillations @ LHCb



Antusch, Cazzato, OF; arXiv:1709.03797

- ▶ Benchmark: $M = 10 \text{ GeV}$, $|\theta|^2 = 10^{-6}$, $\gamma = 50$ (fixed)
- ▶ Linear seesaw with IO for the light neutrino masses
- ▶ The orange envelope curve shows event distribution at distance x from the primary vertex
- ▶ Range x-axis \propto VErtex LOcator
- ▶ 70 events with displacements $\in [2, 50] \text{ cm}$ at HL-LHC

Conclusions

- ▶ Searches at LHCb for displaced vertices with muons yield best constraints on $|\theta_\mu|^2$ for $5 \leq M \leq 10$ GeV
- ▶ Dedicated analyses...
 - ... should search for displaced electrons and taus
 - ... should include the prompt lepton to reject background
 - ... might search for lepton-jets
 - ... might use other LHCb components (VELO-veto)
- ▶ In linear and inverse seesaw models the mass splitting of heavy neutrinos \sim light neutrino mass spectrum.
- ▶ Heavy neutrino-antineutrino oscillations yield unique signature:

$$\ell_\alpha^\pm (\ell_\beta^\pm jj)_{\text{displaced}}$$

- ▶ Oscillations between LNV and LNC may be visible @ HL-LHC
- ⇒ Work in progress...

Thank you for your attention.