Flavourful Z' portal for vector-like neutrino Dark Matter and $R_{K^{(*)}}$ [arXiv:1803.04430]

Mathias Pierre

In collaboration with **A. Falkowski, S. F. King** and **E. Perdomo**

Dark Side of the Universe, LAPTH, June 26 2018

Contents

Motivation

The Waning of the WIMP?

- The **WIMP miracle** $\Omega_{\rm DM}h^2 \propto \langle\sigma v\rangle^{-1}_{\rm relic} \sim 0.12$

$$\langle\sigma v\rangle_{\rm relic} \sim 10^{-26}\ \text{cm}^3\ \text{s}^{-1} \sim 10^{-9}\ \text{GeV}^{-2} \sim \frac{g^4}{m_Z^4} m_{\rm DM}^2$$

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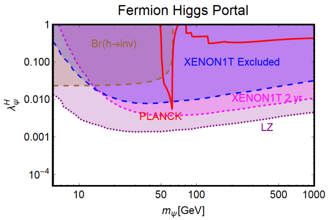

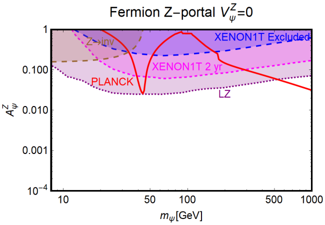

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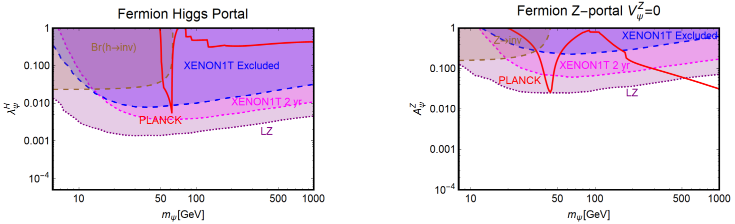

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- Test of **Lepton Flavor Universality (LFU) violation** in $b \to s\ell\ell$

$$R_{K^{(*)}}^{[q^2_{\min},q^2_{\max}]} \equiv \left.\frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}\right|_{q^2 \in [q^2_{\min},q^2_{\max}]}$$

- **Theory under control:** hadronic uncertainties cancels out, below $\bar{c}c$ resonance

$$R^{\rm SM}_{K^{(*)}} = 1.00(1)$$

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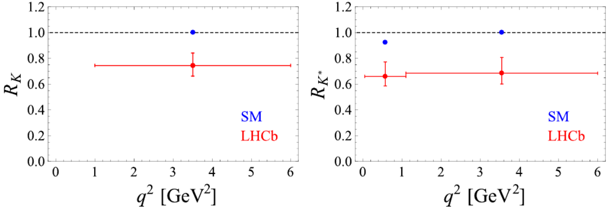
$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.113}_{-0.074}\,,$$
$$R_{K^*}^{[1.1,6]} = 0.685^{+0.122}_{-0.083}\,,$$
$$R_{K}^{[1,6]} = 0.745^{+0.097}_{-0.082}\,.$$



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- **Flavor Changing Neutral Current (FCNC)** loop generated in SM
  $\rightarrow R_{K^{(*)}}$ sensitive to **New Physics** (**NP**) featuring FCNC!
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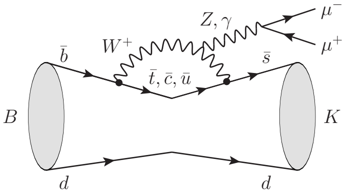
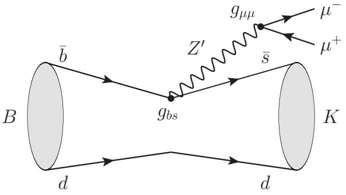
$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i,\ell} \left(C_{i\ell}^{\text{NP}} \mathcal{O}_i^\ell + C_{i\ell}'^{\text{NP}} \mathcal{O}_i'^\ell \right)$$





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$$\mathcal{O}_9^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_{10}^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \ .$$

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$$G_{bs\mu} \sim \frac{1}{(30\ \text{TeV})^2} \simeq 10^{-9}\ \text{GeV}^{-2} \simeq \langle \sigma v \rangle_{\text{relic}}$$ **Same scale!**

A flavourful model for $R_{K^{(*)}}$ & Dark Matter

A flavourful model including a 4^{th} generation

- Consider a **4^{th} vector-like (V-L) family** charged under extra $U(1)'$
  SM particle content not charged under $U(1)'$

Field	Representation/charge			
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
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d_{Ri}	**3**	**1**	$-1/3$	0
L_{Li}	**1**	**2**	$-1/2$	0
e_{Ri}	**1**	**1**	-1	0
ν_{Ri}	**1**	**1**	0	0
H	**1**	**2**	$1/2$	0
$Q_{L4}, \tilde{Q}_{R4}$	**3**	**2**	$1/6$	q_{Q4}
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$e_{R4}, \tilde{e}_{L4}$	**1**	**1**	-1	q_{e4}
$\nu_{R4}, \tilde{\nu}_{L4}$	**1**	**1**	0	$q_{\nu 4}$
$\phi_{Q,u,d,L,e}$	**1**	**1**	0	$-q_{Q_4,u_4,d_4,L_4,e_4}$

- The **4^{th} V-L neutrino** $\nu_4 \equiv \nu_{R4} + \tilde{\nu}_{L4}$ is a **dark matter** candidate
  SM **singlets** scalars ϕ responsible for **generation mixing**

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The flavourful Lagrangian

- Mass and Yukawa terms in **flavour basis** ($i = 1, 2, 3$)

$$\mathcal{L} \supset x_i^Q \phi_Q \bar{Q}_{Li} \tilde{Q}_{R4} + x_i^u \phi_u \bar{\tilde{u}}_{L4} u_{Ri} + M_4^Q \bar{Q}_{L4} \tilde{Q}_{R4} + M_4^u \bar{\tilde{u}}_{L4} u_{R4} + M_4^\nu \bar{\tilde{\nu}}_{L4} \nu_{R4}$$

- **Non-diagonal** mass terms generated **after the** $U(1)'$ **breaking** $\langle \phi \rangle \neq 0$
$\rightarrow$ diagonalized with 4×4 unitary matrices $V_{\alpha\beta}$ ($\alpha, \beta = 1, ..., 4$)
- **After** $U(1)'$ **SSB:** Mixing mostly with **3rd** gen. of Q and **2nd** gen. of L

$$\mathcal{L}_{Z'}^{\text{gauge}} = g' Z'_\mu \left(q_{Q_4} (s_{34}^Q)^2 \bar{Q}'_{L_3} \gamma^\mu Q'_{L_3} + q_{L_4} (s_{24}^L)^2 \bar{L}'_{L_2} \gamma^\mu L'_{L_2} \right)$$

- Expanding the **primed field** in mass eigenstates **after EW SSB**

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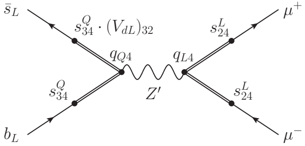
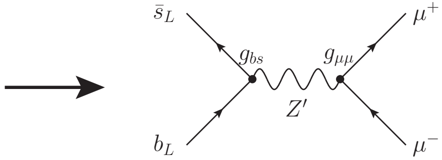
The phenomenological Lagrangian





- The **relevant terms** at the end are:

$$\mathcal{L} \supset Z'_\mu \Big(g_{bb} \sum_{q=b,t} \bar{q}_L \gamma^\mu q_L + g_{bs} \bar{b}_L \gamma^\mu s_L + g_{\mu\mu} \sum_{\ell=\mu,\nu_\mu} \bar{\ell}_L \gamma^\mu \ell_L + g_{\nu\nu} \bar{\nu}_4 \gamma^\mu \nu_4 \Big),$$

  with the relations $g_{bs} = g_{bb} V_{ts}$ and $g_{\nu\nu} = g' q_{\nu 4}$
- A **dark matter** candidate $\nu \equiv \nu_4$ **stable**
- A heavy Z' **mediator** featuring **tree-level FCNC**

5 parameters: $g_{\nu\nu}$, $g_{\mu\mu}$, g_{bb}, $m_{Z'}$ and m_ν

Flavour constraints

$R_{K^{(*)}}$ relation

$$G_{bs\mu} = -\frac{g_{bs}g_{\mu\mu}}{M_{Z'}^2} = -\frac{V_{ts}g_{bb}g_{\mu\mu}}{M_{Z'}^2} \approx \frac{1}{(31.5\ \text{TeV})^2}$$

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Neutrino trident: $\nu_\mu \gamma^* \to \nu_\mu \mu^+ \mu^-$

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$B_s - \bar{B}_s$ mixing

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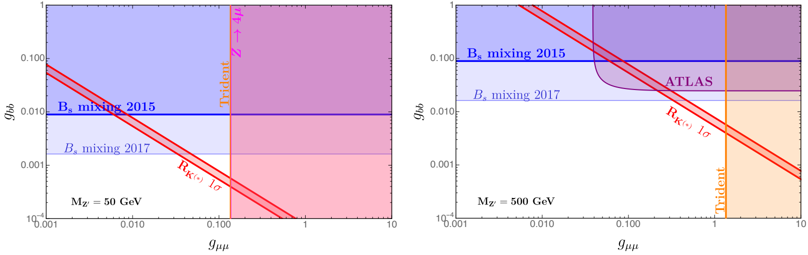
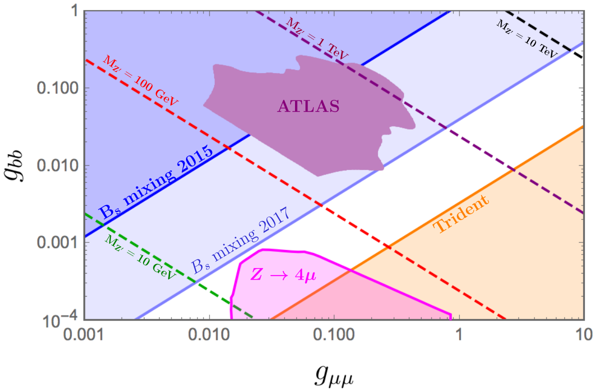
$$-\frac{1}{(180\ \text{TeV})^2} \lesssim G_{bs} \lesssim \frac{1}{(770\ \text{TeV})^2}$$

Collider and other constraints

- $pp \to \gamma^* Z \to 4\mu$ constrains **low masses** $5 \lesssim M_{Z'} \lesssim 70$ GeV
- $pp \to Z' \to \mu^+\mu^-$ constrains **higher masses** $200 \lesssim M_{Z'} \lesssim 1000$ GeV
- Precise measurements of LFU $R_{1s}^{\tau/\mu}$ of Υ_{1s} and $(g-2)_\mu$ set weaker constraints



Summary of the constraints



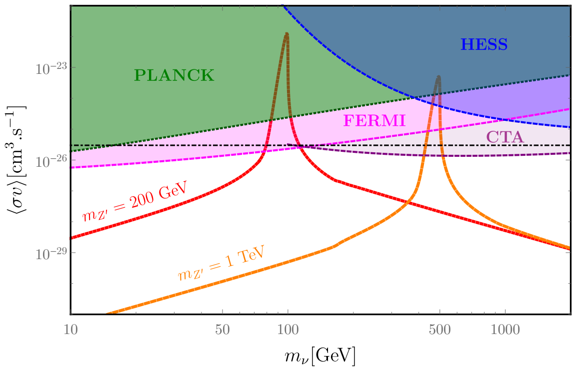
- $M_{Z'} \gtrsim$ few TeV **unnatural**
- $M_{Z'} \lesssim 50$ GeV **strongly constrained**
- Hierarchy $g_{\mu\mu} \gg g_{bb}$ satisfied in the **natural** parameter space

Dark matter relic density

- Dark matter **annihilations** $\bar{\nu}\nu \to \bar{\psi}\psi, Z'Z'$ with $\psi = b, t, \mu, \nu_\mu$

$$\Omega_\nu h^2 \simeq 0.12 \left(\frac{3 \times 10^{-26} \text{cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right) \quad \text{with} \quad \langle \sigma v \rangle = \sum_\psi \langle \sigma v \rangle_{\bar{\psi}\psi} + \langle \sigma v \rangle_{Z'Z'}.$$

- $\langle \sigma v \rangle$ is **s-wave** dominated $\to$ contraints from **Indirect Searches: Fermi** and **HESS** ($\bar{b}b$), **Planck** ($\mu^+\mu^-$) and upcoming **CTA** ($\mu^+\mu^-$)



Dark matter direct searches

- Effective operators generated at the scale $\mu \simeq M_{Z'}$

$$\mathcal{L}_{\text{eff}} \supset -\sum_{f=\mu,b} \frac{g_{\nu\nu} g_{ff}}{M_{Z'}^2} \bar{f}_L \gamma^\alpha f_L \bar{\nu} \gamma_\alpha \nu \ ,$$

- Below $\mu < M_{Z'}$, **DM couplings** to **light quarks** are induced via **RGE**

$$\mathcal{L}_{\text{eff}} \supset \sum_{q=u,d} C_{1,f}^{(6)}(\mu) \bar{q} \gamma^\alpha q \bar{\nu} \gamma_\alpha \nu \quad \text{with} \quad C_{1,f}^{(6)}(\mu) \sim \frac{\alpha}{4\pi} \frac{g_{\nu\nu} g_{ff}}{M_{Z'}^2} \log\left(\frac{M_{Z'}}{\mu}\right)$$

- Effective operator generated at **nuclear scale** $\mu \simeq 2$ GeV

$$\mathcal{L}_{\text{eff,NR}} \supset \sum_{N=p,n} c_1^N \bar{\nu} \nu \bar{N} N \ \rightarrow \ \sigma_{\text{DD}} \sim \left(\frac{g_{\nu\nu}}{0.2}\right)^2 \left(\frac{g_{\mu\mu}}{0.1}\right)^2 \left(\frac{m_Z}{M_{Z'}}\right)^4 10^{-45}\,\text{cm}^2.$$

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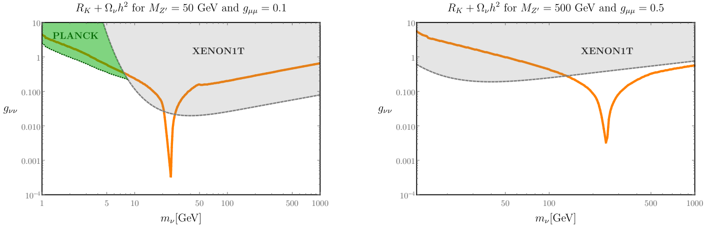
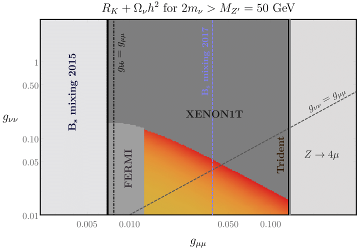
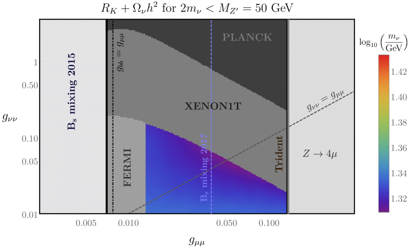


The surviving parameter space

- Each point satisfies $R_{K^{(*)}}$ and $\Omega_\nu h^2$, **color code** represents **DM mass**
- All the grey points are excluded





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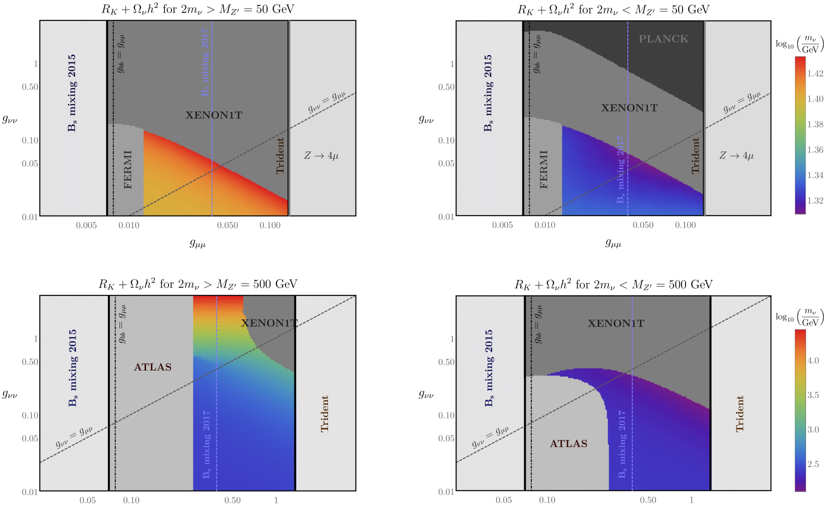
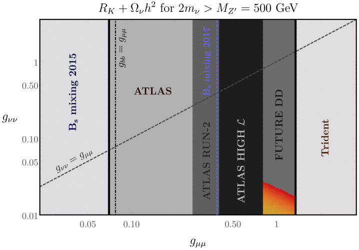
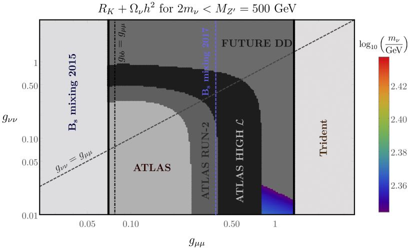


The future parameter space

- Assuming $3000\ \text{fb}^{-1}$ and 2 orders of magnitude improvement on σ_{DD}





- The **viable parameter space** should be **probed** in the (near) future!

Conclusion

Summary

- Considered $4^{\textbf{th}}$ vector-like family charged under $U(1)'$
- Non-diagonal couplings generate mixing between generations
- The $4^{\textbf{th}}$ right-handed neutrino is a good DM candidate
- $R_{K^{(*)}}$ and $\Omega_{\rm DM}h^2$ can be explained simultaneously
- The remaining parameter space will be probed

Thank you for your attention!

Back-up slides

The flavourful Lagrangian: Standard Model sector

- Mass and Yukawa terms in **flavour basis** $(i = 1, 2, 3)$

$$\mathcal{L} \supset x_i^Q \phi_Q \bar{Q}_{Li} \tilde{Q}_{R4} + x_i^u \phi_u \bar{\tilde{u}}_{L4} u_{Ri} + M_4^Q \bar{Q}_{L4} \tilde{Q}_{R4} + M_4^u \bar{\tilde{u}}_{L4} u_{R4} + M_4^\nu \bar{\tilde{\nu}}_{L4} \nu_{R4}$$

- **Non-diagonal** mass terms generated **after the** $U(1)'$ **breaking** $\langle \phi \rangle \neq 0$
  $\rightarrow$ diagonalized with 4×4 unitary matrices $V_{\alpha\beta}$ $(\alpha, \beta = 1, ..., 4)$

$$Q_L'^{\alpha} = V_{Q_L}^{\alpha\beta} Q_L^{\beta}\,, \quad u_R'^{\alpha} = V_{u_R}^{\alpha\beta} u_R^{\beta}$$ $\rightarrow$ **mixing between the 4 generations**

- $\mathcal{L} \supset y_{ij}^u \bar{Q}_{Li} \tilde{H} u_{Rj}$ becomes $\mathcal{L} \supset y_{ij}'^u \bar{Q}'_{Li} \tilde{H} u'_{Rj}$ with $y_{ij}'^u = (V_{Q_L} y_{ij}^u V_{u_R}^\dagger)_{ij}$
- Diagonalization after EW SSB:

$$V_{uL}^\dagger y'^u V_{uR}'^\dagger = \text{diag}(y_u, y_c, y_t) \rightarrow \boxed{V_{\text{CKM}} \equiv V'_{uL} V_{dL}'^\dagger}$$

- Gauge sectors $\mathcal{L}_Z$ and $\mathcal{L}_{W^\pm}$ unchanged $\rightarrow$ **GIM mechanism**

The flavourful Lagrangian: The hidden gauge sector

- **Before $U(1)'$ SSB:**

$$\mathcal{L}^{Z'} \supset g' Z'_\mu \bar{Q}_L D_Q \gamma^\mu Q_L \quad + \quad (Q \to L) \quad \text{with} \quad D_Q \equiv \text{diag}(0,0,0,q_{Q4})$$

- **After $U(1)'$ SSB:** Mixing mostly with **3rd** gen. of Q and **2nd** gen. of L

$$D'_Q = q_{Q_4} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & (s^Q_{34})^2 & c^Q_{34} s^Q_{34} \\ 0 & 0 & c^Q_{34} s^Q_{34} & (c^Q_{34})^2 \end{pmatrix}, \quad D'_L = q_{L_4} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & (s^L_{24})^2 & 0 & c^L_{24} s^L_{24} \\ 0 & 0 & 0 & 0 \\ 0 & c^L_{24} s^L_{24} & 0 & (c^L_{24})^2 \end{pmatrix}$$

$$\mathcal{L}^{\text{gauge}}_{Z'} = g' Z'_\mu \left(q_{Q_4} (s^Q_{34})^2 \bar{Q}'_{L_3} \gamma^\mu Q'_{L_3} + q_{L_4} (s^L_{24})^2 \bar{L}'_{L_2} \gamma^\mu L'_{L_2} \right)$$

- Expanding the **primed field** in mass eigenstates **after EW SSB**

$$\begin{aligned} b'_L &= (V'^\dagger_{dL})_{33} b_L + (V'^\dagger_{dL})_{32} s_L + \ldots && \simeq b_L + (V'^\dagger_{dL})_{32} s_L \\ \mu'_L &= (V'^\dagger_{eL})_{22} \mu_L + \ldots && \simeq \mu_L \end{aligned}$$

Assuming $(V'^\dagger_{eL})_{22} \approx (V'^\dagger_{dL})_{33} \approx 1$ and $|(V'^\dagger_{dL})_{32}| \approx |V_{ts}| \approx 0.04$