A dark matter relic from muon anomalies

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LAPTH-ANNECY

Bélanger, CD, Westhoff, **PRD 92 (2015) 055021**

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From flavor anomalies to direct discoveries of New Physics

CERN | October 26, 2018

What's wrong with muons?

several anomalies indicating new physics:

- ***B* decays (R_K, R_{K^*}...) → $\Lambda \sim O(10)$TeV**
- **g_μ-2 → $\Lambda \sim O(100)$GeV**
- ***μH* (proton radius) → $\Lambda \sim O(1)$GeV**

but very different scales → challenging to explain all with the same dynamics

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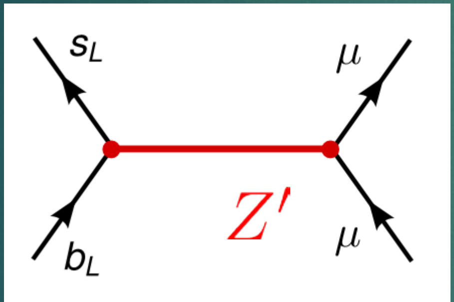
- ~~**μH (proton radius) $\rightarrow$ $\Lambda \sim O(1)$GeV**~~

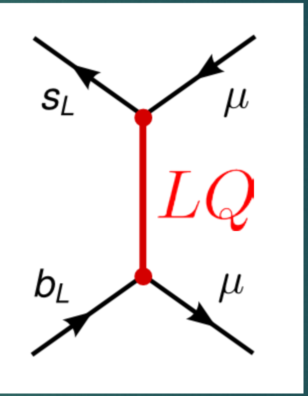
is there a simple framework explaining *both*?

Starting from B anomalies

simplest (tree-level) explanations:



neutral vector



leptoquark

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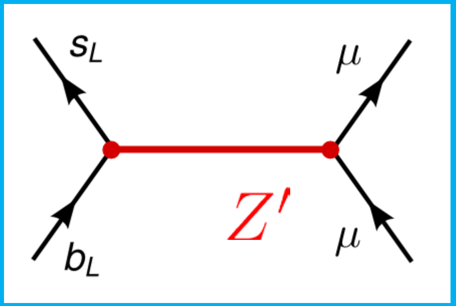

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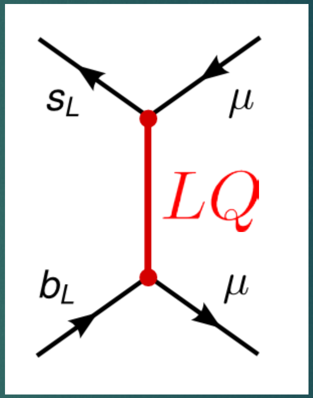


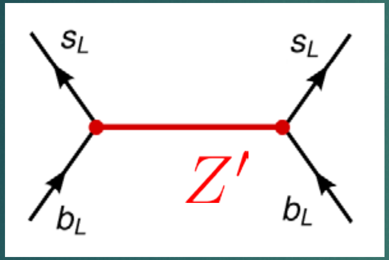
leptoquark

R_K and R_{K*} favors LL chiral couplings with

$$m_{Z'}/\sqrt{g_\mu g_{bs}} \approx 35\ \mathrm{TeV}$$

Generic constraints

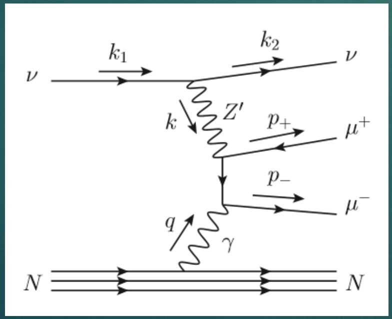
- ***B_0* meson oscillations:**



$$\rightarrow \quad m_{Z'}/g_{bs} \gtrsim 125\ \mathrm{TeV}$$

Altmannshofer+ ERJC 73 (2013) 2646

- **Neutrino trident production:**



$$\rightarrow \quad m_{Z'}/g_{\mu} \gtrsim 500\ \mathrm{GeV}$$

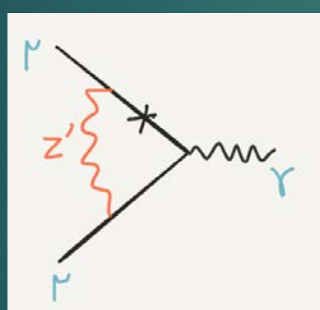
Altmannshofer+ ERJC 73 (2013) 2646
Altmannshofer+ PRL 113 091801 (2014)

g_μ-2 prediction

- **under these constraints, B anomalies imply:**

$$500\,\mathrm{GeV} \lesssim m_{Z'}/g_\mu \lesssim 10\,\mathrm{TeV}$$

- **and a too small correction to g_μ-2:**



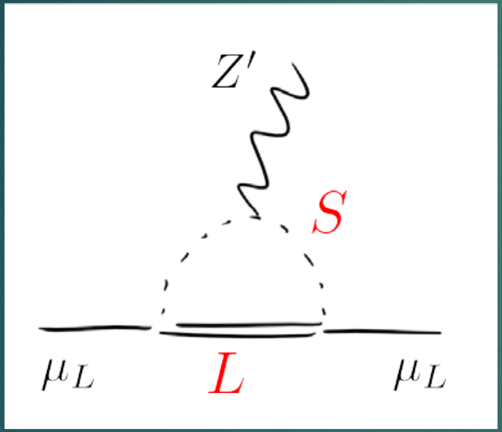
$$\to \quad a_\mu^{Z'} = \frac{m_\mu^2}{12\pi^2}(g_\mu/m_{Z'})^2$$
$$\sim [0.1, 30] \times 10^{-11}$$

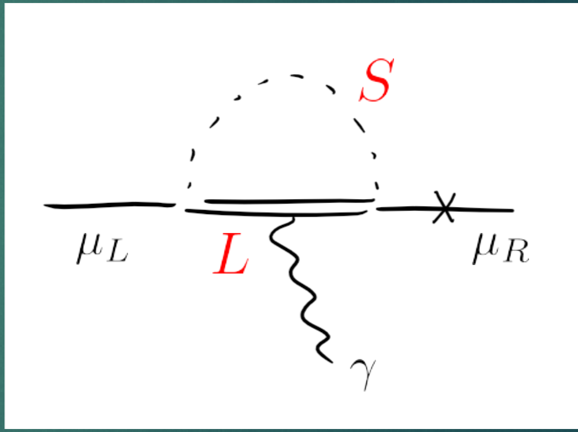
$$a_\mu^{\mathrm{SM}} - a_\mu^{\mathrm{exp}} = -268(43) \times 10^{-11}$$

Davier+, 1706.09436[hep-ph]

Our approach

- Induce $\bar{\mu}_L \not{Z}' \mu_L$ and $\bar{\mu}_L \sigma^{\mu\nu} \mu_R F_{\mu\nu}$ at one-loop, from the **same** fields (*eg.* a scalar and a heavy lepton):





- Use $U(1)'$ symmetry to forbid tree-level coupling to muons

A simple/simplified? model

Bélanger,CD,Westhoff (2015)

	spin	SU(3)$_c$	SU(2)$_L$	U(1)$_Y$	U(1)$_X$
L, L^c	1/2	**1**	**2**	−1/2	1
Q, Q^c	1/2	**3**	**2**	1/6	−2
ϕ	0	**1**	**1**	0	2
S	0	**1**	**1**	0	−1

- **SM fields are neutral under $U(1)'$ and Z' couples to fermions through the vector-like L, Q**

  $\longrightarrow$ **no anomalies** **Fox**+ PRD 84 (2011) 115006

- ϕ **breaks/higgses** $U(1)'$ $\rightarrow$ $m_{Z'} = 2\sqrt{2} g_{Z'} \langle\phi\rangle$

- S **connects LH lepton to** L**:** $y \bar{l} S L_R + \text{h.c.}$

A dark matter candidate

Bélanger,CD,Westhoff (2015)

- **In order to prevent tree-level coupling to leptons in the broken phase, S shall *not* get a vev**

- **In this case, there is a remnant $\mathbb{Z}_2 \supset U(1)'$ in the vacuum: $S, L \to -S, L$, $\phi, Q \to \phi, Q$**

- **Quite remarkably, in this approach, *B* anomalies and g_μ-2 *predict* a dark matter candidate !**

- **DM is leptophilic, most likely scalar $\chi \equiv \mathrm{Re}(S)$**

Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{dark}} + \mathcal{L}_{\mathrm{portal}}$$

Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm dark} + \mathcal{L}_{\rm portal}$$

$$\mathcal{L}_{\rm dark} = \text{kinetic} + \text{mass terms}$$
$$-(r\phi S^2 + \text{h.c.}) - \lambda_\phi |\phi|^4 - \lambda_S |S|^4 - \lambda_{\phi S}|\phi|^2|S|^2$$

induce scalar/pseudoscalar mass splitting

$$S = \frac{1}{\sqrt{2}}(s + ia)$$

$$\rightarrow \delta \equiv \frac{m_a^2 - m_s^2}{m_s^2} = -\sqrt{2}\frac{r m_{Z'}}{g_{Z'} m_s^2}$$

Lagrangian

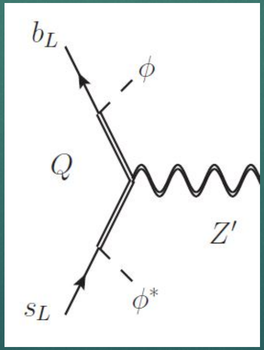
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm dark} + \mathcal{L}_{\rm portal}$$

kinetic portal

Higgs portals

$$\mathcal{L}_{\rm portal} = \epsilon B_{\mu\nu} F'^{\,\mu\nu} - \lambda_{SH}|S|^2|H|^2 - \lambda_{\phi H}|\phi|^2|H|^2$$
$$-w(\bar{q}Q)\phi - y(\bar{l}L)S + \text{h.c.}$$

mass mixing after $U(1)'$ breaking $\longrightarrow$

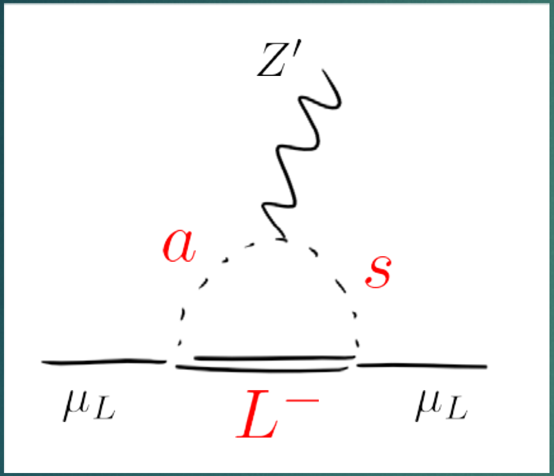


new source of $b \to s$ unless m_Q's are degenerate or w is aligned with SM Yukawas

mixing is $SU(2)_L$ invariant, there is also a new source of $t \to c$ transition

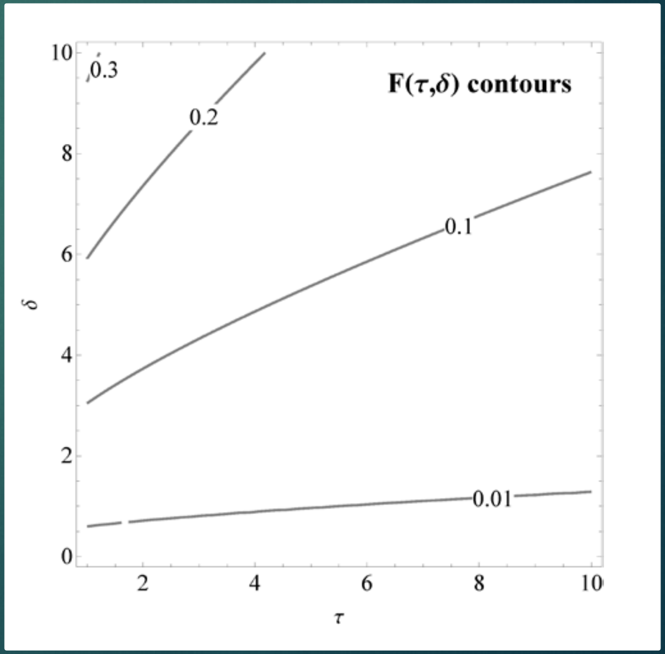
Muon coupling

- induced radiatively by loops of S, L



$$\rightarrow \quad g_\mu = g_{Z'} \frac{|y|^2}{32\pi^2} F(\tau, \delta)$$

$$\tau \equiv m_L^2 / m_s^2$$



- $g_\mu \rightarrow 0$ when $\delta \rightarrow 0$ because there is no $U(1)'$ breaking in this limit

(leading operator = $\phi^* D'_\mu \phi \, \bar{l} \gamma^\mu l + \mathrm{H.c.}$)

Muon coupling

- Large δ (and $\tau \sim 1$) is favoved to avoid too small g_μ
- However, large a/s splitting requires some tuning $\sim 1/\delta$ in the scalar potential:

$$m_s^2 = m_S^2 - 2|r|\langle\phi\rangle \quad \ll \quad m_a^2 = m_S^2 + 2|r|\langle\phi\rangle$$

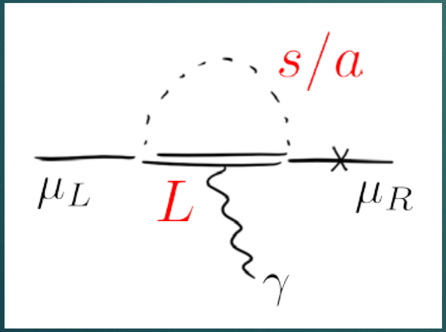
- For $\delta = 10(100)$ and $\tau = 1$, the loop function is $F(\tau, \delta) \approx 0.3(1.)$ so mild tuning is enough to avoid large suppression $\rightarrow$ *« compressed » scenario*
- Also possible to slightly decouple the lepton: *eg.* $\tau = 10$ gives $F(\tau, \delta) \approx 0.1(0.7)$ for $\delta = 10(100)$
  $\rightarrow$ *heavy lepton scenario*

Addressing the anomalies

- **Under the Δm_B constraint, *B* anomalies requires $m_{Z'}/g_\mu < 10\,\mathrm{TeV}$, which implies a light Z' and a rather large lepton portal coupling**

$$|y| \gtrsim 3 \times \left[\frac{m_{Z'}/300\,\mathrm{GeV}}{g_{Z'}F(\tau,\delta)}\right]^{1/2}$$

- **Accomodating g_μ-2 then sets the scalar mass**

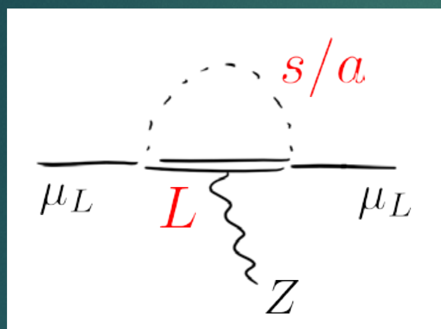


$$a_\mu^{\mathrm{BSM}} = \frac{|y|^2 m_\mu^2}{384\pi^2 m_s^2} G(\tau,\delta)$$

$$\rightarrow m_s \sim 50 - 100\,\mathrm{GeV} \times \left[\frac{m_{Z'}/g_{Z'}}{300\,\mathrm{GeV}}\right]^{1/2}$$

Collider constraints

- $Z\bar{\mu}\mu$ **at LEP:** $-4.4\times 10^{-3} \lesssim \frac{\delta g_{\mu_L}}{g_{\mu_L}^{\rm SM}} \lesssim 8.9\times 10^{-4}$ **(** 2σ **)**



the loop is m_Z^2/m_L^2**-suppressed since there is no Higgs involved**

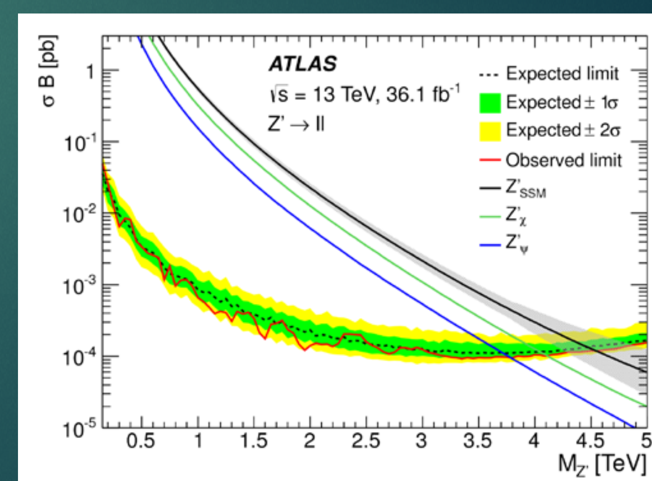
($H^\dagger D_\mu H\, \bar{l}\gamma^\mu l + {\rm h.c.}$ **not generated)**

$\delta g/g \approx -1.2\times 10^{-3}$ **for** $\tau \sim 1$

- **dimuon resonance at LHC:**
  - **light** Z' **production suppressed by sea quarks PDFs:**

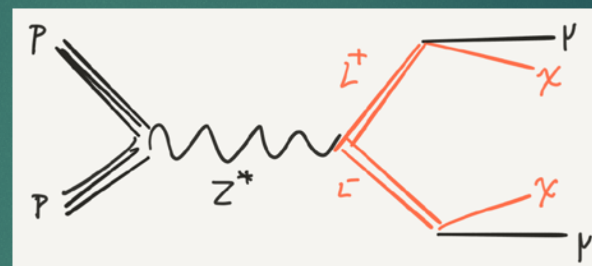
$\sigma^{13\,\rm TeV}_{pp\to Z'} \sim \mathcal{O}(\text{few fb})$ **for** $m_{Z'} = 300\,{\rm GeV}$

  - $\mathrm{BR}(Z'\to\mu\mu) \approx 0.5$

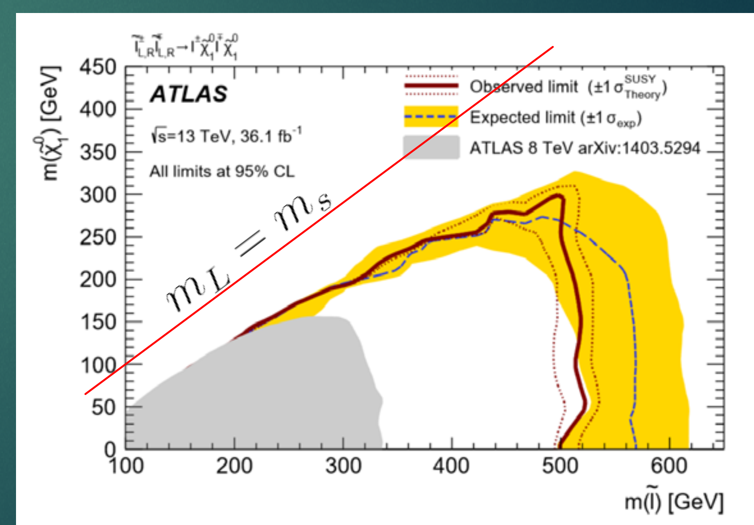


Collider constraints

- the real threat comes from DY production of L^+L^- giving, for $m_L > m_s$, a signal in $\mu^+\mu^- + \not{E}_T$ similar to sleptons in SUSY

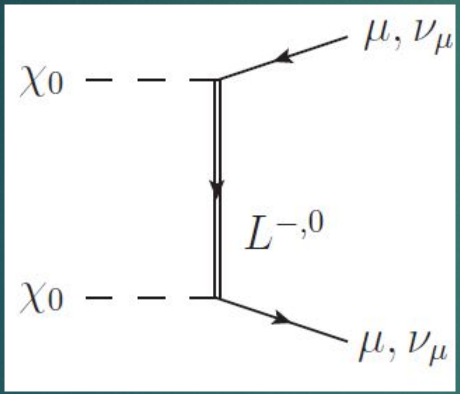


- Recasting 8TeV data implied $m_L \gtrsim 450\,\mathrm{GeV}$ Arina+ JHEP1505 (2015) 142 while a rough estimate of 13TeV data gives $m_L \gtrsim 900\,\mathrm{GeV}$
- This search requires sizable $\not{E}_T$ and is *not* probing the compressed scenario



Dark matter relic

- DM annihilates through the *same* interaction responsible for the anomalies
- Assuming scalar DM ($\chi_0 \equiv s$):



***d*-wave**

$$\rightarrow \langle \sigma v \rangle = \frac{|y|^4 x_f^{-2}}{2\pi(1+\tau)^4 m_s^2}$$

thermal relic also favors large y coupling to balance *d*-wave suppression

$$x_f = \frac{m_s}{T_f} \approx 25$$

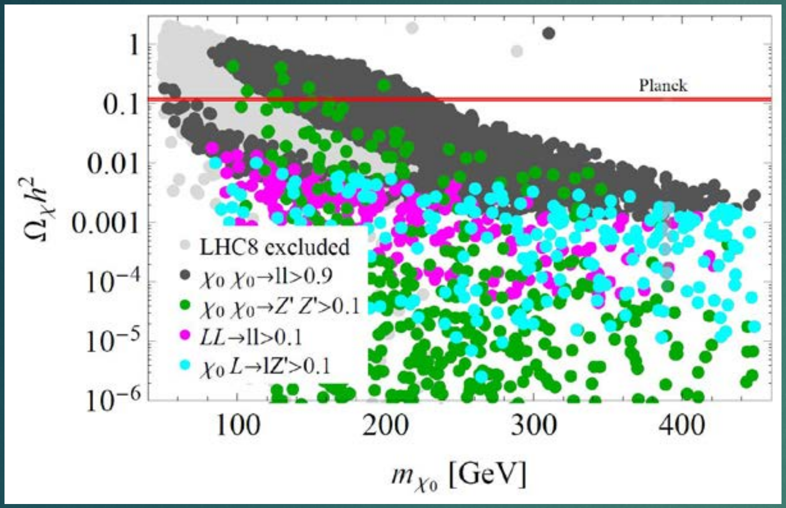
- Accomodating the anomalies fixes the relic:

$$\Omega_\chi h^2 \approx 0.003 \times (1+\tau)^4 F(\tau,\delta) G(\tau,\delta) \left(\frac{300\ \mathrm{GeV}}{m_{Z'}/g_{Z'}} \right)$$

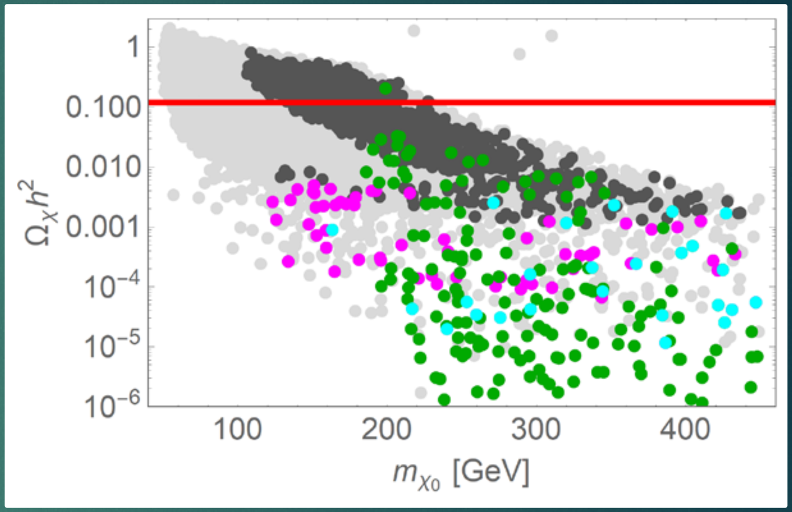
and observations favors the heavy lepton scenario $\tau \gg 1$

Dark matter relic vs. LHC

8TeV

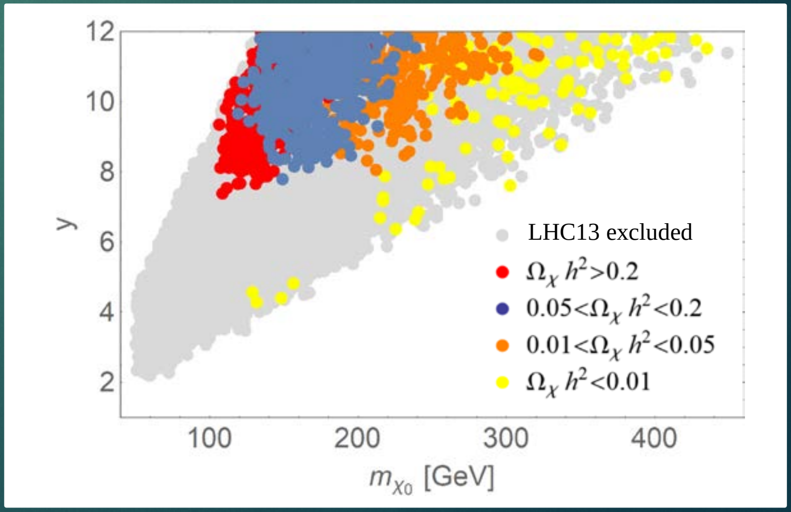


13TeV



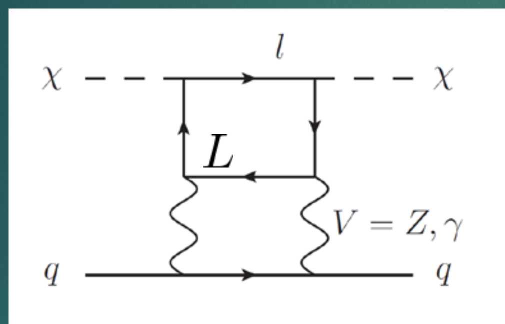
It remains possible to explain $R_{K(*)}$, $g_\mu - 2$ and obtain the correct DM abundance!

However, the coupling is barely perturbative…



Dark matter detection

- **Direct signal at 2loop, well below ν-floor**

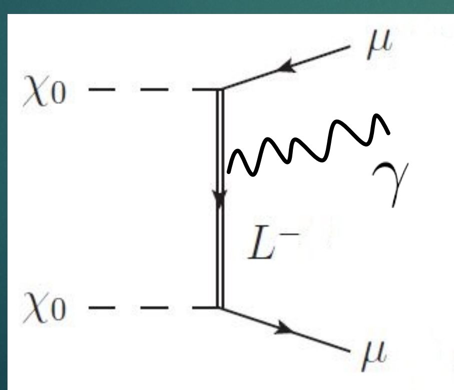


$$\rightarrow \quad \sigma^p_{\mathrm{SI}} \sim \frac{\alpha_w^4 |y|^4}{64\pi^5} \frac{m_p^4}{m_L^4 m_\chi^2}$$ **(NDA)**

$$\sim \mathcal{O}(10^{-50})\ \mathrm{cm}^2$$

- **Indirect signal from internal photon emission**

Giacchino+ JCAP 1310, 025 (2013),
Toma PRL 111, 091301 (2013)



2body annhilation is v^4-suppressed,
3body is s-wave and dominates

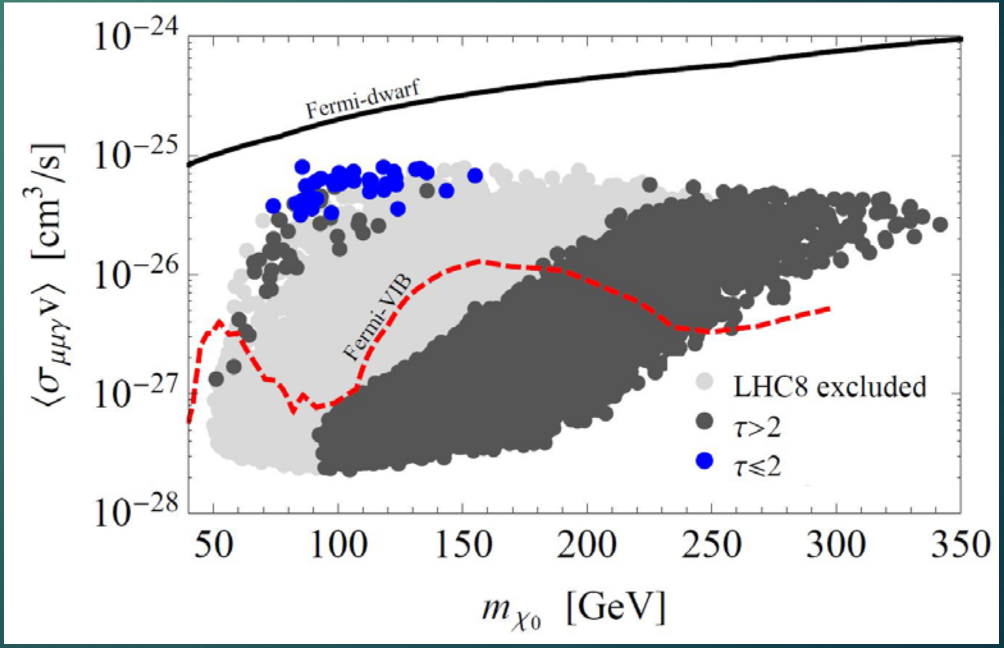
$$\langle \sigma_{\bar{\mu}\mu\gamma} v \rangle = \frac{\alpha}{32\pi^2} \frac{|y|^4}{m^2_{\chi_0}} F_\gamma(\tau)$$

γ rays at the Fermi telescope

- **In the heavy lepton scenario, 3body annihilation yields a continuous spectrum of energetic photons with $E_\gamma^{\max} = m_{\chi_0}$, constrained by dwarves galaxies observations** **Bringmann**+ JHEP 01 (2008) 049

- **Predicted signals are 1-2 orders of magnitude below Fermi sensitivity**

  (not up-to-date)



Conclusions

- If *B* anomalies are indeed new physics:
  - $\rightarrow$ *Can it also explain other known anomalies?*
  - $\rightarrow$ *Is it linked to problems of the SM?*

- We explored the possibility to address $R_{K^{(*)}}$, $g_\mu - 2$ in simplified (loop) Z' model and found an interesting connection with dark matter

- This is a rich phenomenological framework with correlated signals in *B* physics, high-*pT* physics and astrophysics.