Dark Sectors for μ and $\gamma\gamma$ anomalies

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Outline

1. $g_\mu - 2$ / $b \to s\mu\mu$ → dark matter + $\gamma\gamma$
2. Models for muon-philic DM
3. DM relic density
4. Collider signatures

Signs of DM

in B/μ physics?

$B \to (K, K^*, \phi) + \mu^+\mu^-$ anomalies

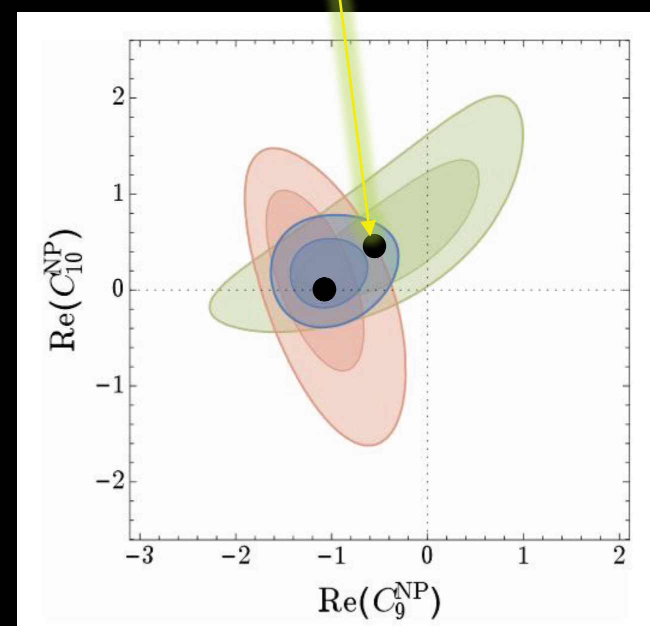
Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^{0}\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{0}\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

2 favored simple NP structure:

$C_9 \simeq -1, C_{10} = C'_{9,10} = 0$

or TH favored

$\boxed{C_{10} = -C_9 \simeq 0.5}, C'_{9,10} = 0$



$$\mathcal{H}_{\mathrm{eff}}^{\mathrm{NP}} = -\frac{\alpha G_F}{2\sqrt{2}\pi} V_{tb} V_{ts}^* \sum_i C_i \mathcal{O}_i + \mathrm{h.c.}$$

$$\mathcal{O}_9^\ell \equiv \bar{b}\gamma_\rho(1-\gamma_5)s\ \bar{\ell}\gamma^\rho\ell$$
$$\mathcal{O}_{10}^\ell \equiv \bar{b}\gamma_\rho(1-\gamma_5)s\ \bar{\ell}\gamma^\rho\gamma_5\ell$$

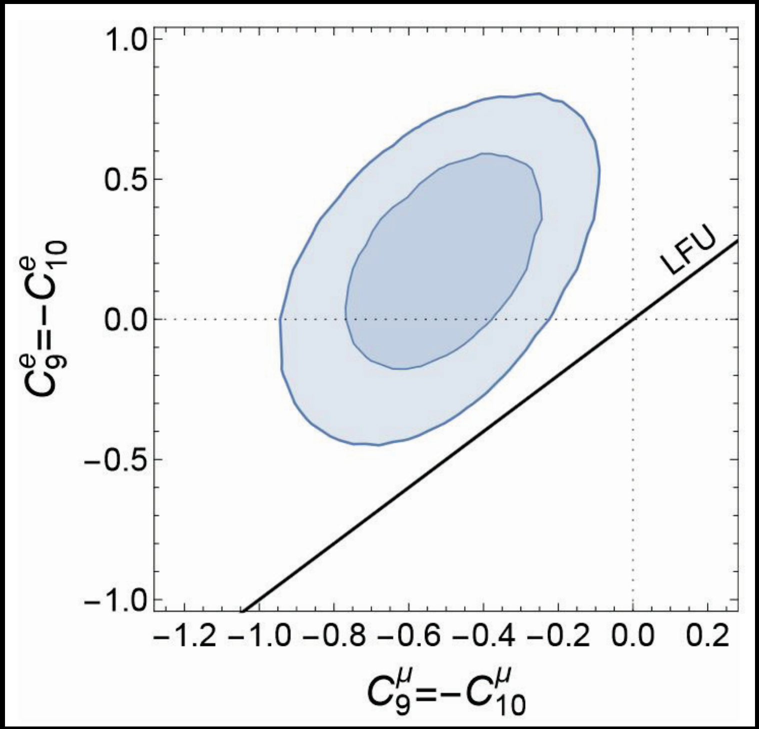
R_K anomaly

Adding electron data, in particular

$$R_K \equiv \frac{\mathrm{BR}(\mathrm{B} \to \mathrm{K}\mu^+\mu^-)_{[1,6]}}{\mathrm{BR}(\mathrm{B} \to \mathrm{K}e^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \lesssim 1$$

global fits indicate violation of Lepton Flavor Universality

$$C^e_{9,10} \ll C^\mu_{9,10}$$



$g_\mu - 2$ anomaly

Long story with many bounces between TH and EXP,
But current status still anomalous: $\left(a_\mu \equiv \frac{g_\mu - 2}{2}\right)$

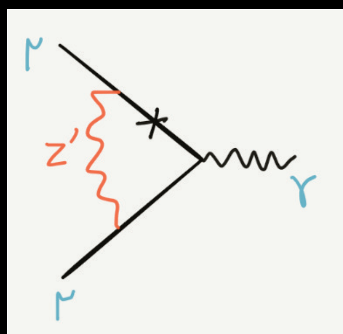
$$\Delta a_\mu \equiv a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (287 \pm 80) \times 10^{-11}$$

If discrepancy originates from one-loop new physics,
weak scale/coupling are favored

$$a_\mu^{\mathrm{BSM}} \sim \frac{g^2 m_\mu^2}{16\pi^2 M^2} \sim 3 \times 10^{-9} \left(\frac{g}{0.6}\right)^2 \left(\frac{100\,\mathrm{GeV}}{M}\right)^2$$

A hint for DM?

- Tree-level explanations of $b \to s$ typically yields a too small contribution to $g_\mu - 2$:



$$\to a_\mu^{Z'} \sim \mathcal{O}(10^{-11}) \left(\frac{1\,\mathrm{TeV}}{m_{Z'}} \right)^2$$

- If $b \to s$ arises at one-loop, $g_\mu - 2$ in the right ballpark.
- A simple way with a Z' : seclude it from SM, break $\mathrm{U}(1)_X \to Z_2$ ➡ DM + $\gamma\gamma$ candidates

Dark Matter Models

For Muon Anomalies

U(1)’ toy models

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

Dark $\mathrm{U}(1)_X$ field, SM carry no X charge,

Dark sector fields:

	spin	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_X$
$L,\ L^c$	$1/2$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	1
$Q,\ Q^c$	$1/2$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	-2
ϕ	0	$\mathbf{1}$	$\mathbf{1}$	0	2
χ	0	$\mathbf{1}$	$\mathbf{1}$	0	-1

mediators to SM fermions

U(1) breaking 75 GeV scalar

Dark Matter

U(1)' toy models

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

hypercharge portal *Higgs portal*

~closed ~closed

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

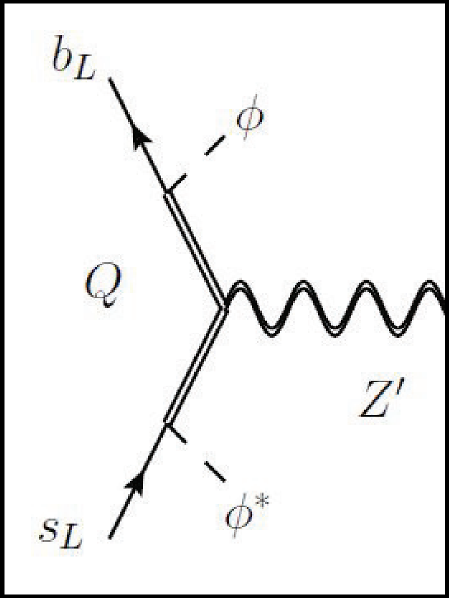
'Yukawa' portal *mass mixing = "partial darkness"*

The X charge assignment forbids tree-level $Z'\bar{l}l$ coupling, makes DM leptophilic, explaining direct detection null results

Z' coupling to SM fermions

- Quarks: partial darkness

$$w(\bar{q}Q)\langle\phi\rangle + \text{h.c.}$$
$$+M_Q\bar{Q}Q + \text{h.c.}$$



switching on couplings to 2-3 generations only:

$$g^{Z'}_{\bar{s}s,\bar{b}b} = 2\left(\cos^2\theta_Q \sin^2\theta_{s,b} + \sin^2\theta_Q \sin^2\theta_{b,s}\right)$$
$$g^{Z'}_{\bar{b}s} = \sin(2\theta_Q)(\sin^2\theta_s - \sin^2\theta_b)\,.$$

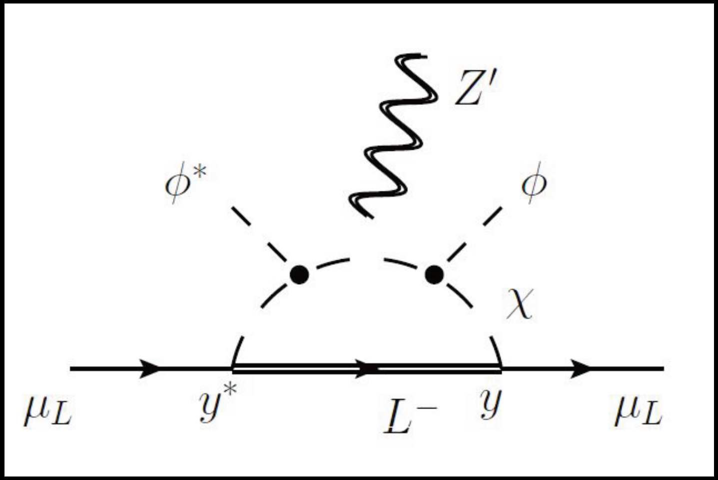
$B-\bar{B}$ mixing constraint*:

$$g^L_{bs} \lesssim 2.4\times10^{-3}\left(\frac{m_{Z'}/g_X}{300\,\text{GeV}}\right)$$

*NP<0.1SM

Z' coupling to SM fermions

- Leptons: $(\bar{l}L)\phi$ not allowed ⟶ one-loop



$$g^L_{\mu\mu} = \frac{|y|^2}{32\pi^2} F(\tau, \delta)$$

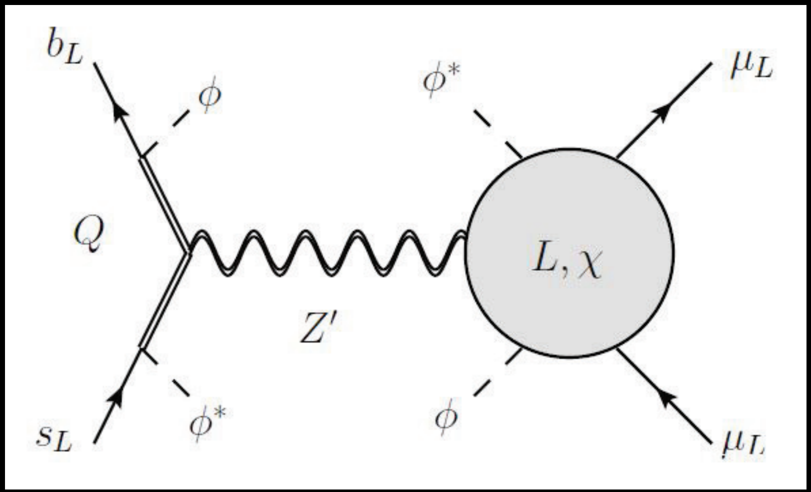
$$\tau \equiv \frac{m_L^2}{m_\chi^2}\,,\, \delta \equiv \frac{m_{\chi'}^2}{m_\chi^2} - 1$$

For $\delta \to 0$, $g^L_{\mu\mu}(q^2 = 0) = 0$, $\langle\phi\rangle$-insertion needed

$(\phi^* D_\rho \phi \bar{\mu}_L \gamma^\rho \mu_L)$

⟹ significant DM-DM’ splitting

Explaining $b \to s\mu\mu$ anomalies



$$C^{\mu}_{10,-9} = \frac{g_X^2 \Lambda_{\rm SM}^2}{m_{Z'}^2} \frac{|V_{ts}^* V_{tb}|}{V_{ts}^* V_{tb}} g^L_{bs} g^L_{\mu\mu}$$

$$\Lambda_{\rm SM} \equiv [2\sqrt{2}\pi/(\alpha G_F |V_{ts}^* V_{tb}|)]^{1/2} \simeq 50\,\text{TeV}$$

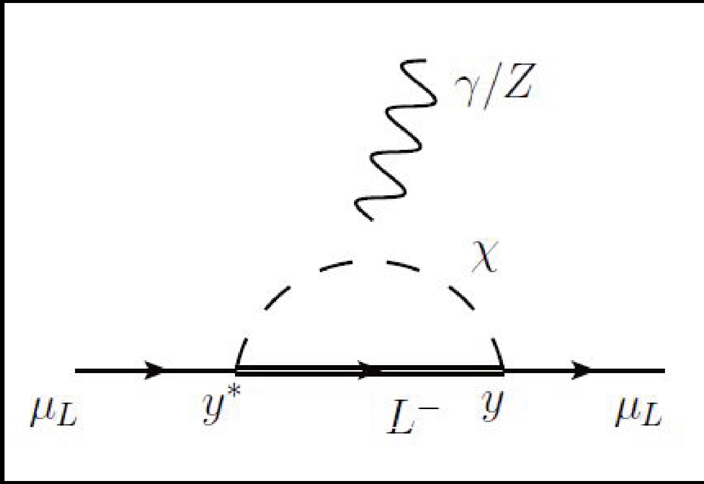
Under $B - \bar{B}$ constraint, explaining LHCb requires:

$$g^L_{\mu\mu} \gtrsim 0.03 \left(\frac{m_{Z'}/g_X}{300\,\text{GeV}} \right)$$

In turns, one needs: $y \gg 1, \;\; \delta \gg 1$, a light Z' and $\tau \simeq [1, \delta]$

Accomodating Δa_μ sets DM mass

$g_\mu - 2$ further constrains the parameter space:



$$\Delta a_\mu = \frac{|y|^2 m_\mu^2}{32\pi^2 m_\chi^2} G(\tau, \delta)$$

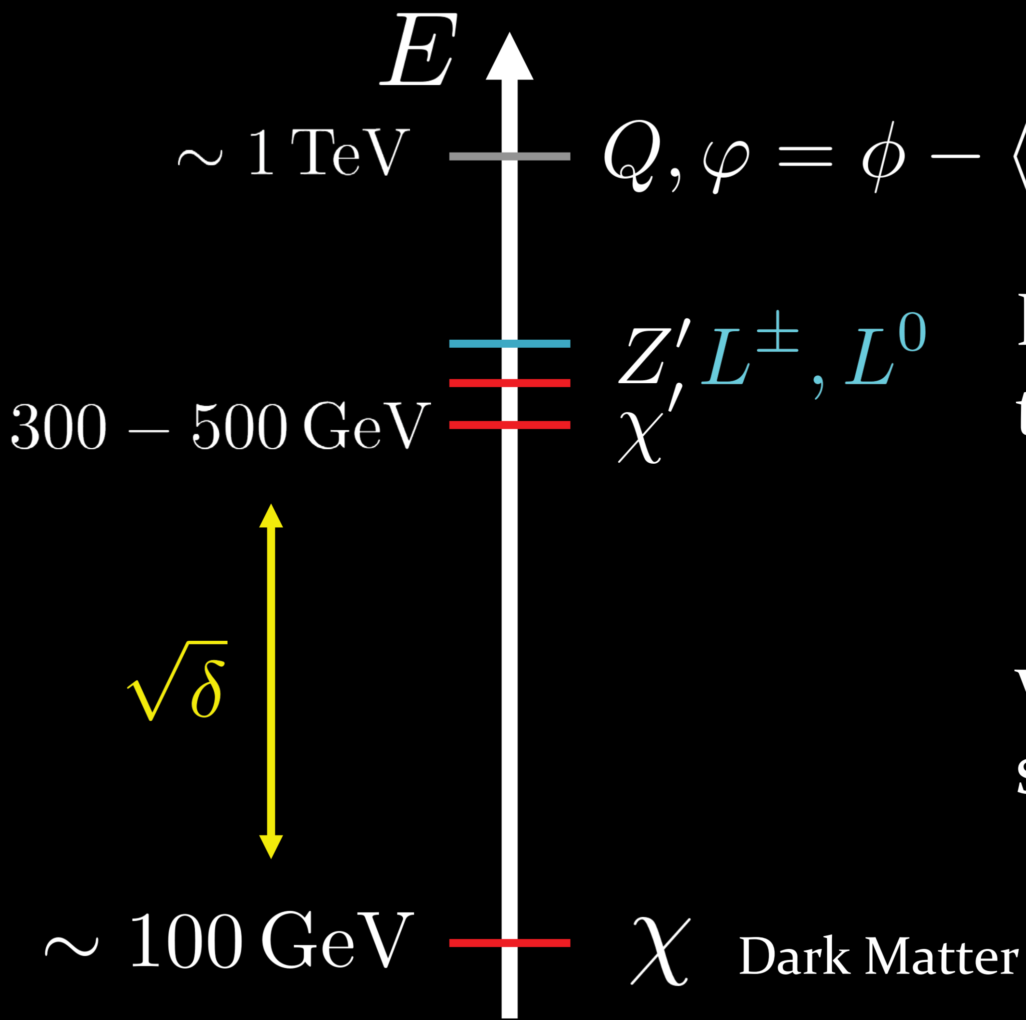
$$\tau \equiv \frac{m_L^2}{m_\chi^2}, \; \delta \equiv \frac{m_{\chi'}^2}{m_\chi^2} - 1$$

2 limiting scenarios:

$$\tau \simeq 1 \longrightarrow m_\chi \simeq 30|y|(1 + 2/\delta)\,\mathrm{GeV}$$

$$\tau \simeq \delta \longrightarrow m_\chi \simeq 55 \frac{|y|}{\sqrt{\delta}}\,\mathrm{GeV}$$

So, muon anomalies favors:



Large δ needs tuning in the dark scalar potential:

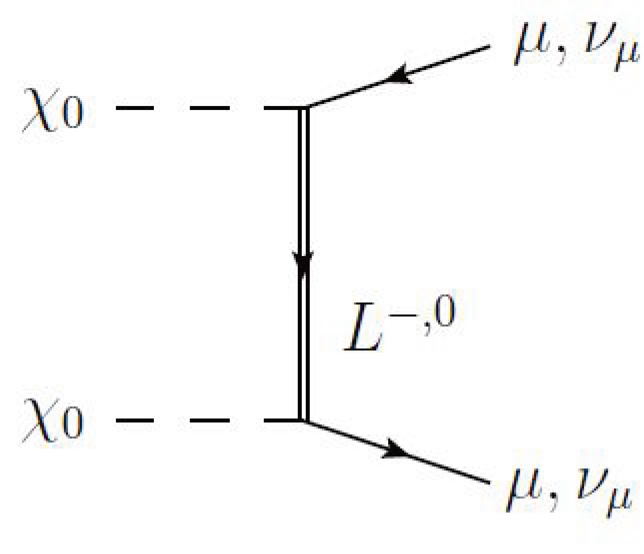
$$\delta \sim \mathcal{O}(10)$$

which guarantees DM is scalar (see relic later)

Predictions for DM relic density

Scalar DM annihilation

- At freeze-out dominant process is d-wave:



$$\langle \sigma v \rangle = \frac{|y|^4 x^{-2}}{2\pi(1+\tau)^4 m_\chi^2}$$

$$\langle v^2 \rangle^{-1} \sim x \equiv \frac{m_\chi}{T} \simeq 25$$

- Thus DM relic also favors large y ,
  for weak scale m_χ

Relic density prediction

- Note that: $\Delta a_\mu \propto \frac{|y|^2}{m_\chi^2}\,, \quad C_{9,-10} \propto |y|^2$

Hence: $\Omega_\chi \sim \int_T \langle \sigma v \rangle^{-1} \propto \Delta a_\mu^{-1} \times C_{9,-10}^{-1}$

and

$$\Omega_\chi h^2 \simeq 0.01 R(\tau,\delta) \times \left(\frac{x}{25}\right)^3 \left(\frac{100\,\mathrm{GeV}}{m_{Z'}/g_X}\right)$$

with

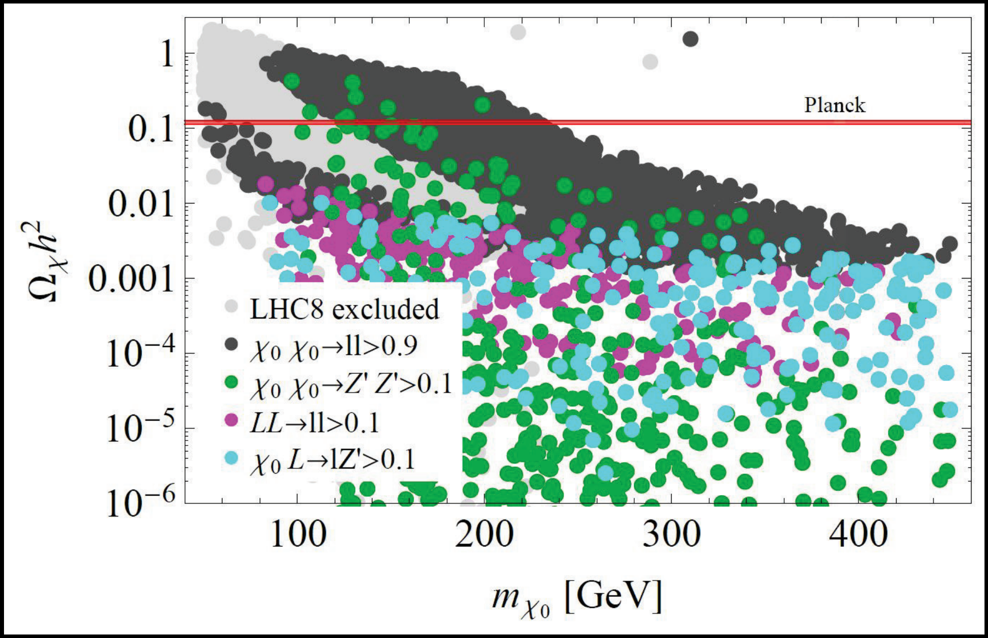
$$R(\tau,\delta) \equiv F(\tau,\delta) G(\tau,\delta)(1+\tau)^4 \sim \mathcal{O}(10)$$

Muon anomalies yields DM relic
in the right ballpark!

$\Omega_{\mathrm{DM}}^{\mathrm{CMB}} h^2 \simeq 0.11$

How robust is the relic prediction?

Sniffing around the parameter space with micrOMEGAs, under the anomalies constraints ⟶



Relatively robust, except in peculiar corners with:

1) strong coannihilation $m_L \gtrsim m_\chi$

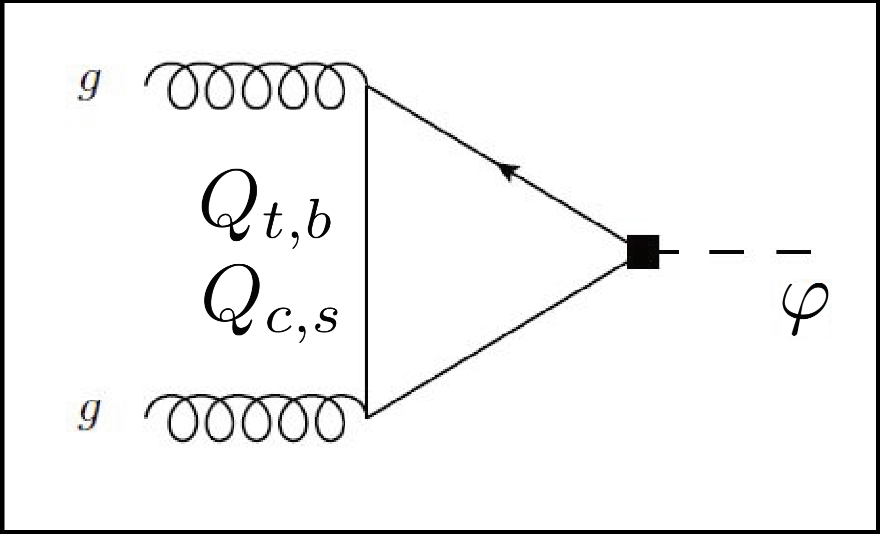
and/or

2) open Z' channel $m_{Z'} < m_\chi$

750GeV Diphoton excess at ATLAS/CMS

750GeV scalar production at LHC

- $U(1)_X$ breaking scalar φ = 750GeV resonance
- Main production through loops of Q :



$$g^{\varphi}_{Q_{c,s}} = g^{\varphi}_{Q_{t,b}} \frac{\sin\theta_s}{\sin\theta_b}$$
$$= 2 g_{Z'} \sin^2\theta_s \frac{m_{Q_{c,s}}}{m_{Z'}}$$

$$\sigma_{13}^{\mathrm{LO}}(pp \to \varphi) \approx 0.4\mathrm{pb} \left(\frac{650\,\mathrm{GeV}}{m_{Z'}/g_{Z'}}\right)^2 \sin^4\theta_b \, |1 + I_{bs}|^2$$

Diphoton Branching Ratio

- One needs $\mathrm{BR}_{\gamma\gamma} \simeq \mathrm{few} \times 10^{-3}$
- Diphoton width also through loops of Q:

$$\Gamma_{\varphi\to\gamma\gamma} \approx 0.8\mathrm{MeV} \left(\frac{650\,\mathrm{GeV}}{m_{Z'}/g_{Z'}}\right)^2 \sin^4\theta_b \left|1 + I_{bs}\right|^2$$

- Works if φ width dominated by $\Gamma_{\varphi\to gg} \sim \mathrm{GeV}$
- Implies $\varphi \to \chi\chi, Z'Z', qQ$ as well as 3-body

  $\varphi \to Z'Z'^*, qQ^* \to Z'qq$ decays are forbidden

Signatures of the model at colliders

Resonant Z' production

- Z' has $\mathcal{O}(1)$ coupling to heavy quarks:

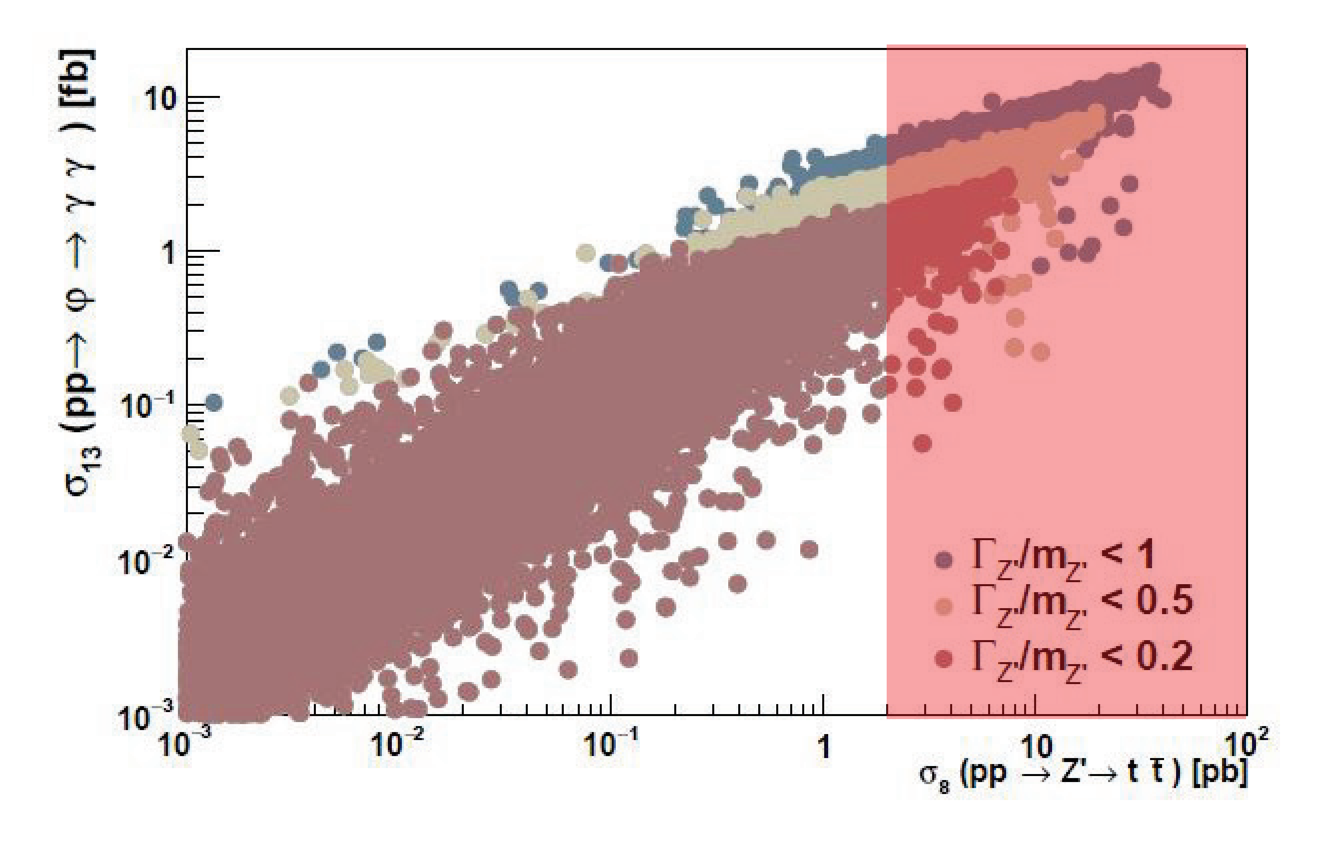
$$\sigma_8^{\rm LO}(pp \to Z') \approx 60\text{pb}\ g_{Z'}^2 \left(\sin^4\theta_s + 0.13\sin^4\theta_b\right)$$

(assuming $m_{Z'} = 650\,\text{GeV}$)

- with $BR_{Z'\to jj} \approx 100\%$ large dijet signal
- Yet the Z' is rather broad with $\Gamma_{Z'} \gtrsim 0.3 m_{Z'}$ and difficult to dig out of the QCD bkg.

Z' to top pairs

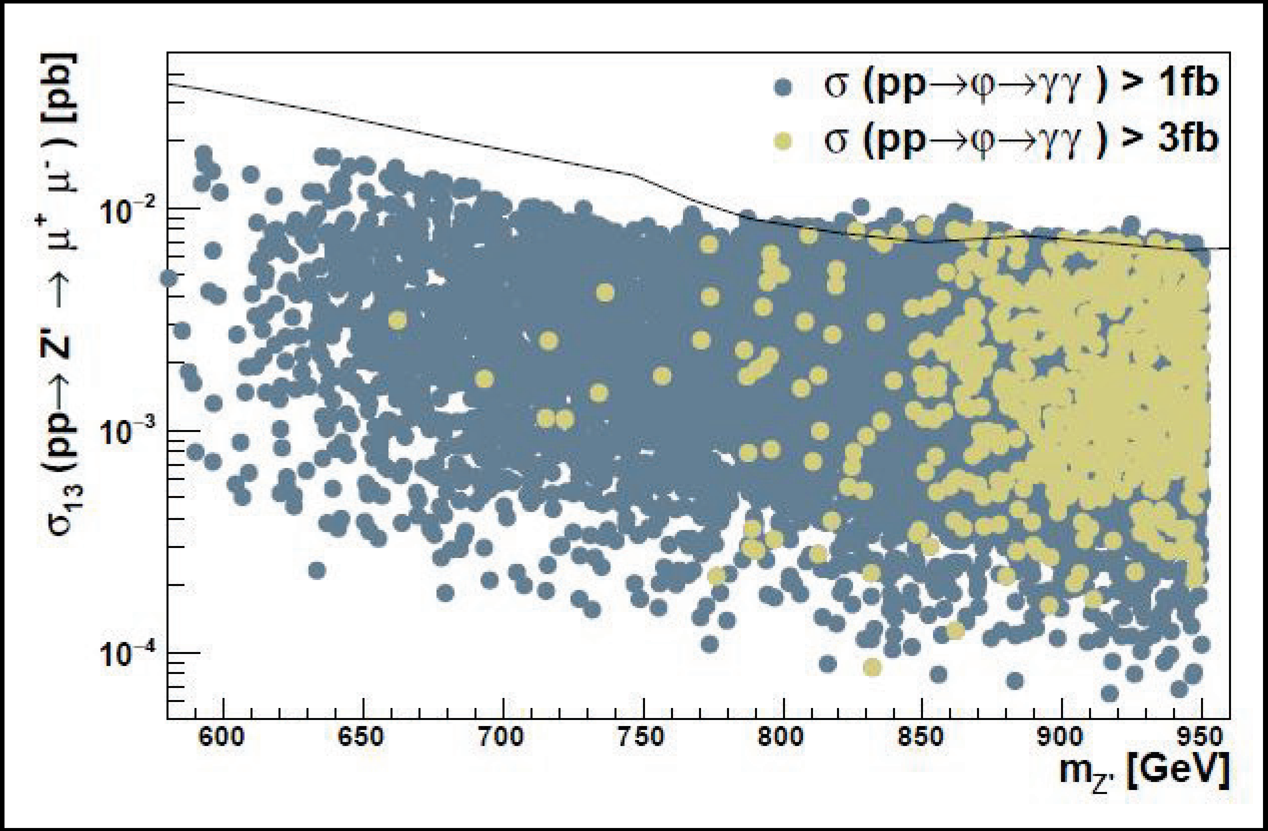
- Tension with correlated signal in top pairs:



$$\sigma_{13}^{\gamma\gamma} \lesssim 4\,\mathrm{fb}$$

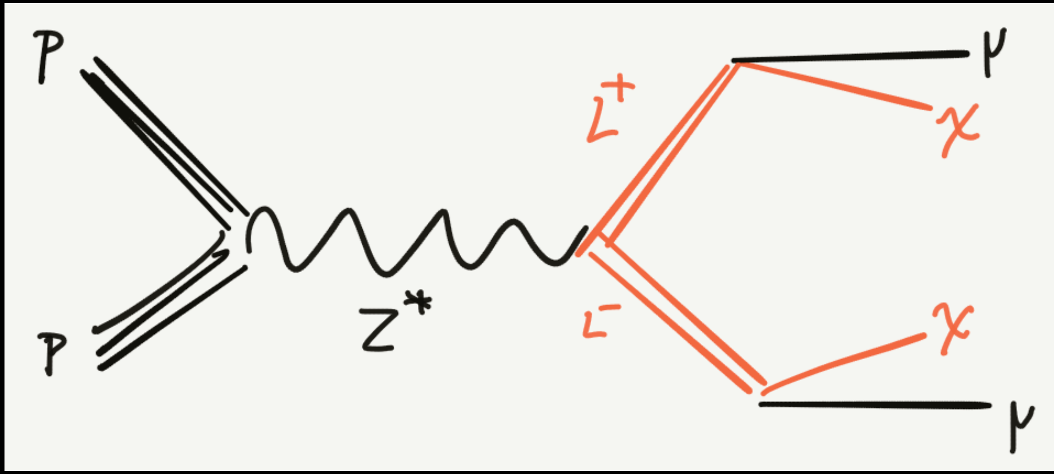
Z’ to muon pairs

- Cleaner but loop-induced: $\mathrm{BR}_{Z' \to \mu\mu} \sim 10^{-3}$



Heavy lepton searches at LHC

- $pp \to Z^* \to LL \to \mu\mu + \not{E}_T$



- Recasting SUSY searches for smuons:

$m_L \gtrsim 450\,\mathrm{GeV}$

unless $\tau \simeq 1$
where missing E_T is missing

Conclusions

Conclusions

- Loop-induced Z' couplings to SM allow to simultaneously address $g_\mu - 2$ and $b \to s\mu\mu$
- The $U(1)' \to Z_2$ breaking sector generically implies DM and diphoton candidates.
- 750GeV resonance can be further explained
- If diphoton signal is a (cruel) fluctuation, DM can be a thermal relic, otherwise it's underabundant