# $B$ decay anomalies and dark matter*

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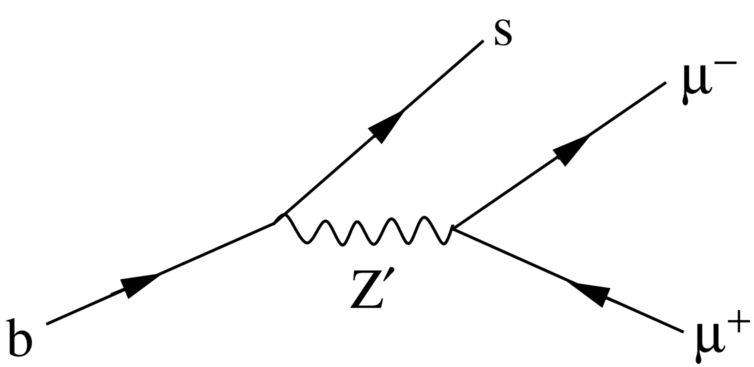
CERN Workshop on high-energy implications of flavor anomalies,

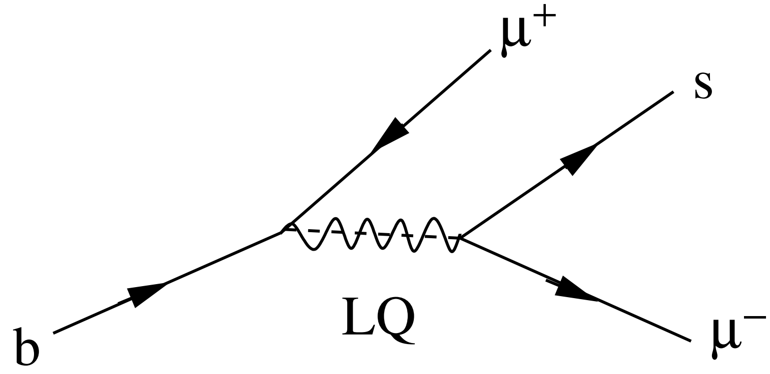
22 Oct., 2018

* for $(g-2)_\mu +$ DM, see *e.g.* Calibbi, Ziegler, Zupan. 1804.00009

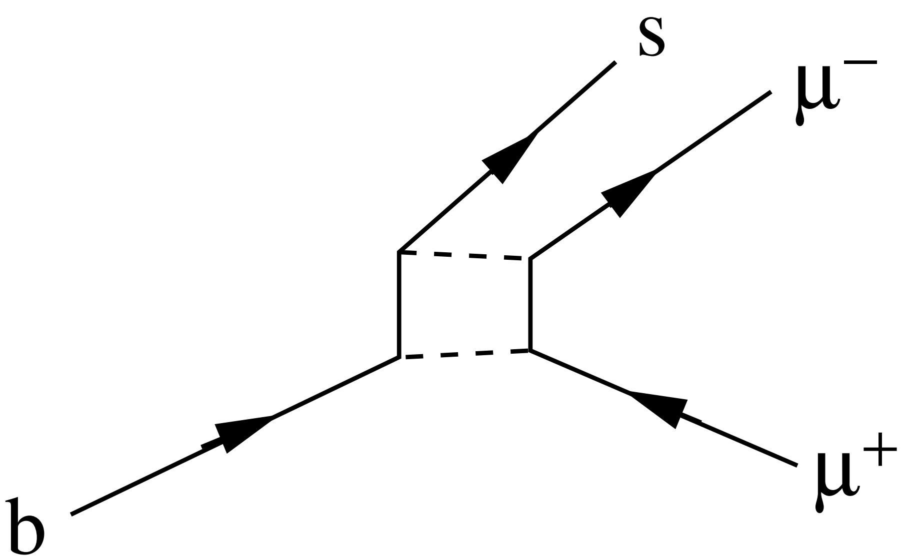
# Popular models for $R_K^{(*)}$




$Z'$ exchange

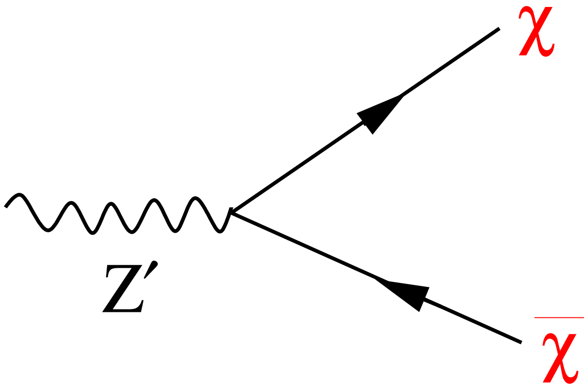



leptoquark exchange



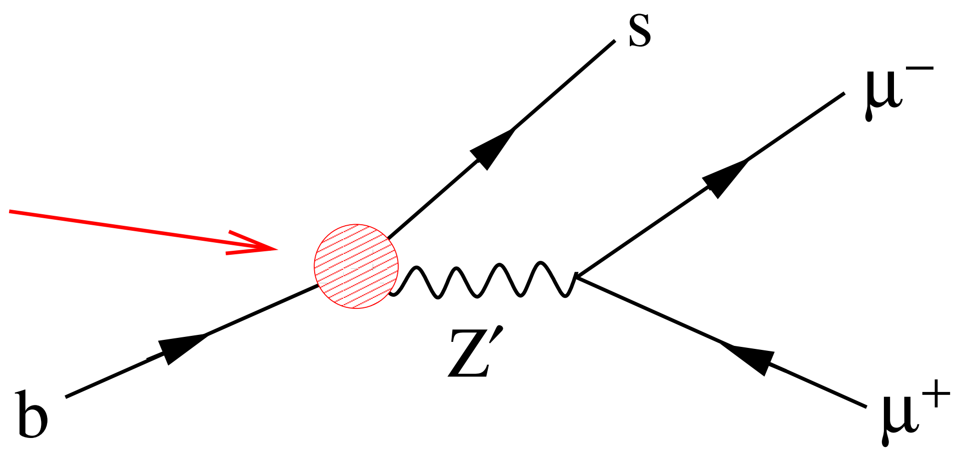

new physics in loop

# Including dark matter: $Z'$ models



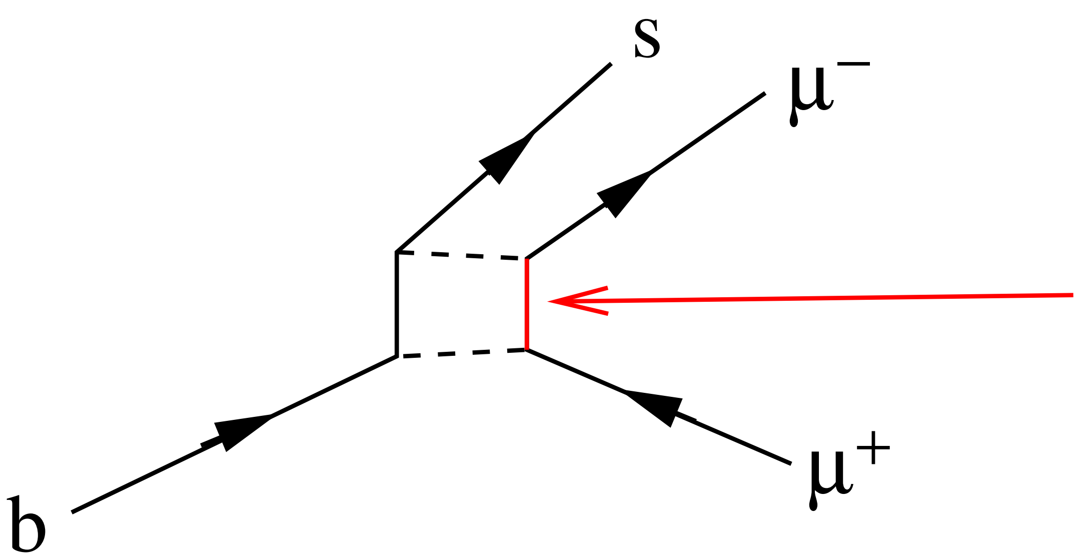

Couple $Z'$ directly to DM $(\chi)$

Generate effective coupling of $Z'$ to quarks or leptons using DM exchange in loop



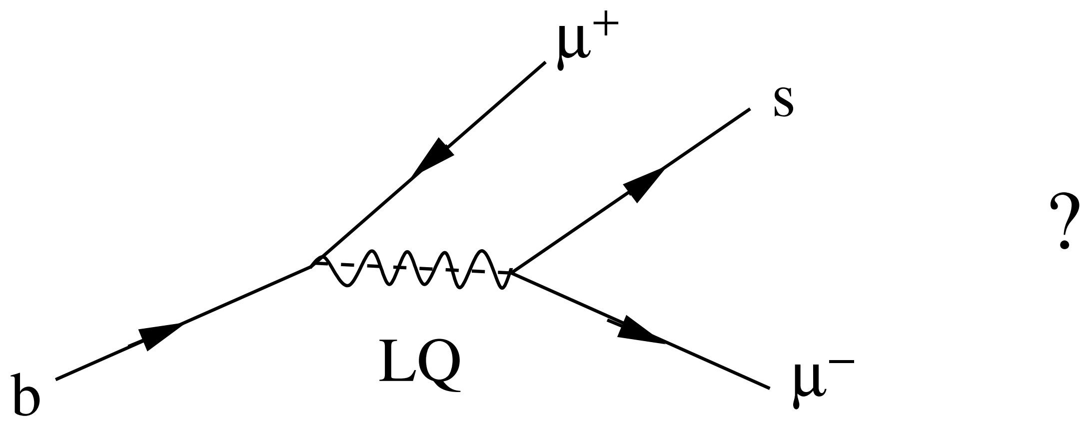

Or let $Z'$ be “vector meson” in a composite model; DM could be a “pion”

# Including dark matter: loop models




Let DM be one of the particles in the loop

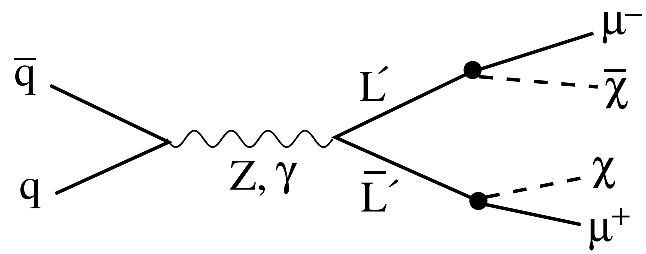
# Including dark matter: leptoquarks




Requires some creativity!

# Possible extra features

- DM direct detection
- DM indirect detection
- Missing $E_T$ at LHC $\rightarrow$
- $a_\mu$, anomalous muon $g-2$




(↑ connect the $\chi$-$\bar{\chi}$ lines to make loop)

- Other flavor observables (*e.g.*, $B_s$ mixing, $\mu \to e\gamma \ldots$)
- Radiative neutrino masses
- 750 GeV diphoton excess ☺

# Assessing models

- Is DM scalar or fermionic?
- If scalar, must Higgs portal coupling be suppressed?
- Is fine-tuning needed to get relic density?
- How credible are predictions of large $a_\mu$?
- Are very large couplings required?
- LHC dimuon constraints

# $Z'$ models

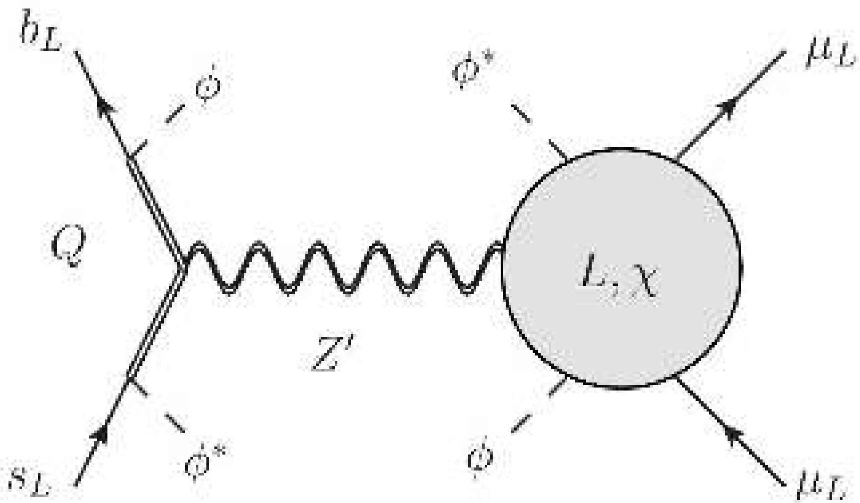
Classified by the nature of the U(1)$'$,

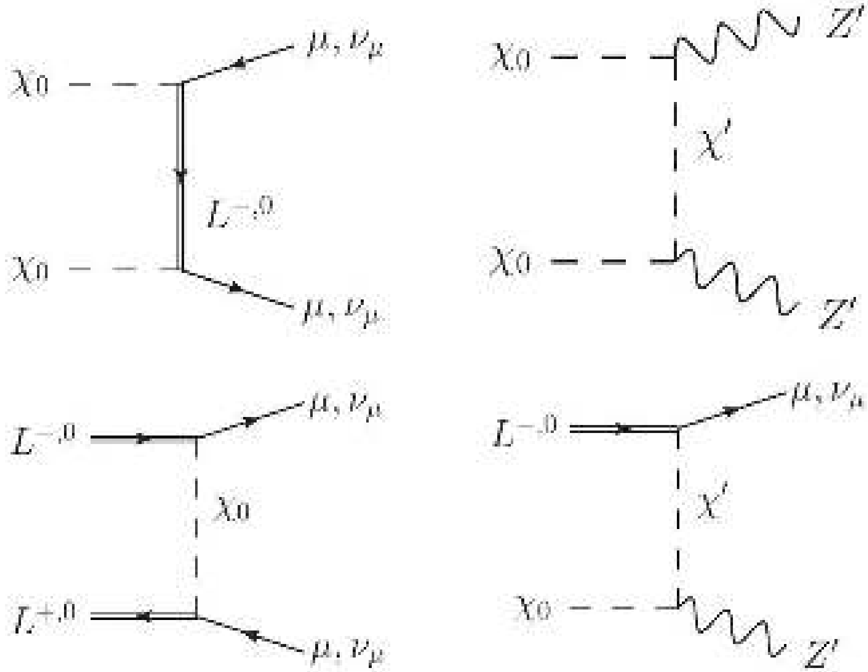
- purely dark:
  Bélanger, Delauny, Westhoff 1507.06660
  Fuyuto, Li, Yu, 1712.06736
  Falkowski, King, Perdomo, Pierre, 1803.04430
- $L_\mu - L_\tau$:
  Altmannshofer, Gori, Profumo, Queiroz, 1609.04026
  Baek, 1707.04573
  Darmé, Kowalska, Roszkowski, Sessolo, 1806.06036
  Singirala, Sahoo, Mohanta, 1809.03213
- $B_1 + B_2 - 2B_3$: Celis, Feng, Vollmann, 1608.03894
- $B_3 - L_3$: Cox, Han, Yanagida, 1710.01585
- generic tree-level couplings:
  JC, Cornell, London, Watanabe, 1702.00395
- composite $Z'$: Ballesteros, Carmona, Chala, 1704.07388

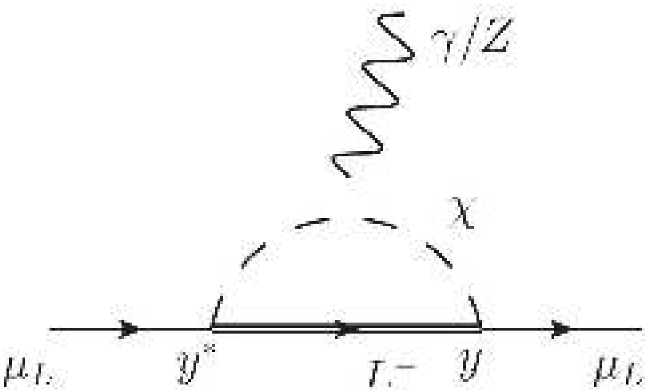
# The first $Z'$ model for $R_K$ + DM

Bélanger, Delauny, Westhoff 1507.06660
DM is scalar, $m_{\chi_0} \sim 100\,\mathrm{GeV}$,
large $a_\mu$ is sought

| | 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 |
| $\phi$ | 0 | **1** | **1** | 0 | 2 |




They set Higgs portal coupling $|\chi|^2|H|^2$ to zero by hand. Need $|y| = 6$, $m_{Z'} = 300\,\mathrm{GeV}$, $m_L \sim 450\,\mathrm{GeV}$ to fit everything.

(Is $p\bar{p} \to L\bar{L} \to \mu^+\mu^-\chi_0\chi_0^*$ still allowed?)

# An $L_\mu - L_\tau$ model

Altmannshofer, Gori, Profumo, Queiroz, 1609.04026

Generate $Z'$-quark couplings as in previous model

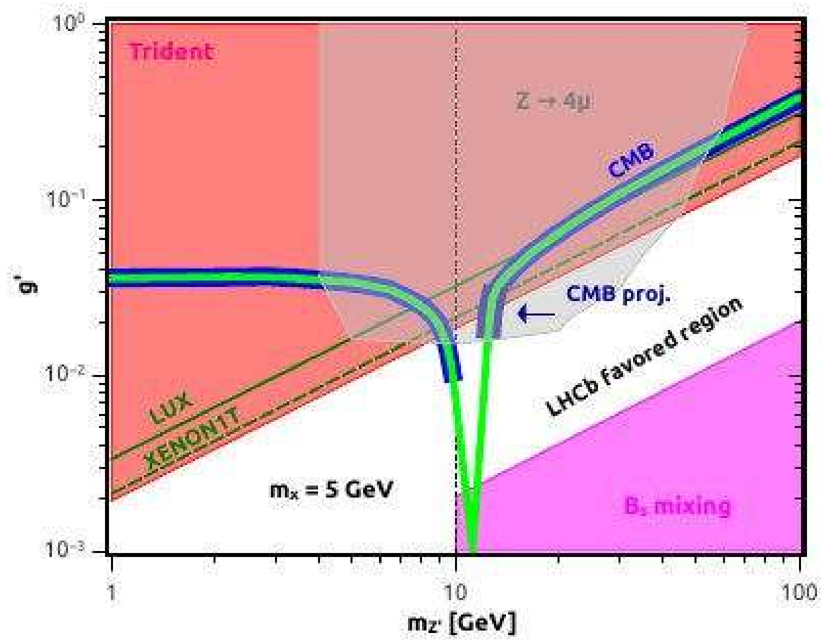
To satisfy all constraints, need

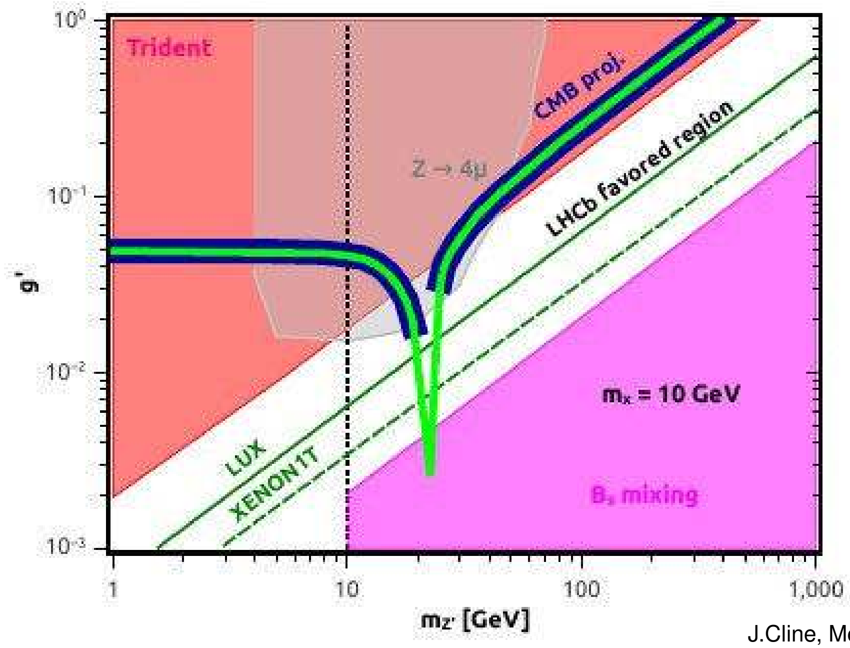
$$m_\chi \sim 5\text{-}10\,\mathrm{GeV}$$

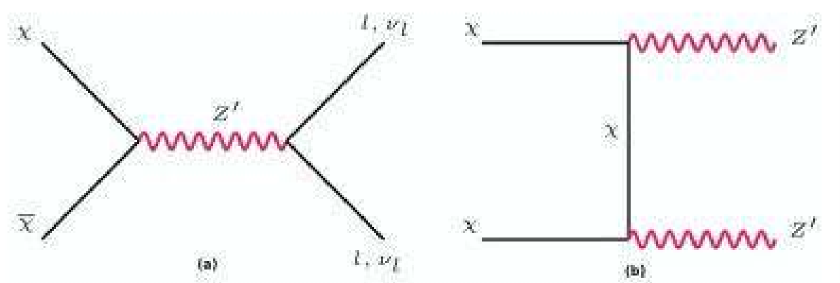
and

$$m_{Z'} \sim 2m_\chi$$

(nearly resonant annihilation for relic density)



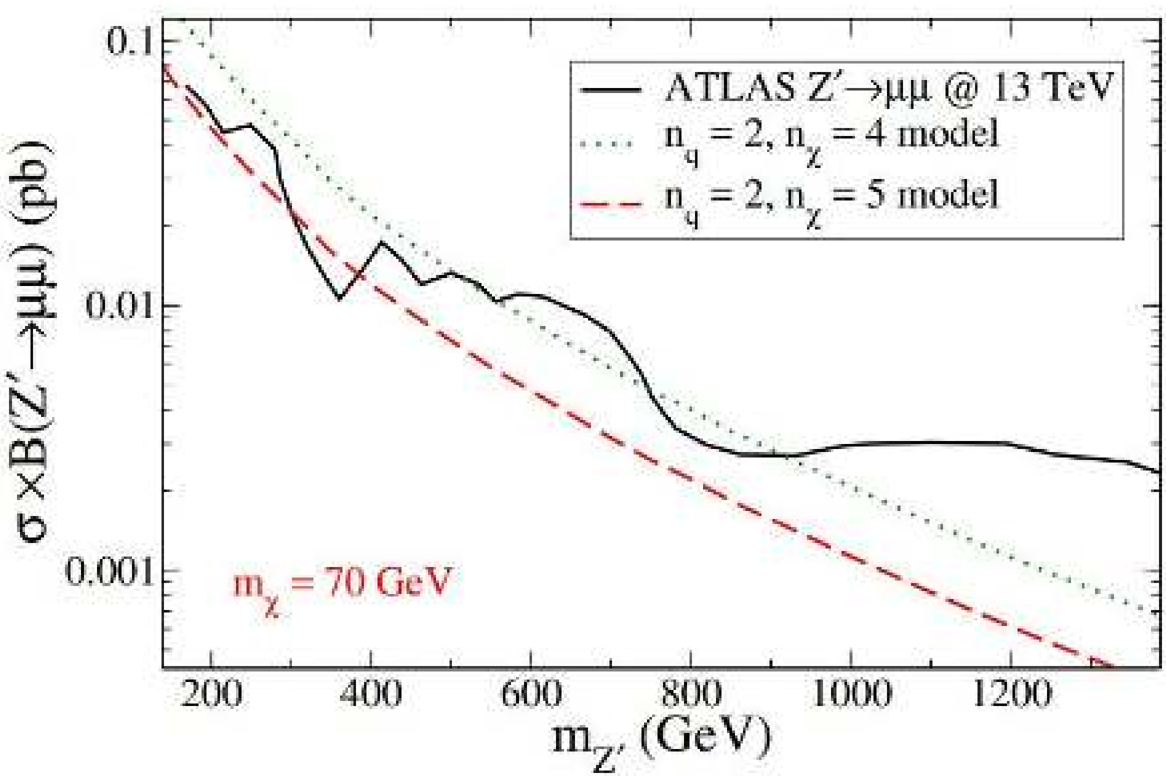



# $Z'$ vs. dimuon constraint

If $Z'$ couples directly to $\mu^+\mu^-$, resonant $p\bar{p} \to Z' \to \mu^+\mu^-$ may give a severe constraint.

It is softened by PDFs if $Z'$ couples mainly to $b$ quarks.

But DM provides an alternative: large BR($Z' \to \chi\bar{\chi}$) weakens dimuon constraint (JC, Cornell, London, Watanabe, 1702.00395)




$$n_q = g_q/g_l, \quad n_\chi = g_\chi/g_q$$

# Loop models

Classified by nature of the DM,

- singlet scalar:
  Kawamura, Okawa, Omura, 1706.04344
  Chiang, Okada, 1711.07365

- inert Higgs doublet:
  Barman, Borah, Mukherjee, Nandi, 1808.06639

- singlet fermion:
  JC, Cornell, 1711.10770

# Loop model possibilities

Arnan, Hofer, Mescia, Crivellin 1608.07832: need two exotic fermions and one scalar, or vice versa

Gripaios, Nardecchia, Renner, 1509.05020: if two scalars, one could be DM, but ruled out by its large coupling to $Z$.

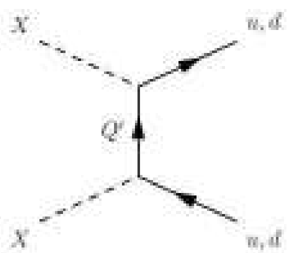
Kawamura, Okawa, Omura, 1706.04344 and Chiang, Okada, 1711.07365 study the one-scalar case, where scalar is the DM.

| Fields | spin | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_X$ |
|---|---|---|---|---|---|
| $Q'$ | 1/2 | **3** | **2** | 1/6 | 1 |
| $L'$ | 1/2 | **1** | **2** | $-1/2$ | 1 |
| $X$ | 0 | **1** | **1** | 0 | $-1$ |

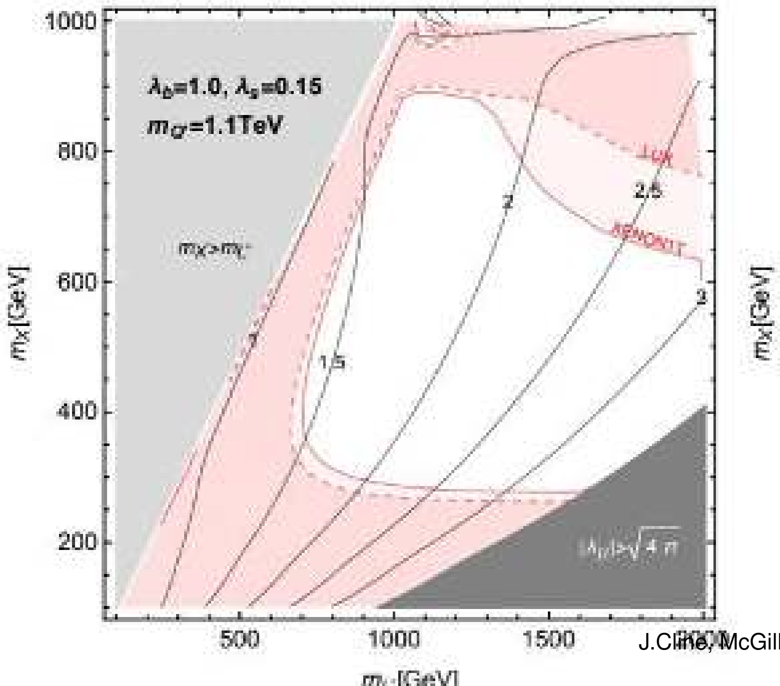
Need large values of $\lambda_\mu \bar{L}' X \mu_L$ coupling (black contours) for relic density,

$$\lambda_\mu \gtrsim 1.5 \gg \lambda_{e,\tau} \text{ (avoid } \mu \to 3e)$$

and set Higgs portal coupling to zero by hand.




gives scattering on nucleons



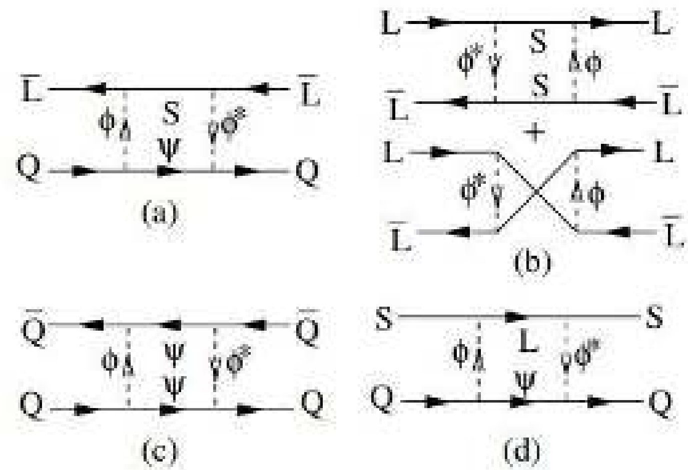
# Fermionic DM in the loop

JC, Cornell, 1711.10770: let singlet fermion $S$ be the DM; scalar is inert Higgs doublet.

| | SU(3) | $SU(2)_L$ | $U(1)_y$ | $U(1)_{em}$ | $Z_2$ | $L$ | $B$ |
|---|---|---|---|---|---|---|---|
| $\Psi$ | 3 | 1 | $+2/3$ | $+2/3$ | $-1$ | $-1$ | $+1/3$ |
| $S$ | 1 | 1 | 0 | 0 | $-1$ | 0 | 0 |
| $\phi$ | 1 | 2 | $-1/2$ | $(0,-1)$ | $-1$ | $+1$ | 0 |

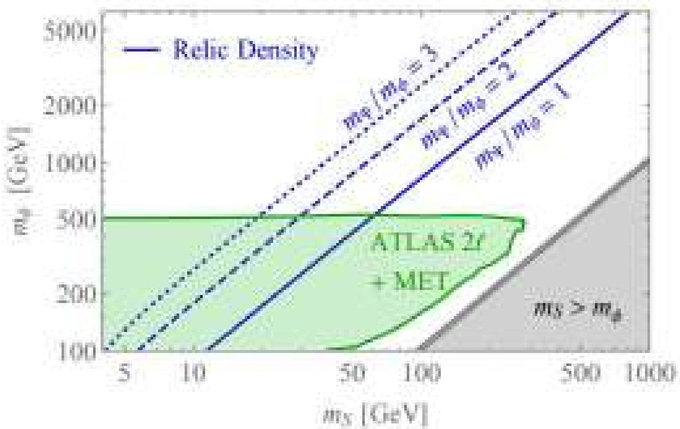
$S$ must by Majorana to avoid large charge-radius interaction with nuclei. Then there are crossed boxes canceling $\mu \to 3e$, *etc.* No need for $\lambda_\mu \gg \lambda_{e,\tau}$.

And no renormalizable Higgs portal to DM.




LHC constrains $m_\phi < 500\,\mathrm{GeV}$

Relic density likes $m_S \sim 10\text{-}100\,\mathrm{GeV}$



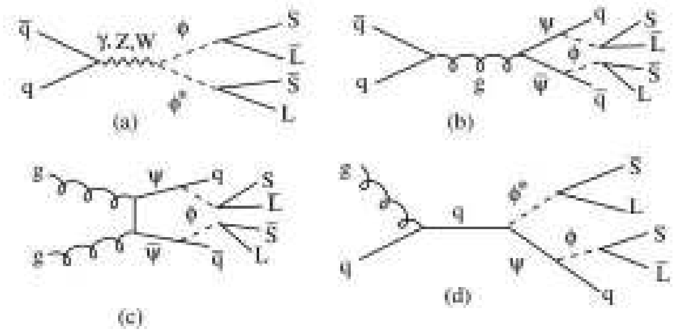




Figure 6. Processes for production of quark jets, leptons, and missing energy.

# Leptoquark models

Classified by nature of the LQ,

- scalar SU(2) triplets:
  Hati, Kumar, Orloff, Teixeira, 1806.10146

- scalar SU(2) singlet (for $R_D$) and triplet (for $R_K$):
  Choi, Kang, Lee, Ro,1807.06547

- composite vector SU(2) singlet:
  JC, 1710.02140

- generic leptoquarks, with scalar mediator to DM:
  de Medeiros Varzielas, Fischer, 1512.00869
  Bauer, Neubert, 1512.06828

# LQ model with radiative $m_\nu$

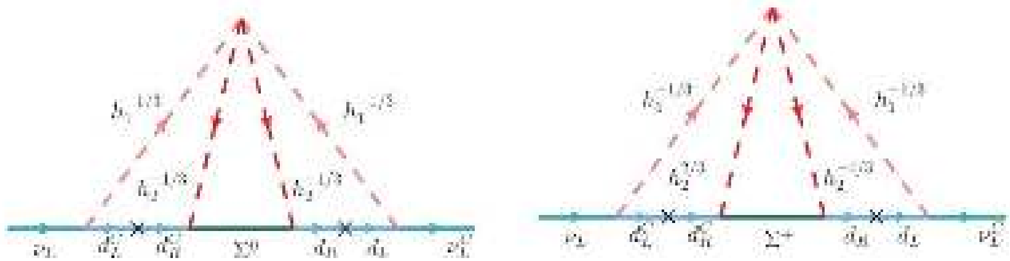
Hati *et al.*, 1806.10146:
scalar LQ's $h_i$ and matter triplet $\Sigma_R$.

Neutral $\Sigma_R^0$ is the DM.

$h_1$ exchange generates $R_K$.

| | Field | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | $Z_2$ |
|---|---|---|---|
| Fermions | $Q_L \equiv (u,d)_L^T$ | $(\mathbf{3},\mathbf{2},1/6)$ | 1 |
| | $u_R$ | $(\mathbf{3},\mathbf{1},2/3)$ | 1 |
| | $d_R$ | $(\mathbf{3},\mathbf{1},-1/3)$ | 1 |
| | $\ell_L \equiv (\nu,e)_L^T$ | $(\mathbf{1},\mathbf{2},-1/2)$ | 1 |
| | $e_R$ | $(\mathbf{1},\mathbf{1},-1)$ | 1 |
| | $\Sigma_R$ | $(\mathbf{1},\mathbf{3},0)$ | $-1$ |
| Scalars | $H$ | $(\mathbf{1},\mathbf{2},1/2)$ | 1 |
| | $h_1$ | $(\bar{\mathbf{3}},\mathbf{3},-1/3)$ | 1 |
| | $h_2$ | $(\mathbf{3},\mathbf{3},-1/3)$ | $-1$ |

$h_1$, $h_2$, and $\Sigma$ generate $m_\nu$



An example of minimal DM, where $\Sigma^0\Sigma^0 \to W^+W^-$ coupling is fixed by SM value of $g_2$, and relic density implies

$$2.425\,\mathrm{TeV} < m_\Sigma < 2.465\,\mathrm{TeV}$$

—very predictive

# Composite LQ model

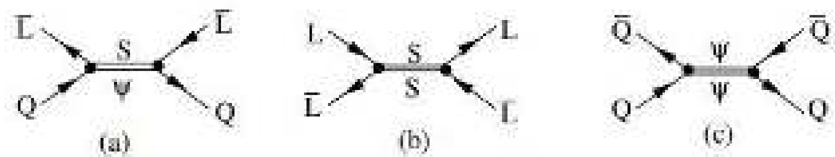
A theoretical problem with leptoquarks: “who ordered that?”

But if new physics is vectorlike confinement, LQ’s could arise as bound states, and so could the DM.

JC, 1710.02140:
Add confining SU($N$) to the loop model of JC + Cornell.

| | SU(3) | $SU(2)_L$ | $U(1)_y$ | $U(1)_{em}$ | $SU(N)_{HC}$ | $Z_2$ |
|---|---|---|---|---|---|---|
| $\Psi$ | 3 | 1 | 2/3 | 2/3 | $N$ | $-1$ |
| $S$ | 1 | 1 | 0 | 0 | $N$ | $-1$ |
| $\phi$ | 1 | 2 | $-1/2$ | $(0,-1)$ | $\bar{N}$ | $-1$ |

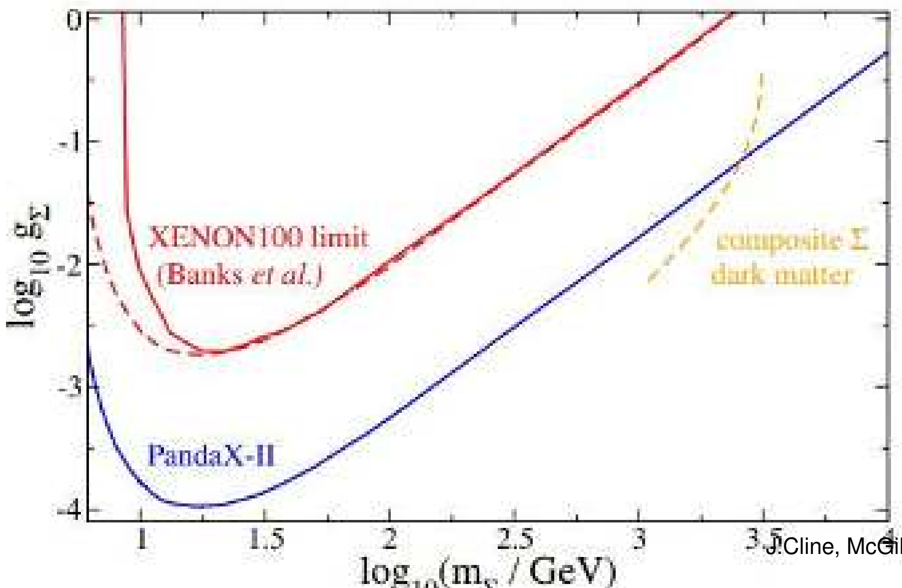
Now flavor anomalies come from tree-level exchange of bound states instead of loops




DM is the “baryon,”

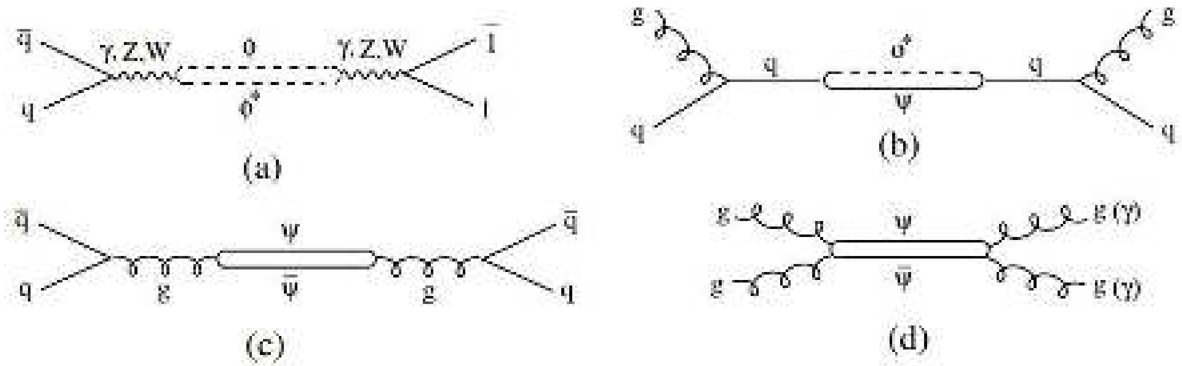
$$\Sigma = S^N$$

It has loop-induced magnetic moment, $\mu_\Sigma$, and gyromagnetic ratio $g_\Sigma = 4\mu_\Sigma m_\Sigma / e$

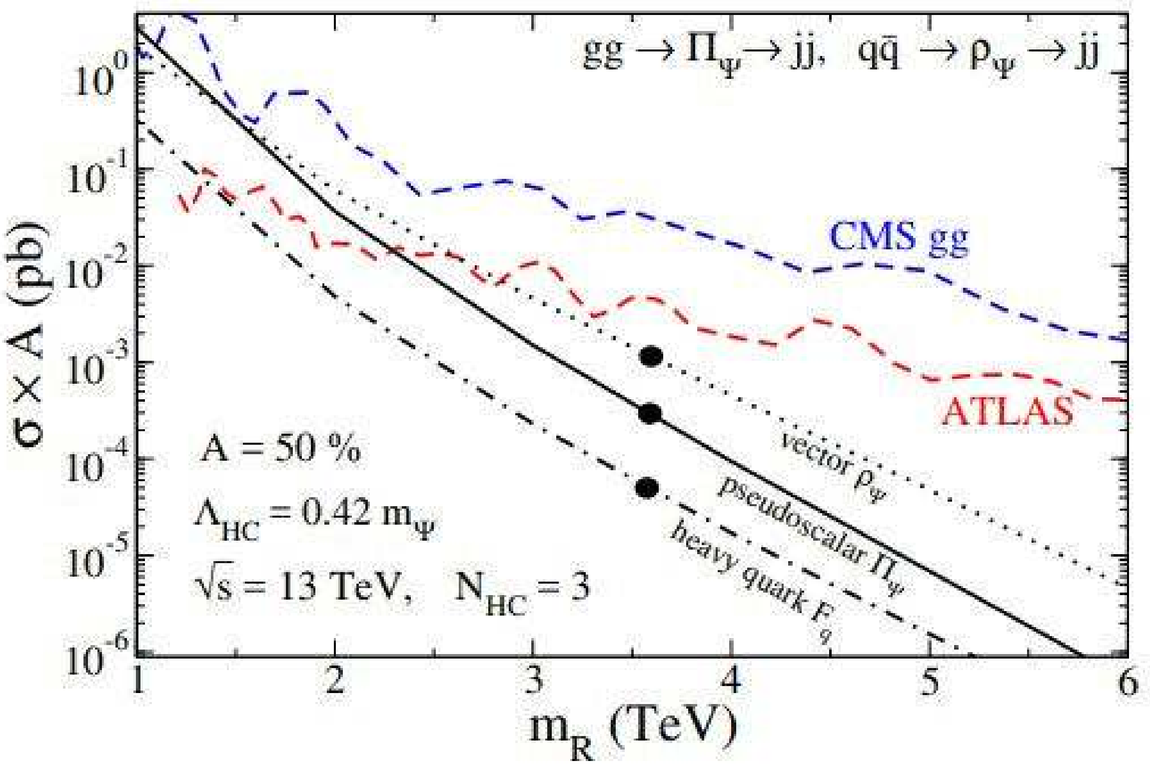


# Composite LQ: LHC constraints

Vector bound states can be resonantly produced at LHC:




Dijet search provides strongest constraint on the mass of the resonances



# Conclusions

$R_K$ anomaly: wouldn't it be great if it survives.

Dark matter: we know it's there; maybe one day we'll see it.

$R_K$ plus DM: way more fun to think about than teaching.

# Conclusions

You are encouraged to draw in this box