Hidden sector explanation of B-decay & cosmic-ray anomalies

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[What I will explain today]

\( Z' \) can simultaneously explain

1. B anomaly

SM/data deviations in \( b \rightarrow s \mu^+ \mu^- \)

2. Cosmic ray anomaly

AMS anti-proton excess interpreted as Dark Matter annihilation
constraint/prospect: $pp \rightarrow \mu^+ \mu^-$

LHC bound

correlations

B physics

DM issue

anomaly: $b \rightarrow s \mu^+ \mu^-$
constraint: $\bar{B}_s - B_s$ mixing
$\nu N \rightarrow \nu N \mu^+ \mu^-$

anomaly: antiproton excess
consistency: relic density
prospect: direct detections
[B anomaly]

Deviations from SM in $b \to s \mu^+\mu^-$

**Obs. 1**

$$R_K = \frac{\Gamma(\bar{B} \to K \mu^+\mu^-)}{\Gamma(\bar{B} \to Ke^+e^-)}$$

SM: $1 \pm \mathcal{O}(0.01)$

LHCb: $0.745 \pm 0.090 \pm 0.074 \pm 0.036 \sim 2.6 \sigma$ 1406.6482 (LHCb)

**Obs. 2** Angular analyses of $\bar{B} \to K^* \ell^+\ell^-$

$\sim 100$ observables.

Including all, $\sim 4.0 \sigma$

$1308.1707$ (LHCb)  
$1512.04442$ (LHCb)  
$1604.04042$ (Belle)

**Obs. 3** Angular analyses of $\bar{B}_s \to \phi \ell^+\ell^-$

$\sim 3.5 \sigma$

$1305.2168$ (LHCb)  
$1506.08777$ (LHCb)
The deviations can be explained by New Physics in \( b \to s\mu^+\mu^- \) with the form of

\[
H_{\text{eff}}^{\text{NP}} = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V^*_{ts} [\bar{s}\gamma^\mu P_L b] [\bar{\mu}\gamma^\mu (C_V + C_A \gamma^5) \mu]
\]

Global fit to data suggests existence of \textbf{NP} [1510.04239]

Point 1: with V - A current \( C_V = -C_A \sim -0.65 \) (best fit)

Point 2: only in muon sector

Point 3: comparable with SM \( C_V^{\text{SM}} \sim -C_A^{\text{SM}} \sim 0.94 \)
[B anomaly : a model]

The simplest thought = $Z'$ with left-handed current

$$\mathcal{L}_{Z'} = g_{bs} (\bar{s} \gamma^\mu P_L b) Z'_\mu + g_{\mu\mu} (\bar{\mu} \gamma^\mu P_L \mu) Z'_\mu$$
[B anomaly : a model]

The simplest thought = \( Z' \) with left-handed current

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To implement this interaction in a realistic model

- \( Z' \) should be a new gauge boson (will get mass after symmetry broken)
- Interactions should respect the SM gauge invariance

This work = \( U(1)' \) gauge
[B anomaly : $U(1)'$ model]

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$$
\mathcal{L}_{U(1)'} = g'Q_q (\bar{q}_L \gamma^\mu q_L) Z'_{\mu} + g'Q_\ell (\bar{\ell}_L \gamma^\mu \ell_L) Z'_{\mu}
$$

$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, $\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ are charged under $U(1)'$
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Structure of the couplings

- 3rd gene. quarks ($tt$, $bb$) and 2nd gene. leptons ($\mu\mu$, $\nu\nu$) are charged

- $b$-$s$-$Z'$ coupling is generated by a mixing of the quark field
[B anomaly : $U(1)'$ model]

The minimum form to address the issues:

• In the gauge basis

$$\mathcal{L}_{U(1)'} = g_q (\bar{q}^3_L \gamma^\mu q^3_L) Z'_\mu + g_\ell (\bar{\ell}^2_L \gamma^\mu \ell^2_L) Z'_\mu$$

$$q^3_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \quad \ell^2_L = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \quad (g_f = g' Q_f)$$
The minimum form to address the issues:

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\[
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\]

\[
q_L^3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \quad \ell_L^2 = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \quad (g_f = g' Q_f)
\]

- b-s coupling is obtained from a mixing in the mass eigen basis

\[
\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\text{gauge}} = D \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\text{mass}}, \quad D \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_D & \sin \theta_D \\ 0 & -\sin \theta_D & \cos \theta_D \end{pmatrix}
\]

- For the other fermion fields, gauge eigenstates = mass eigenstates
\[ U(1)' \text{ model : processes} \]

**Allowed parameter space:**
- parameters
  \[ g_q, \ g_\ell, \ \theta_D, \ \text{and mass } (m_{Z'}) \]
- relevant flavor constraints

\[
\begin{align*}
B \rightarrow K^{(*)} \mu^+ \mu^- & \quad [1510.04239] \\
B \rightarrow K^{(*)} \nu \bar{\nu} & \quad [1409.4557] \\
B_s - \bar{B}_s \text{ mixing} & \quad [\text{PDG 2016}] \\
N \nu \rightarrow N \nu \mu^+ \mu^- & \quad [1609.04026]
\end{align*}
\]

- Branching ratio (upper limit)
- Mass difference of $B_s$
- Cross section
**[\(U(1)'\) model : processes]**

**Allowed parameter space:**

- parameters
  
  \[g_q, \quad g_\ell, \quad \theta_D, \quad \text{and mass } (m_{Z'})\]

- relevant flavor constraints

<table>
<thead>
<tr>
<th>Process</th>
<th>Observable</th>
<th>Constraint on</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b \to s\mu^+\mu^-)</td>
<td>global fit ((\sim 100) observables)</td>
<td>(g_q g_\ell \sin \theta_D \cos \theta_D m_{Z'}^{-2})</td>
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<tr>
<td>(\bar{B}_s^0 - B_s^0) mixing</td>
<td>mass difference ((\Delta M_s))</td>
<td>(g^2_q \sin \theta_D \cos \theta_D m_{Z'}^{-2})</td>
</tr>
<tr>
<td>(\nu N \to \nu N \mu^+\mu^-)</td>
<td>production cross section</td>
<td>(g^2_\ell m_{Z'}^{-2})</td>
</tr>
</tbody>
</table>

- we define ratio of the couplings: *“hierarchy of the couplings”*

\[
\begin{align*}
  n_q & \equiv \frac{g_q}{g_\ell} \\
  \text{(ex) } n_q > 1 & \implies g_q > g_\ell
\end{align*}
\]
Space on \( (g_q g_\ell m_{Z'}^{-2}, \theta_D) \) for several choices of \( n_q \equiv \frac{g_q}{g_\ell} \)

- Region in \( \text{blue region} \) explains the \( b \rightarrow s \mu^+ \mu^- \) anomaly

- A small mixing in limited range is only allowed
**U(1)’ model : constraints**

Space on \( (g_q g_\ell m_{Z’}^{-2}, \, \theta_D) \) for several choices of \( n_q \equiv \frac{g_q}{g_\ell} \)

- Region in blue explains the \( b \rightarrow s \mu^+ \mu^- \) anomaly
- Region in circle satisfies all the flavor constraints
- The reference point (★) \( \theta_D = 0.005 \)
  \[ g_q g_\ell / m_{Z’}^2 = 0.12 / \text{TeV}^2 \]
- A small mixing in limited range is only allowed
[\textit{U(1)'} model : summary]

Reference point ★

\[
g_q \equiv n_\ell g_\ell \simeq 0.35 \sqrt{n_\ell} \left( \frac{m_{Z'}}{1 \text{ TeV}} \right)
\]

(Just keep this in mind)

Next point

- introduction of Dark Matter to our model
- DM solution to Cosmic Ray anomaly
- Correlation between B and CR anomalies
Z' as a mediator of Dark Matter:

- We can easily introduce (Dirac) DM into our model

\[ \mathcal{L}_{U(1)'} = g_q \left( \bar{q}_L^3 \gamma^\mu q_L^3 \right) Z'_\mu + g_\ell \left( \bar{\ell}_L^2 \gamma^\mu \ell_L^2 \right) Z'_\mu + g_\chi \left( \bar{\chi} \gamma^\mu \chi \right) Z'_\mu \]

- DM annihilation channel

\[ \langle \sigma v \rangle = \frac{g_\chi^2 (3g_q^2 + 2g_\ell^2)}{2\pi} \left( \frac{m_\chi^2}{m_{Z'}^4} \right) \]

So, what can we play with this?
[CR anomaly]

AMS-02 antiproton observation

- Precise measurement of antiproton flux in cosmic rays at ISS

**Figure 1:**
- **Phys. Rev. Lett. 117, 091103**
- Comparison of antiproton flux ratios from AMS-02 and PAMELA measurements.
- The red curve represents the antiproton to proton flux ratio, showing a significant anomaly at low rigidities.
- The blue curve depicts the positron flux ratio, which is nearly constant across different rigidities.

**Figure 2:**
- **Antiproton flux** (red, left axis)
- **Proton flux** (blue, right axis)
- **Positron flux** (green, right axis)
- Data points are placed at the center of each bin with rigidity independence.
- The flux ratios are used to determine the lowest rigidity above which the ratio is consistent with expectations.

**Equation:**

\[ \frac{\Phi^-}{\Phi^+} \]

Where \( \Phi^- \) and \( \Phi^+ \) represent the antiproton and proton fluxes, respectively.

**Analysis:**
- Above 60.3 GV, the antiproton-to-proton ratio is nearly constant, indicating rigidity independence.
- Below this value, the ratio shows significant variation, indicating an anomaly.

**Conclusion:**
- The AMS-02 measurements provide evidence for a CR anomaly at low rigidities, which is consistent with earlier experiments.

**Figure 3:**
- **Graph showing measured data points and fitted lines.**
- The figure presents the measured ratios and fitted lines for different rigidities.
- The mean value of the slope is determined above 60.3 GV, as determined above, together with the 68% C.L. range of the fit parameter (shaded region).

**Discussion:**
- The low rigidities range is critical for understanding the behavior of cosmic rays and their interactions.
- Continued monitoring and analysis are essential to resolve the CR anomaly.
[CR anomaly : DM interpretation]

AMS-02 antiproton observation

- Recent studies for re-fit to AMS data taking DM into account suggest

$$\chi\bar{\chi} \rightarrow b\bar{b} \text{ is favored when}$$

$$m_\chi \sim 70 \text{ GeV and } \langle \sigma v \rangle \sim \text{Relic density}$$

**Phys.Rev.Lett. 118.191102**

**Phys.Rev.Lett. 118.191101**
[CR anomaly : DM solution]

Implication with respect to our model

- [Relic density] + [DM favored by AMS-02 data]

\[
\langle \sigma v \rangle = \frac{g_x^2 (3g_q^2 + 2g_{\ell}^2)}{2\pi} \left( \frac{(70 \text{ GeV})^2}{m_Z^4} \right) \approx 4.4 \times 10^{-26} \text{ cm}^3/\text{s}
\]

- DM solution in our model

\[
g_x \equiv n_x g_q \approx 1.09 \sqrt{n_x} \left( \frac{m_{Z'}}{1 \text{ TeV}} \right)
\]
[CR anomaly : DM solution]

Implication with respect to our model

- [Relic density] + [DM favored by AMS-02 data]

$$\langle \sigma v \rangle = \frac{g^2 \sqrt{3 g^2_q + 2 g^2_{\ell}}}{2\pi} \left( \frac{(70 \text{ GeV})^2}{m_{Z'}^4} \right) \simeq 4.4 \times 10^{-26} \text{ cm}^3/\text{s}$$

($\chi \bar{\chi} \rightarrow b \bar{b}$ dominated)

- DM solution in our model

$$g_{\chi} \equiv n_{\chi} g_q \simeq 1.09 \sqrt{n_{\chi}} \left( \frac{m_{Z'}}{1 \text{ TeV}} \right)$$
[CR anomaly : DM solution]

Implication with respect to our model

- **[Relic density] + [DM favored by AMS-02 data]**

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\langle \sigma v \rangle = \frac{g_\chi^2 (3g_q^2 + 2g_\ell^2)}{2\pi} \left( \frac{\left(70 \text{ GeV}\right)^2}{m_{Z'}^4} \right) \approx 4.4 \times 10^{-26} \text{ cm}^3 / s
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(\(\chi \bar{\chi} \rightarrow b \bar{b} \) dominated) \hspace{1cm} (AMS-02 data favored)

- **DM solution in our model**

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g_\chi \equiv n \chi g_q \approx 1.09 \sqrt{n \chi} \left( \frac{m_{Z'}}{1 \text{ TeV}} \right)
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Implication with respect to our model

- **[Relic density] + [DM favored by AMS-02 data]**

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\langle \sigma v \rangle = \frac{g_X^2 (3g_q^2 + 2g_\ell^2)}{2\pi} \left( \frac{(70 \text{ GeV})^2}{m_{Z'}^4} \right) \approx 4.4 \times 10^{-26} \text{ cm}^3 / s
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(\( \chi \bar{\chi} \rightarrow b \bar{b} \) dominated) (AMS-02 data favored) (Relic density)

- **DM solution in our model**

\[
g_X \equiv n_X g_q \approx 1.09 \sqrt{n_X} \left( \frac{m_{Z'}}{1 \text{ TeV}} \right)
\]
[B and CR anomalies]

Requirement

- In terms of couplings

**$B$ physics:** $g_q^2 \simeq 0.12 n_q \times \left( \frac{m_{Z'}}{1 \text{ TeV}} \right)^2$ for the point ★

**Astrophysics:** $g_q^2 \simeq \frac{1.2}{n_\chi} \times \left( \frac{m_{Z'}}{1 \text{ TeV}} \right)^2$ for $m_\chi = 70 \text{ GeV}$

\[ n_\chi \cdot n_q \simeq 10 \quad (g_\chi \equiv n_\chi g_q, \ g_q \equiv n_q g_\ell) \]

- The DM re-fit to AMS data indicates $\chi \bar{\chi} \rightarrow b \bar{b}$ is dominant process

At least, $n_q > 1 \ (g_q > g_\ell)$

Indeed, $n_q = 2 \ (g_q = 2g_\ell)$ is sufficient (86% of full $b\bar{b}$ case)
Collider limit and prospect

Hierarchical couplings are favored: \( g_\chi > g_q > g_\ell \)

Small \( Z' \) mass is (1) still viable (2) rather favored

\( m_{Z'} \sim 500 \text{ GeV} \)
**Current & future limits of DM direct detection**

**DM-proton scattering in nucleon**

- Kinetic mixing ($\epsilon$) of $Z'$ and photon induces a contribution

- Our naive estimation obtains

\[
\sigma_p = \frac{(\epsilon e g \chi m_p)^2}{\pi m_{Z'}^4} \lesssim 1.7 \times 10^{-45} \text{cm}^2
\]

sufficiently detectable in near future
**[Summary]**

$Z'$ can simultaneously explain

SM/data deviations in $b \rightarrow s \mu^+ \mu^-$

AMS anti-proton excess
interpreted as **Dark Matter** annihilation

**One viable scenario :**

$$\mathcal{L}_{U(1)'} = g_q (\bar{q}^3_L \gamma^\mu q^3_L) Z'_\mu + g_\ell (\bar{\ell}^2_L \gamma^\mu \ell^2_L) Z'_\mu + g_\chi (\bar{\chi} \gamma^\mu \chi) Z'_\mu$$

with

$$g_\chi \simeq 5 \ g_q, \ g_q \simeq 2 \ g_\ell,$$

\[
\begin{pmatrix}
  d_L \\
  s_L \\
  b_L
\end{pmatrix}_{\text{gauge}} \simeq \begin{pmatrix}
  1 & 0 & 0 \\
  0 & \sim 1 & 0.005 \\
  0 & -0.005 & \sim 1
\end{pmatrix}
\begin{pmatrix}
  d_L \\
  s_L \\
  b_L
\end{pmatrix}_{\text{mass}}
\]
[Summary]

constraint/prospect: \( pp \rightarrow \mu^+ \mu^- \)

LHC bound

\[ Z' \]

B physics: anomaly: \( b \rightarrow s \mu^+ \mu^- \)
constraint: \( \bar{B}_s - B_s \) mixing
\( \nu N \rightarrow \nu N \mu^+ \mu^- \)

DM issue: anomaly: antiproton excess
consistency: relic density
prospect: direct detections
[Summary]

LHC bound

constraint/prospect: $pp \rightarrow \mu^+ \mu^-$

$Z'$

B physics

anomaly: $\bar{B}_s - B_s$ mixing
constraint: $\nu N \rightarrow \nu N \mu^+ \mu^-$

explained

DM issue

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explained
**Summary**

- **B physics**
  - anomaly: $\bar{B}_s - B_s$ mixing
  - constraint: $\nu N \rightarrow \nu N \mu^+ \mu^-$

- **DM issue**
  - anomaly: antiproton excess
  - consistency: relic density
  - prospect: direct detections

- **LHC bound**
  - constraint/prospect: small $Z'$ mass is still viable/detectable

- **Z'**


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**Explained**

- anomaly: $\bar{B}_s - B_s$ mixing
- constraint: $\nu N \rightarrow \nu N \mu^+ \mu^-$

**Detectable**

- in $\sigma_p$
DM-direct detection

DM-nucleon scattering

- Coupling to up-quark is very much suppressed, but exists

\[ \mathcal{L}_{u\bar{u}Z'} = g_q X_{uu}(\bar{u}\gamma^\mu P_L u)Z'_\mu \]

\[ X_{uu} \sim |V_{ub} - \theta_D V_{us}|^2 \sim 6 \times 10^{-6} \text{ for } \star \]

(no interaction of d-\bar{d}-Z')

- Still, it gives rise to a contribution to \( \chi N \rightarrow \chi N \)

\[ \sigma_N = (1 + Z/A)^2 \frac{g_\chi^2 g_q^2 X_{uu}^2}{4\pi} \frac{m_n^2}{m_{Z'}^2} \]

\( \approx 2 \times 10^{-51} \text{ cm}^2 \)

keeping the conditions from B-physics & Astrophysics for the \( n_q = 2, \ n_\chi = 5 \) scenario and for xenon
**Kinetic mixing of $Z'$ & photon**

\[ \frac{\epsilon}{2} F^{\mu\nu} Z'_\mu\nu \]

- **Natural size** at one loop (for “marginal” point)

1. Log divergence at UV cancels only if $g_q = g_\ell$
2. The present case is, however, $g_q > g_\ell$
3. Possible solution is to introduce **heavy vector-like fermion (F)**
4. In this case, contribution at the low energy is calculable

\[ \epsilon \sim 0.04 \, e \, g_q \quad (\text{for } m_F \sim 100 \text{ TeV and } g_q = 2g_\ell) \]

- **DM can then interact with proton in nucleon**

\[ \sigma_p = \frac{(\epsilon e g_\chi m_p)^2}{\pi m_Z^4} \sim 1.7 \times 10^{-45} \text{ cm}^2 \]

1. Just below the bound from PandaX-II $1.8 \times 10^{-45} \text{ cm}^2$
2. Well above the expected reach of LZ experiment $\sim 10^{-47} \text{ cm}^2$

sufficiently detectable in near future
[UV completion]

Simple example

- Gauged flavor symmetries

\[ SU(3)_q \times SU(3)_u \times SU(3)_d \times SU(3)_{e} \times O(3)_{\nu R} \]
\[ SU(3)_q \times SU(3)_{\ell} \to U(1)' \text{ at TeV scale} \]

- Direction of U(1)'

We assign U(1)' in a way that \( q^3 \) and \( \ell^2 \) are charged under U(1)'

- Some requirements (unimportant for today's topic)

Scalar field that breaks U(1)' to get Z' mass
Chiral fermion(s) to ensure anomaly free
Cut-off scale (>100TeV for <1TeV Z' mass) due to running effect of \( g_\chi \)
Realization of $U(1)'$

- gives a prediction on hierarchy of coupling

**arXiv:1704.08158**

$SU(3)_H \times U(1)_{B-L} \rightarrow U(1)'$

\[ n_q = 5/9 , \quad n_\chi = ? \quad (DM = \nu_R) \]

\[ \theta_D \sim V_{tb}V_{ts}^* \]

**arXiv:1706.08510**

$SU(3)_L \times SU(3)_R \rightarrow U(1)'$

\[ n_q = 4 , \quad n_\chi = ? \quad (DM \text{ is not considered}) \]

\[ \theta_D \sim V_{tb}V_{ts}^* \]
[LHC bound]

Two relevant analyses

[ATLAS-CONF-2016-045]
(also, CMS-PAS-EXO-16-031)

[arXiv:1611.03568]
**[LHC bound]**

**Usual bound vs Our bound**

\[ pp \to \mu^+ \mu^- \]

**[ATLAS-CONF-2016-045]**
(also, CMS-PAS-EXO-16-031)
AMS-02 antiproton observation

- Fit including DM

[arXiv:1610.03071]
[Cosmic Ray anomaly]

Conflict with dwarf spheroidal galaxies?

The most recent Fermi-LAT searches for emission from dark matter annihilation in dwarf spheroidal galaxies currently exclude cross sections of $\langle \sigma v \rangle > 1.9 \times 10^{-26}$ cm$^3$/s at 95% C.L. for 80 GeV DM annihilating to $b\bar{b}$ [53]. This is in tension with the cross sections suggested by the DM interpretation of the $\bar{p}$ excess. However, recent works [54, 55] have pointed out that the dark matter content of some of the dwarf spheroidals in the Fermi analysis may have been overestimated, resulting in a less stringent limit that can be compatible with DM explanations of cosmic ray excesses.

[arXiv:1504.02048]
[arXiv:1603.07721]