Looking for a Muonic Force in the Muon Anomalies

Anders Eller Thomsen

Based on work with A. Greljo, Y. Soreq, P. Stangl, and J. Zupan

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The flavor puzzle

Quark sector:

\[ y_{u,d} \sim \begin{pmatrix} \text{light} & \text{light} \\ \text{heavy} & \text{heavy} \end{pmatrix} \]

\[ V_{\text{CKM}} \sim \begin{pmatrix} \text{heavy} & \text{light} & \text{light} \\ \text{light} & \text{heavy} & \text{light} \\ \text{light} & \text{light} & \text{heavy} \end{pmatrix} \]

Lepton sector:

\[ y_e \sim \begin{pmatrix} \text{light} \end{pmatrix} \]

\[ V_{\text{PMNS}} \sim \begin{pmatrix} \text{heavy} & \text{light} \\ \text{light} & \text{heavy} \\ \text{light} & \text{light} \end{pmatrix} \]

Not visible in colliders
The flavor puzzle

Quark sector:

\[ y_{u,d} \sim \begin{pmatrix} \text{...} & \text{...} \\ & \text{...} \end{pmatrix} \]

\[ V_{\text{CKM}} \sim \begin{pmatrix} \text{...} & \text{...} & \text{...} \\ & \text{...} \ & \text{...} \\ & & \text{...} \end{pmatrix} \]

Lepton sector:

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- Is there structure to the flavor sector?
- How does potential new physics couple to flavor?
- Can this give hints towards an underlying model of flavor?
$b \to s \ell^+ \ell^-$ anomalies

\[ R_{K(*)} = \frac{\text{BR}(B \to K(*) \mu^+ \mu^-)}{\text{BR}(B \to K(*) e^+ e^-)} \]

- LHCb measurements of $R_K^{[1.1,6]}$, $R_{K^*}^{[1.1,6]}$, and $R_{K^*}^{[0.045,1.1]}$ deviate from SM by $3.1\sigma$, $2.5\sigma$, and $2.3\sigma$, respectively.

- Average ATLAS, CMS, and LHCb $B_s \to \mu^+ \mu^-$ branching ratio deviate from SM by $2\sigma$.

- Angular observables in $B \to K^* \mu^+ \mu^-$ and branching ratios in $B \to K(*) \mu^+ \mu^-$ and $B_s \to \phi \mu^+ \mu^-$.

- Consistent picture emerges in the EFT: tentative global $4.3\sigma$ significance for the NP hypothesis.

\[ Aaij et al. \ [2013.11769] \]
\[ Altmannshofer, Stangl \ [2013.13370] \]
\[ Lancierini et al. \ [2014.05631] \]
New physics in $b \rightarrow s \mu^+ \mu^-$?

At low energies, a good fit involves (LEFT)

$$\mathcal{L} \supset \frac{4G_F e^2 V_{tb} V_{ts}^*}{\sqrt{2}(4\pi)^2} (\bar{b} \gamma_{\nu} s)_{\text{L}} (\bar{\mu} \gamma^\nu (C_9 + C_{10} \gamma_5) \mu)$$

In the unbroken phase of the SM (SMEFT), a left-handed current works well:

$$\mathcal{L}_{\text{SMEFT}} \supset \frac{1}{(40 \text{ TeV})^2} (\bar{q}_3 \gamma_{\nu} q_2)_{\text{L}} (\bar{\ell}_2 \gamma^\nu \ell_2)_{\text{L}}$$

Analyses from Algueró et al. [2104.08921], Ciuchini et al. [2011.01212], Hurth et al. [2104.10058], largely agree but in some cases favor $C_9$ over $C_9 - C_{10}$. Altmannshofer, Stangl [2103.13370]
New physics in $b \rightarrow s\mu^+\mu^-$?

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Tree-level mediators:

- $Z'$ neutral vector boson
  UV completion required

- $U_1$ ($U_3$) vector LQ
  UV completion required

- $S_3$ scalar triplet LQ
  single-field extension is possible

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Altmannshofer, Stangl [2103.13370]
First measurement of the Fermilab Muon $g-2$ Experiment is compatible with the Brookhaven experiment. Combined $4.2\sigma$ discrepancy with the Muon $g-2$ Theory Initiative. Aoyama et al. [2006.04822]

HVP is the dominant error of the SM prediction. Tension between Lattice results (BMWc) and the data-driven approach ($R$-ratio) used in SM prediction.
Many types of NP can account for the discrepancy: VL leptons, 2HDM, MSSM, *light vector bosons*, *leptoquarks*, ...

EFT fit to \((g - 2)_\mu\), 

\[ -\frac{e_v}{(4\pi)^2} C_{e\gamma}^{ij} \bar{e}_L^i \sigma^{\mu\nu} e_R^j F_{\mu\nu}, \]

gives

\[ |C_{e\gamma}^{ij}| \sim \frac{1}{(14 \text{ TeV})^2} \left( \begin{array}{ccc} \lesssim 10^{-1} & \lesssim 2 \cdot 10^{-5} & \lesssim 1/4 \\ & 1 & \lesssim 1/4 \\ & & \lesssim 2 \cdot 10^5 \end{array} \right) \]
New physics in \((g - 2)_\mu\)?

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\[
|C^{ij}_{e\gamma}| \sim \frac{1}{(14 \text{ TeV})^2} \begin{pmatrix}
\lesssim 10^{-1} & \lesssim 2 \cdot 10^{-5} & \lesssim 1/4 \\
1 & \lesssim 1/4 & \lesssim 2 \cdot 10^5
\end{pmatrix}
\]

Also very strong CP constraints from EDM \((\lesssim 10^{-8})\)

- Alignment between all SMEFT operators is required

Isidori, Pagès, Wilsch [2111.13724]; Calibbi et al. [2104.03296]

\[\begin{align*}
&\begin{array}{c}
\text{SMEFT operators} \\
\hline
\ell_i & e_j \\
H & B, W \\
\ell_i \rightarrow e\gamma \\
\ell_i & e_j \\
q_k & u\ell \\
\ell_i & e_j
\end{array}
\end{align*}\]
Many types of NP can account for the discrepancy: VL leptons, 2HDM, MSSM, light vector bosons, leptoquarks, ...

EFT fit to \( (g - 2)_\mu \), 
\[
\left( \frac{e v}{\pi} \right)^2 C^{ij}_{e\gamma} \bar{e}_L^i \sigma_{\mu\nu} e_R^j F_{\mu\nu},
\]
gives
\[
|C^{ij}_{e\gamma}| \sim \frac{1}{(14 \text{ TeV})^2}
\]
\[
\lesssim 10^{-1} \quad \lesssim 2 \cdot 10^{-5} \quad \lesssim 1/4 \quad \lesssim 1/4 \quad \lesssim 2 \cdot 10^5
\]

Alignment between all SMEFT operators is required

Isidori, Pagès, Wilsch [2111.13724]; Calibbi et al. [2104.03296]

No charged LFV in NP if it satisfies SM accidental symmetries
Introducing muoquarks

Scalar LQ explanations of the anomalies can only have a particular set of interactions

Diquark interactions

LQ interactions
Introducing muoquarks

Diquark interactions

\[ p \xrightarrow{\pi} \ell \]

Scalar LQ explanations of the anomalies can only have a particular set of interactions

Solution: \textit{Lepton-flavored gauged} \( U(1)_X \)


\[ U(1)_X \quad e \quad \mu \quad \tau \]

Approximate recovery of SM accidental symmetries:

\[ G_{SM}^F = U(1)_B \times U(1)_{L_e} \times U(1)_{L_{\mu}} \times U(1)_{L_{\tau}} \]

\[ S \sim (\frac{-1}{3}, 0, -1, 0) \]

\~500 quark-universal anomaly-free models with integer charge ratios \( \leq 10 \) in SM+3\( \nu_R \).

Examples: \( X = L_{\mu} - L_{\tau}, X = B - 3L_{\mu} \), and many, many others

Anders Eller Thomsen (Bern U.)

A New Muonic Force

DIS2022
An explanation with two muoquarks

Muoquark (LQ) mediated anomalies:
Crivellin, Müller, Ota [1703.09226]; Gherardi, Marzocca, Venturini [2008.09548]

\[
\begin{align*}
&b & \mu \\
&s & \mu \\
&S_3 & \text{mediates anomaly}
\end{align*}
\]

Couplings respecting lepton-flavored $U(1)_X$

- Direct searches give only modest constraints: $M_{1,3} \gtrsim 1.7 \text{ TeV}$
  
  \[\text{ATLAS collaboration [2006.05872]}\]

- Decoupling limit ($\nu_X \to \infty$) ensures NP contribution exclusively from $S_{1,3}$

- Approximate $U(2)$ flavor symmetry
  
  \[\text{Kagan et al. [0903.1794]; Barbieri et al. [1105.2296]}\]

- Existing 1-loop $S_{1,3}$ matching results
  
  \[\text{Gherardi, Marzocca, Venturini [2003.12525]}\]

- \textbf{Global fit} with smelli (also using wilson and flavio)
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- **Global fit** with smelli (also using wilson and flavio)

Greljo, Stangl, AET [2103.13991]
Do we need two muoquarks?

Solution: *Gauged lepton-flavored* \( U(1)_X \)

Scenarios:

- \( S_3 \) muoquark for \( b \rightarrow s\mu\mu \) and \( S_1 \) muoquark for \( (g - 2)_\mu \)
Do we need two muoquarks?

Solution: *Gauged lepton-flavored* $U(1)_X$

Scenarios:

- $S_3$ muoquark for $b \rightarrow s\mu\mu$ and $S_1$ muoquark for $(g-2)_\mu$
- $S_3$ muoquark for $b \rightarrow s\mu\mu$ and $X_\mu$ vector boson of $U(1)_X$ for $(g-2)_\mu$

Which $U(1)_X$ groups allow for this scenario?

\[
\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu}^2 + \frac{1}{2} \epsilon X_{\mu\nu} F_{\mu\nu} + \frac{1}{2} m_X^2 X_\mu^2 + g_X X_\mu \sum_f x_f \bar{f} \gamma_\mu f
\]

Charges of SM (chiral) fermions

kinitx mixing parameter
Addressing \((g - 2)_\mu\) with the muonic force

\[ x_f: \text{charge of fermion } f \]
\[ \varepsilon: \text{kinetic mixing of } X \text{ and } \gamma \]

\( m_X \)

\((g - 2)_\mu\) preffered region

Baek et al. [hep-ph/0104141]; Ma, Roy, Roy [hep-ph/0110146]; many, many more...
Addressing $(g - 2)_\mu$ with the muonic force

$x_f$: charge of fermion $f$

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CCFR colaboration '91;
Altmannshofer et al. [1406.2332];
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\[ gX \]

\[ m_X \]

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\[ \nu_\mu \]

\[ (x_\mu - \varepsilon \frac{e}{g_X}) \]

\[ \mu \]

\[ N \]

\[ gX \]

\[ \text{Borexino colaboration [1707.09279; } \]
\[ \text{Altmannshofer et al. [1902.06765; } \]
\[ \text{Banerjee et al. [1906.00176]} \]

Baek et al. [hep-ph/0104141];
Ma, Roy, Roy [hep-ph/0110146];
many, many more...
Light vector solution: $X = L_\mu - L_\tau$

$L_\mu - L_\tau$, $\mu/\tau$-loop effective kinetic mixing

$g_X$ vs. $m_X$ [GeV]

Data from CCFR, Borexino, NA64, BaBar 2014, BaBar 2016, LHCb.

Greljo, Stangl, AET, Zupan [2203.13731]
Complementary constraints on a light $X$

Charge density: $\rho \sim 2.05 x_B + x_e$

Coloma, Gonzalez-Garcia, Maltoni [2009.14220]; Esteban et al. [1805.04530]; Heeck et al. [1812.04067] Wolfenstein '78
Complementary constraints on a light X

Charge density:
\[ \rho \sim 2.05 x_B + x_e \]

Eff. charge:
\[ Q = A x_B + Z \epsilon \frac{e}{g_X} \]

References:
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Denton, Gehrlein [2008.06062];
Esteban et al. [1805.04530];
COHERENT collaboration [1708.01294];
Freedman '74; Drukier, Stodolsky '84
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- Denton, Gehrlein [2008.06062]; Esteban et al. [1805.04530]; COHERENT collaboration [1708.01294]; Freedman ’74; Drukier, Stodolsky ’84
- BaBar collaboration [1606.03501]; BaBar collaboration [1406.2980]; LHCb collaboration [1710.02867]; darkcast: Ilten et al. [1801.04847]
Light, quark-universal $X$ solutions to $(g - 2)_\mu$ in the space of vector-like $U(1)_X$ at $m_X = 200$ MeV. Includes NSI osc., NA64, and Borexino bounds.
Allowed model with $B$ charge

\[ 3B - 6L_e - 3L_\tau + 3(L_\mu - L_\tau), \varepsilon = -6.06 \frac{g_X}{e} \]
Lepton-flavored gauge symmetries provide a good organizing principle for scalar-Leptoquark explanations of the muon anomalies.

Kinetic mixing between $X$ and $\gamma$ opens up one new direction in models of light $X$ solutions to $(g - 2)_\mu$ with charged quarks.

We have to be prepared for the possibility (Type A) that new physics in the anomalies can be elusive.
Backup
The $B - 3L_\mu$ model

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<th>SU(2)$_L$</th>
<th>U(1)$_Y$</th>
<th>U(1)$<em>{B-3L</em>\mu}$</th>
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<td>$\Phi$</td>
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</table>

SM: Standard Model

Muquarks

X-breaking SM singlet

Muonic force
A single mediator seems unlikely

- Float $X$-couplings in $b$–$s$ current, and muon vector and axial charges $q_V$, $q_A$. Assume $\varepsilon = 0$.

- Upper bound on $b$–$s$ couplings to $X$ from $\text{BR}(B \to K\nu\nu)$.

- $B \to K\nu\nu$ bound might be looser for $m_X > 2.5 \text{ GeV}$

[Crivellin et al. [2202.12900]]

- Using kinetic mixing to relax CCFR bound, EW precision excludes $m_X \gtrsim 5 \text{ GeV}$

[Greljo, Soreq, Stangl, AET, Zupan [2107.07518]]
Addressing \((g - 2)_\mu\) with the muonic force

\[ \tilde{L}_{\mu-\tau}, \varepsilon = g_X/10 \]

\[ 6 \times 10^{-4} \]

\[ 4 \times 10^{-4} \]

\[ 3 \times 10^{-4} \]

\[ 2 \times 10^{-4} \]

\[ 1 \times 10^{-4} \]

\[ 6 \times 10^{-5} \]

\[ m_X \text{ [GeV]} \]

Greljo, Stangl, AET, Zupan [WIP]
Minimum $\chi^2$ from $(g - 2)_\mu$, CCFR, and EW T parameter

SM
$\varepsilon_Y = 0$
$X_{L2} = X_{E2} = 0$
global
global excl.

Greljo, Stangl, AET, Zupan [WIP]