New signatures of BSM physics hiding in QCD

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Searching for new forces

SM based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry. Are there any additional gauge symmetries? Look for new gauge bosons.

Motivations:

1. **Grand unified theories**: Generically have additional gauge bosons, but typically very heavy ($10^{16}$ GeV).

2. **Dark matter**: Stability of dark matter related to new gauge symmetry? Can also give the right relic density.
Motivations for new GeV-scale forces

Dark matter indirect detection anomalies
e.g. Pamela/AMS-02 positron excess

\[ \text{Pospelov & Ritz (2008); Arkani-Hamed et al (2008)} \]

\[
\begin{align*}
\text{Dark matter annihilation} \\
\text{AMS-02 (2014)}
\end{align*}
\]

\[(g-2)_{\mu} \text{ anomaly} \]

\[Pospelov (2008)\]
Dark matter and structure of galaxies

Kinematics of stars and gas in galaxies are tracers of dark matter mass distribution

Galaxies and clusters are less dense than predicted from “vanilla” cold dark matter theory predictions  
Dark matter and structure of galaxies

The “core-cusp” problem

THINGS (dwarf galaxy survey)

Dwarf galaxies observed by 21cm emission from their H gas

Oh et al. (2011)

Cored profile

$\alpha = -0.29 \pm 0.07$

Cusp profile

$\alpha \sim -1.0$
Dark matter and structure of galaxies

Dark matter cores are extremely prevalent in the Universe

• Dwarf galaxies in the field
  Oh et al (2011)
• Dwarf galaxy satellites of the Milky Way
  Walker & Penarrubia (2011)
• Low surface brightness spiral galaxies
• Galaxy clusters

Explained by:

• Messy baryonic dynamics from gas, star formation, etc.
• Dark matter physics

\( m_{A'} \sim \text{MeV} – \text{GeV} \) to get a large enough cross section to explain cores  
ST, Yu, Zurek (2013)
Motivations for new GeV-scale forces

Whether or not you take these anomalies seriously, intermediate energy experiments have a unique capability to explore new forces beyond the SM.

We don’t know in which direction beyond the Standard Model physics might be.
Dark photons and other new forces

Also a third axis: decays to invisible states (neutrinos, light dark matter)
Dark photons and other new forces

Leptophillic models
*Gauged lepton symmetry*

*Dark photon model, Gauged B-L*

Leptophobic models
*Gauged baryon number*

Lepton coupling vs. Quark coupling

Also a third axis: decays to invisible states (neutrinos, light dark matter)
Dark photon searches

Most dark photon searches are for $A'$ coupling to leptons (or light dark matter)

Dark photon searches

Most dark photon searches are for $A'$ coupling to leptons (or light dark matter)

Includes more recent results from MAMI, PHENIX, HADES

$(g-2)_{\mu}$ region now excluded at 85% CL

*Merkel et al [PHENIX] (2014)*
Dark photons and other new forces

- Leptophillic models
  *Gauged lepton symmetry*

- *Dark photon model, Gauged B-L*

- Blind spot for dark photon searches
  *Leptophobic models
    *Gauged baryon number*

- Dark photon searches (di-lepton resonances)

- Also a third axis: decays to invisible states (neutrinos, light dark matter)
New force coupling to quarks

Most dark photon searches are for $A'$ coupling to leptons (or light dark matter)

What if a new force couples mainly to quarks?


Simplest model: Gauge boson $(B)$ coupled to baryon number

\[ \mathcal{L} = \frac{g_B}{3} \bar{q} \gamma^\mu q B_\mu \]

Flavor-universal charge $g_B$

coupling to all quarks

Also known as: “leptophobic Z’” or “baryonic photon $\gamma_B$” or “$Z'_B$” or “$B$ boson”
New force coupling to quarks

$B =$ gauge boson coupled to baryon number

Discovery signals depend on the $B$ mass

- Departures from inverse square law

- Long range nuclear forces
  Barbieri & Ericson (1975);
  Leeb & Schmiedmayer (1991)

- Meson physics
  Nelson & Tetrads (1989),
  Carone & Murayama (1995)

- Colliders: hadronic Z, dijet resonances, ...

Is it possible to discover light weakly-coupled forces hiding in nonperturbative QCD regime?
Theoretical constraints from anomalies

• $U(1)_B$ gauge symmetry is anomalous

• Requires introducing new electroweak fermions at mass scale $\Lambda$ to cancel the $(\text{electroweak})^2 \times U(1)_B$ anomalies

• Cannot have $\Lambda$ arbitrarily large. Typically* $m_B/\Lambda \gtrsim g_B/(4\pi)$

* but not always

• The absence of new fermions at colliders: $\Lambda > 100$ GeV

• Small gauge couplings: $g_B \lesssim 10^{-2} \times (m_B/100 \text{ MeV})$

$$\alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100 \text{ MeV})^2$$
Detecting the B boson

• Can a weakly-coupling force \((g_B \ll 1)\) be detected in the nonperturbative regime of QCD?

• B boson preserves the symmetries of QCD
  • Charge conjugation, parity, and isospin or \(SU(3)_{\text{flavor}}\)

• Previous lore:  *Nelson & Tetradis (1989)*
  • Above \(2m_\pi\), decay dominated by \(B \rightarrow \pi\pi\)
  • B boson buried under huge \(\rho \rightarrow \pi\pi\) background
Baryonic force at the QCD scale

- How are the gauge bosons produced?
- What are the experimental signatures?

Direct production:

Dark photon

\[ \text{electron} \rightarrow A' \rightarrow \ell^+ \ell^- \]

\[ \text{proton} \]

Meson decays:

\[ \eta \rightarrow A' \rightarrow \ell^+ \ell^- \]

\[ \gamma \]

B boson

\[ \text{electron} \rightarrow B \rightarrow ??? \]

\[ \gamma \]

\[ p \rightarrow \text{proton} \rightarrow p' \]
Baryonic force at the QCD scale

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Direct production:

Dark photon

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\[ \text{proton} \]

Meson decays:

\[ \eta \rightarrow A' \rightarrow \ell^+\ell^- \]

\[ \gamma \]
B bosons signals in meson factories

• How are B bosons produced?
  
  Focus on light mesons: \( \pi^0, \eta, \eta', \omega, \phi \)

• How do B bosons decay?
B bosons production

- How are B bosons produced in meson decays?

\[ \pi^0 \rightarrow B\gamma, \quad \eta \rightarrow B\gamma, \quad \eta' \rightarrow B\gamma, \quad \omega \rightarrow \eta B, \quad \phi \rightarrow \eta B \]

- Like Standard Model processes with \( \gamma \) replaced by B

\[ \pi^0 \rightarrow \gamma\gamma, \quad \eta \rightarrow \gamma\gamma, \quad \eta' \rightarrow \gamma\gamma, \quad \omega \rightarrow \eta\gamma, \quad \phi \rightarrow \eta\gamma \]

- Calculating the decay rate: take \( \eta \rightarrow B\gamma \) as an example

\[
\frac{\Gamma(\eta \rightarrow B\gamma)}{\Gamma(\eta \rightarrow \gamma\gamma)} = 2\frac{\alpha_B}{\alpha_{em}} \left(1 - \frac{m_B^2}{m_\eta^2}\right)^3 \left| \frac{1}{3} c_\theta - \frac{\sqrt{2}}{3} s_\theta \right| F_\omega(m_B^2) + \left(\frac{\sqrt{2}}{3} c_\theta + \frac{\sqrt{2}}{3} s_\theta \right) F_\phi(m_B^2) \left| c_\theta - 2\sqrt{2}s_\theta \right|^2
\]

\[\sim O(1)\]

- Ratio of gauge couplings
- Phase space
- Combinatorical factors and form factors (vector meson dominance)
  \( \theta = \eta - \eta' \) mixing angle
B bosons production

B production rate in meson decays relative to SM process (normalized to $\alpha_B = 1$)
B boson decay

How does B decay? Worry: $B \rightarrow \pi\pi$ is hopeless.

Recall the original Lagrangian: $\mathcal{L} = \frac{g_B}{3} \bar{q} \gamma^\mu q B_\mu$

The quantum numbers for B:

- $J = 1$
- $P = C = -$ 
- $l = 0$
- $G = -$
B boson decay

$B$ has same quantum numbers as the $\omega$ meson

$\omega(782)$

$\omega \rightarrow \pi\pi$ forbidden by G-parity (Isospin-violating $\rho$–$\omega$ mixing)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fraction ($\Gamma_i/\Gamma$)</th>
<th>Scale factor/Confidence level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_1$</td>
<td>$(89.2 \pm 0.7)%$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>$(8.28\pm0.28)%$</td>
<td>S=2.1</td>
</tr>
<tr>
<td>$\Gamma_3$</td>
<td>$(1.53\pm0.11)%$</td>
<td>S=1.2</td>
</tr>
<tr>
<td>$\Gamma_9$</td>
<td>$(7.28\pm0.14) \times 10^{-5}$</td>
<td>S=1.3</td>
</tr>
<tr>
<td>$\Gamma_{15}$</td>
<td>$(9.0 \pm 3.1 ) \times 10^{-5}$</td>
<td>CL=95%</td>
</tr>
<tr>
<td>$\Gamma_{16}$</td>
<td>$&lt; 1.9 \times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>
B boson decay

Expect B decays to be qualitatively similar to $\omega$ decays

- $B \rightarrow \pi\pi$ is forbidden by G-parity

- $m_B \sim m_\pi - 1$ GeV:
  - Dominated by $B \rightarrow \pi^0\gamma$ or $\pi^+\pi^-\pi^0$ (when allowed)
  - New signatures that are not being covered in dark photon searches

- $m_B < m_\pi$:
  - Dominated by $B \rightarrow e^+e^-$
  - Covered by dark photon searches

Leptonic couplings to B arise because B mixes with $\gamma$ through heavy quark loops
B is mostly leptophobic with a subleading (and model-dependent) lepton coupling
B boson decay

Hadronic decay rates calculated using vector meson dominance

+ permutations

Isospin-violating mixing
Not well-known away from $\omega$ pole
B boson branching ratios

Solid vs dashed shows model dependence of leptonic couplings due to B-γ mixing

Solid: \( \varepsilon = \frac{e g_B}{16 \pi^2} \)  
Dotted: \( \varepsilon = 0.1 \frac{e g_B}{16 \pi^2} \)
B boson signal channels

<table>
<thead>
<tr>
<th>Decay → Bγ</th>
<th>B → e⁺e⁻</th>
<th>B → π⁰γ</th>
<th>B → π⁺π⁻π⁰</th>
<th>B → ηγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>m_B ~ 1 – 140 MeV</td>
<td>140–620 MeV</td>
<td>620–1000 MeV</td>
<td></td>
</tr>
<tr>
<td>π⁰ → Bγ</td>
<td>π⁰ → e⁺e⁻γ</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>η → Bγ</td>
<td>η → e⁺e⁻γ</td>
<td>η → π⁰γγ</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>η' → Bγ</td>
<td>η' → e⁺e⁻γ</td>
<td>η' → π⁰γγ</td>
<td>η' → π⁺π⁻π⁰γ</td>
<td>η' → ηγγ</td>
</tr>
<tr>
<td>ω → ηB</td>
<td>ω → ηe⁺e⁻</td>
<td>ω → ηπ⁰γ</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>φ → ηB</td>
<td>φ → ηe⁺e⁻</td>
<td>φ → ηπ⁰γ</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Covered by dark photon searches
Limits are more model dependent

New signals not being covered in dark photon searches

A new type of signature for meson factories:
π⁰γ resonances in rare decays
B boson signal channels

<table>
<thead>
<tr>
<th>Decay →</th>
<th>( B \rightarrow e^+ e^- )</th>
<th>( B \rightarrow \pi^0 \gamma )</th>
<th>( B \rightarrow \pi^+ \pi^- \pi^0 )</th>
<th>( B \rightarrow \eta \gamma )</th>
</tr>
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<tr>
<td>( m_B \sim 1 - 140 \text{ MeV} )</td>
<td>( 140 - 620 \text{ MeV} )</td>
<td>( 620 - 1000 \text{ MeV} )</td>
<td>( \text{...} )</td>
<td></td>
</tr>
<tr>
<td>( \pi^0 \rightarrow B \gamma )</td>
<td>( \pi^0 \rightarrow e^+ e^- \gamma )</td>
<td>( \pi^0 \rightarrow e^+ e^- \gamma )</td>
<td>( \pi^0 \rightarrow \pi^0 \gamma \gamma )</td>
<td></td>
</tr>
<tr>
<td>( \eta \rightarrow B \gamma )</td>
<td>( \eta \rightarrow e^+ e^- \gamma )</td>
<td>( \eta \rightarrow e^+ e^- \gamma )</td>
<td>( \eta \rightarrow \pi^0 \gamma \gamma )</td>
<td></td>
</tr>
<tr>
<td>( \eta' \rightarrow B \gamma )</td>
<td>( \eta' \rightarrow e^+ e^- \gamma )</td>
<td>( \eta' \rightarrow e^+ e^- \gamma )</td>
<td>( \eta' \rightarrow \pi^0 \gamma \gamma )</td>
<td></td>
</tr>
<tr>
<td>( \omega \rightarrow \eta B )</td>
<td>( \omega \rightarrow \eta e^+ e^- )</td>
<td>( \omega \rightarrow \eta e^+ e^- )</td>
<td>( \omega \rightarrow \eta \pi^0 \gamma )</td>
<td></td>
</tr>
<tr>
<td>( \phi \rightarrow \eta B )</td>
<td>( \phi \rightarrow \eta e^+ e^- )</td>
<td>( \phi \rightarrow \eta e^+ e^- )</td>
<td>( \phi \rightarrow \eta \pi^0 \gamma )</td>
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Covered by dark photon searches
Limits are more model dependent

New signals not being covered in dark photon searches

A new type of signature for meson factories:
\( \pi^0 \gamma \) resonances in rare decays
\[ \eta \rightarrow \pi^0 \gamma \gamma \]

**Particle Data Book**

First measurement claimed at CERN, 1966.

Early history for this channel fraught with controversy (both experiment and theory).

Achasov et al (2001)

Active target of study as a probe of ChPT at $O(p^6)$ and QCD model predictions (using $m_{\gamma\gamma}$ invariant mass spectrum)

**Past and on-going:** GAMS, SND at VEPP-2M, Crystal Ball at AGS/MAMI, KLOE (prelim), WASA (prelim), ... 

**Future:** Jefferson Eta Factory, KLOE 2, ...

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<td>$\Gamma_1$ neutral modes</td>
<td>$(72.12 \pm 0.34)%$</td>
<td>S=1.2</td>
</tr>
<tr>
<td>$\Gamma_2$ $2\gamma$</td>
<td>$(39.41 \pm 0.20)%$</td>
<td>S=1.1</td>
</tr>
<tr>
<td>$\Gamma_3$ $3\pi^0$</td>
<td>$(32.68 \pm 0.23)%$</td>
<td>S=1.1</td>
</tr>
<tr>
<td>$\Gamma_4$ $\pi^0 2\gamma$</td>
<td>$(2.7 \pm 0.5) \times 10^{-4}$</td>
<td>S=1.1</td>
</tr>
</tbody>
</table>
\[ \eta \rightarrow \pi^0 \gamma \gamma \]

Target for Jefferson Eta Factory experiment in Hall D (upgrade for GlueX)

Upgraded PbWO\(_4\) forward calorimeter (FCAL-II)

Enhanced photon detection granularity for detecting multi-photon final states

More recent measurements vs time
η → π⁰γγ

B boson signature: η → Bγ → π⁰γγ mimics the rare SM decay η → π⁰γγ

\[ \frac{\Gamma(\eta \rightarrow B\gamma)}{\Gamma(\eta \rightarrow \gamma\gamma)} = 2 \frac{\alpha_B}{\alpha_{em}} \left(1 - \frac{m_B^2}{m_\eta^2}\right)^3 \times O(1) < \frac{\Gamma(\eta \rightarrow \pi^0\gamma\gamma)}{\Gamma(\eta \rightarrow \gamma\gamma)} \sim 10^{-3} \]

Requires \( \alpha_B < 10^{-5} \ll \alpha_{em} \)
$\eta \rightarrow \pi^0\gamma\gamma$

Kinematics: Boost sensitivity by searching for $\pi^0\gamma$ resonance in $\eta \rightarrow \pi^0\gamma\gamma$

Preliminary Monte Carlo study by JEF collaboration

www.jlab.org/exp_prog/proposals/13/PR12-13-004.pdf

Reconstruction of $m_B$ from $m(\pi^0\gamma)$

Acceptance fraction for a cut around $m_B$
\[ \eta \rightarrow \pi^0 \gamma \gamma \]

Kinematics: Boost sensitivity by searching for \( \pi^0 \gamma \) resonance in \( \eta \rightarrow \pi^0 \gamma \gamma \)

Preliminary Monte Carlo study by JEF collaboration

\( \eta \) decays sensitive to forces hidden in QCD up to \( 10^5 \) times weaker than electromagnetism.
$\phi \rightarrow \eta \pi^0 \gamma$

Active target of study for understanding QCD scalar resonances

$\phi \rightarrow a_0(980)^\ast \gamma \rightarrow \eta \pi^0 \gamma$

Achasov & Ivanchenko (1989)
\( \phi \rightarrow \eta \pi^0 \gamma \)

B boson signature: \( \phi \rightarrow \eta B \rightarrow \eta \pi^0 \gamma \) mimics the rare SM decay \( \phi \rightarrow \eta \pi^0 \gamma \)

\[
\frac{\Gamma(\phi \rightarrow \eta B)}{\Gamma(\phi \rightarrow \eta \gamma)} = \frac{\alpha_B}{\alpha_{em}} \frac{\lambda(m_\phi, m_\eta, m_B)^{3/2}}{\lambda(m_\phi, m_\eta, 0)^{3/2}} |F_\phi(m_B^2)|^2 < \frac{\Gamma(\phi \rightarrow \eta \pi^0 \gamma)}{\Gamma(\phi \rightarrow \eta \gamma)} \sim 1/200
\]

Requires \( \alpha_B < 5 \times 10^{-5} \ll \alpha_{em} \)

Significant improvements could be made by searching for a \( \pi^0 \gamma \) resonance in the \( \phi \rightarrow \eta \pi^0 \gamma \) events
Constraints on B boson

FIG. 2 (color online). Limits on baryonic gauge boson coupling $\alpha_B$ and mass $m_B$, for different values of kinetic mixing parameter $\epsilon$. Thick black contours are current exclusion limits from radiative light meson decays based on their total rate (assuming the QCD contribution is zero). Dashed gray contours illustrate the reach of possible future constraints at the level of $\text{BR}(\eta \rightarrow B\gamma \rightarrow \pi^0\gamma\gamma) < 3 \times 10^{-6}$ $[50]$, $\text{BR}(\eta' \rightarrow B\gamma \rightarrow \pi^+\pi^-\pi^0\gamma) < 10^{-4}$, and $\text{BR}(\eta' \rightarrow B\gamma \rightarrow \eta\gamma\gamma) < 10^{-4}$. Shaded regions are exclusion limits from low-energy n-Pb scattering and hadronic $Y(1S)$ decay. Hatched regions are excluded by $A'$ searches from KLOE $[58]$ and WASA $[57]$. $A'$ limits applied to $B$ are model dependent, constraining possible leptonic $B$ couplings. Limits shown here are for $\epsilon = \epsilon_g/(4\pi)^2$ (left plot) and $0.1 \times \epsilon_g/(4\pi)^2$ (right plot). Gray shaded regions show where $B$ has a macroscopic decay length $\epsilon\tau > 1$ cm. Dotted contours denote the upper bound on the mass scale $\Lambda$ for new electroweak fermions needed for anomaly cancellation, assuming $\Lambda \lesssim 4\pi m_B/\epsilon_g$. 
Conclusions

• New forces beyond the Standard Model:
  • Motivated by dark matter
  • Would be a game-changing particle physics discovery

• GeV-scale leptophobic forces are a blind spot to dark photon searches, but can be searched for in existing/future light meson factories

• Smoking gun signature: a $\pi^0\gamma$ resonance in rare meson decays.