Exotica Theory at LHCb

Implications of LHCb measurements and future prospects
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BSM exotics at LHCb

Exotics at B-factories. For BSM using B

Advantage compared to ATLAS/CMS or K-factories. Particularly for $O(1-20 \text{ GeV})$ new states.

In conventional final states ($e, \mu, \gamma, \text{had}$),
- Too light for ATLAS and CMS, trigger issues.
- Inaccessible at other precision experiments, BESIII($\sim J/\psi$), GlueX($\sim \eta$), KOTO($K_L$), NA62($K^+$), pion physics.

LHCb vs Belle II

Hadronic production is accessible at LHC
But actually Belle II could test the same particle differently.

[e.g. see talks by M. Santimaria, and by M. Borsato]
Example: Axion-like particles

Axion-like particles (ALPs): pseudo NG boson from global symmetry.

*Not well-defined term*. Here, couplings are similar to those of axion, but $m_a \sim 0.1\text{GeV}/f_a$ is NOT imposed. $m_a$ is a parameter.

**Couplings**

• If the lepton coupling is present, similar to dark photon search

\[ pp \rightarrow X \rightarrow \mu^+\mu^- \text{ or } e^+e^- \quad \text{[S. Knapen’s talk]} \]

• Assume leading couplings are from gauge bosons.
  Coupling to gluon: necessary to address *Strong CP problem*.
  Photon coupling: induced at IR or from UV. expected to be in the same order

\[
\text{EFT} \quad \frac{a}{4\pi f_a} \left[ \alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B} \right] + \text{mass term}
\]

Since $m_Z/W \gg m_a$, basically photon and gluon couplings.
10MeV-10GeV is poorly explored

Theoretical Challenge

Standard Axion

Astro, Cosmology

Beam dump

K+ K
L
invisible

K+ K
Pion

K+ K
L

GlueX

Pion

Babar

LHCb

LHC

Diphoton

LHC Standard Resonance Search

LHC Diphoton cross section

$c_3 \neq 0, a \rightarrow \gamma \gamma, \text{ hadrons}$

If photon coupling is enhanced, heavy-ion collision gives a bound for $m_a \sim 10 \text{GeV}$.

[1607.06083, 1709.07110 S. Knapen, T. Lin, H. K. Lou, T. Melia]

For K bounds, see 2005.05170 S. Gori, G. Perez, KT

Kohsaku Tobioka (FSU)
Search channels at ATLA, CMS

- Diphoton at ATLAS, CMS require $p_T > 40,30\,\text{GeV}, \Delta R_{\gamma\gamma} > 0.4$

\[
m_{\gamma\gamma} > \Delta R \cdot \sqrt{p_{T1}^{\text{min}} p_{T2}^{\text{min}}} \sim 13\,\text{GeV}
\]

- Use mono-trigger with ISR. Need good resolution for $\Delta R_{\gamma\gamma}$.
• At LHCb, simply lower $p_{T\gamma}$ threshold, e.g. $B_s \rightarrow \gamma\gamma$ search

\begin{align*}
A : & \quad 2 < \eta(\gamma) < 5 \\
& \quad E_T(\gamma) > 3.5 \text{ GeV}, \\
\epsilon : & \quad E_{T1}^\gamma + E_{T2}^\gamma > 8 \text{ GeV} \\
& \quad p_T(\gamma_1\gamma_2) > 2 \text{ GeV}
\end{align*}

ALP motivated study moving forward
LHCb 1906.09058

• At Belle II (Babar), produced by $\gamma$ coupling, and decay by $g$ coupling

applicable to $m_a > 2 \text{ GeV}$
[1810.09452] X. Cid Vidal, A. Mariotti, D. Redigolo, F. Sala, KT thanks to LHCb photon experts: S. Benson and A. Puig Navarro
The gluon coupling can be exploited at LHCb, which already allows for a diphoton resonance. The production channel currently has a sensitivity down to masses as low as 2 GeV and constitutes a new range between 4.9 and 6.3 GeV, motivating a dedicated study. This production channel is a strong probe for ALPs in the mass range considered here. If the SM fermions and the Higgs doublet are uncharged under PQ symmetry and carrying a U(1) symmetry, the couplings of the pNGB to them arise from interactions between the pNGBs and the SM-EW states, expected to have masses of order 400 GeV.

In the NP sector, the strength of the interaction can be modified changing the SM representation. Note that this holds even if the NP sector inducing the new phase is in general not aligned with the PQ origin, jeopardizing the solution to the strong CP problem. Taking the width into gluons dominates over the one into photons, unless a non-generic hierarchy of couplings is assumed.

Heavy axions can be exploited at LHCb, which already allows for a diphoton resonance. The production channel currently has a sensitivity down to masses as low as 2 GeV and constitutes a new range between 4.9 and 6.3 GeV, motivating a dedicated study.

In this section, we expand on the two theory lines discussed in Sec. III. We would like to motivate: 1) the couplings of the axion to gluons and photons, 2) the TeV marks motivated by heavy QCD axion models and by ALP-portal Dark Matter described in Sec. III.

The ALP coupling to be within the reach of the LHC. Heavy axions can be exploited at LHCb, which already allows for a diphoton resonance. The production channel currently has a sensitivity down to masses as low as 2 GeV and constitutes a new range between 4.9 and 6.3 GeV, motivating a dedicated study.

LHCb can cover unexplored region

\[ c_1 = c_2 \rightarrow Z \text{ coupling} \]

\[ N = c_3, \quad E = c_2 + 5c_1/3 \]

\[ \mathcal{L}_{\text{eff}} \supset \frac{N\alpha_3}{4\pi} a G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{E\alpha_{\text{em}}}{4\pi} a F_{\mu\nu}\tilde{F}^{\mu\nu} \]
Change photon/gluon ratio

\[ E / f [\text{1/GeV}] \]

\[ 10^0 \]

\[ 10^{-1} \]

\[ 10^{-2} \]

\[ 10^{-3} \]

\[ 10^{-4} \]

\[ N / f [\text{1/GeV}] \]

\[ 10^{-4} \]

\[ 10^{-3} \]

\[ 10^{-2} \]

\[ 10^{-1} \]

\[ 10^0 \]

\[ m_a = 15 \text{ GeV} \]

\[ \text{ATLAS: } Z \rightarrow \gamma a(\gamma\gamma) \]

\[ \text{ATLAS/CMS 20 fb}^{-1} \]

\[ \text{LHCb 300 fb}^{-1} \]

\[ \text{ATLAS/CMS sens. 20 fb}^{-1} \]

\[ \text{Heavy ion 10 nb}^{-1} \]

\[ \text{Heavy ion} \]

\[ \text{LHCb can cover unexplored region} \]

assume current diphoton triggers at ATLAS&CMS

\[ c_1 = c_2 \rightarrow Z \text{ coupling} \]

\[ N = c_3, \quad E = c_2 + 5c_1/3 \]

\[ \mathcal{L}_{\text{eff}} \supset \frac{N \alpha_3}{4\pi} \frac{a}{f} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{E \alpha_{\text{em}}}{4\pi} \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu} \]
More hadronic case for $m_\eta<m_a<3\text{GeV}$

Production estimate for $B\rightarrow K\alpha (b\rightarrow sa)$ @2-loop

[0911.4938, B. Batell, M. Pospelov, A. Ritz]

Hadronic decays, data driven approach
[1811.03474, D. Aloni, Y. Soreq, M. Williams]

Babar/Belle studied
[0804.0411, 1311.6666]

$B\rightarrow K\pi\pi\pi, K\eta\pi\pi, KK\bar{K}\pi, K\phi\phi$
More hadronic case for $m_\eta<m_a<3\text{GeV}$

$\frac{c_\eta}{\Lambda} [\text{GeV}^{-1}]$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-5}$

$10^{-6}$

$m_a$ [GeV]

$m_\eta$

$m_\eta'$

$B \to K a(KK\pi)$

$B \to K a(3\pi)$

$B \to K a(\phi\phi)$

$m_\eta\pi$ & $m_{KK\pi}$ windows

$LHCb/Belle II$

gray constraints depend on UV completion
results shown assume $UV \approx \log\frac{\Lambda_{\text{UV}}^2}{m_a^2} \pm \mathcal{O}(1) \Rightarrow 1$

[1811.03474, D. Aloni, Y. Soreq, M. Williams]
Summary and Prospects

• LHCb has unique opportunities for exotic resonances.

• Fill the gap between ATLAS/CMS and other flavor exes.

• Axion-like particles with gluon coupling
  - well-motivated example
  - can be produced at LHC(b)
  - LHCb will give the best sensitivities for O(2-20GeV).

• $X \rightarrow$ diphoton, hadronic final states will be interesting addition to on-going search programs.
Backup
Theory perspectives for ALPs

• Consider an ALP with \( \frac{\alpha_s}{8\pi F_a} aG\tilde{G} \) for the strong CP problem

• PQ quality problem:
  Global symmetry is not robust. The ALP potential ruined even by gravity.

• Large \( m_a \) and small \( f_a \) are favored

\[
V(a) = m_a^2 F_a^2 \left\{ 1 - \cos \left( \frac{a}{F_a} \right) \right\} + \frac{F_a^2}{\Lambda_{UV}^{D-4}} \cos \left( \frac{a}{F_a} + \Delta \right)
\]

\[\rightarrow \delta\theta = \frac{\delta a_{\min}}{F_a} \sim \frac{F_a^{D-2}}{m_a^2 \Lambda_{UV}^{D-4}},\]

[S. M. Barr, D. Seckel (’92); M. Kamionkowski, J. March-Russell (’92)]

• Models
  Mirror QCD (QCD’x Z₂)
  \( m_a \gg 0.1 \text{GeV}/f_a \)

[V. Rubakov (’97);...Fukuda, K. Harigaya, M. Ibe, T. T. Yanagida(’15);
S. Dimopoulos, A. Hook, J. Huang, G. Marques-Tavares(’16),
P. Agrawal, K. Howe(’17)]

• Important to search for exotics colored states, \( m \sim 4\pi f_a \)