Searching for new spin-0 resonances at LHCb

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mostly based on arXiv:1601.05110
with Uli Haisch
Motivation

Scalar particles ⇔ symmetry breaking

- Examples: pions, Higgs, **axions**, dilaton...
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Portals to dark sectors (possibly including DM)

- Example: FERMI-LAT 1GeV excess

![Graph showing the spectrum of gamma rays from Fermi-LAT, with an excess at a few GeV. The graph includes blue dotted lines and yellow boxes representing data points and error envelopes, with a logarithmic scale on the x-axis for energy (E in GeV) and a linear scale on the y-axis for the differential number of events (dN/dE). The graph is labeled with references to Calore et al., 1409.0042.](attachment:fermi-lat-datepicker-0042.png)
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\[
\mathcal{L} \supset -ig_{\text{DM}} a \bar{\chi} \gamma^5 \chi - ig_{\text{SM}} \sum_q \frac{m_q}{v} a \bar{q} \gamma^5 q
\]

\[
g_{\text{SM}} = 1, \quad m_{\chi} = 45 \text{ GeV}
\]
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Couplings to SM fermions break flavor - existing FCNC constraints imply special structure (~MFV, U(2))

- Examples: Higgs-singlet mixing, THDM I,II,X...
Scalar resonance searches at LHC

Decays to SM final states:

\[ m_a \approx 350 \text{GeV}: \, tt \text{ resonances (challenging)} \]

Gori et al., 1602.02782
Carena & Liu, 1608.07282
Craig et al., 1605.08744
Scalar resonance searches at LHC

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\[ m_a \gtrapprox 350 \text{GeV}: \text{tt resonances (challenging)} \]

\[ 50 \text{GeV} \lessapprox m_a \lessapprox 350 \text{GeV}: \text{di-photon searches} \]
Scalar resonance searches at LHC

Decays to SM final states:

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\[ 50 \text{GeV} \lesssim m_a \lesssim 350 \text{GeV}: \; \text{di-photon searches} \]

\[ m_a \lesssim 10 \text{GeV}: \; \text{rare quarkonium, meson decays,} \ldots \]
Scalar resonance searches at LHC

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\[ 50 \text{GeV} \lesssim m_a \lesssim 350 \text{GeV}: \text{di-photon searches} \]

\[ m_a \lesssim 10 \text{GeV}: \text{rare quarkonium, meson decays,...} \]

\[ 10 \text{GeV} \lesssim m_a \lesssim 50 \text{GeV} \text{ region poorly constrained!} \]

(Far future: 4t, 2t2b searches)
Scalar resonance searches at LHC

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(Far future: 4\text{t}, 2\text{t}2\text{b} searches)

Mono-\((b, t, \ldots)\)-jets, Higgs - probe decays to hidden sector
Can LHCb add something?

LHCb detector has excellent invariant-mass & vertex resolution as well as unique particle-identification & real-time data-analysis capabilities.

These features allow to probe unexplored new-physics territory via dimuon searches:

- Hidden-sector bosons in $B \rightarrow K^* \mu^+ \mu^-$
  [Freytsis et al., 0911.5355; LHCb, 1508.04094]
- Light spin-0 s-channel mediators
  [Haisch & J.F.K., 1601.05110]
- Dark photons through $A' \rightarrow \mu^+ \mu^-$
  [Ilten et al., 1603.08926]
Precision measurement of dimuon spectrum for invariant masses in the $\Upsilon$ region with only 3% of 8 TeV data set.
Bound on $\sigma_{\text{fid}}(pp \rightarrow \phi) \cdot \text{Br}(\phi \rightarrow \mu^+\mu^-)$

**Signal**: light spin-0 dimuon resonance $\phi$

**Acceptances**: $A = 0.23$ for $|\eta| \in [2, 4.5] \& p_T < 30$ GeV independent of $\phi$ mass; final acceptance $A_f$ in $|\eta| \in [3, 3.5] \& p_T \in [3, 4]$ GeV depends mildly on $m_\phi$

**Recast**: inject $\phi$ signal & refit LHCb data on $\Upsilon$ production

\[ \sigma_{\text{fid}}(pp \rightarrow \phi) \cdot \text{Br}(\phi \rightarrow \mu^+\mu^-) \]
Consider bottomonium pseudoscalar production in NRQCD

\[
\sigma(pp \rightarrow \eta_b(n)) = (391^{+174}_{-68}) |R_{\eta_b(n)}(0)|^2 \frac{\text{nb}}{\text{GeV}^3}
\]

From bound on \(\sigma(pp \rightarrow \phi) \cdot \text{Br}(\phi \rightarrow \mu\mu)\), one finds

\[
\text{Br}(\eta_b(1) \rightarrow \mu^+\mu^-) < \frac{38.4\text{ pb}}{\sigma(pp \rightarrow \eta_b(1)) A} = 1.9 \cdot 10^{-4}
\]

- factor of 50 better than current PDG bound
- SM dimuon \(\eta_b\) branching ratios of \(O(10^{-10})\)

[Similar results for scalar \(\chi_b(n)\) states.]
Example BSM application

Pseudoscalar $P$ with Higgs-like couplings to fermions

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} (\partial P)^2 - \frac{1}{2} m_P^2 P^2 - \sum_f \frac{m_f}{v} i \kappa_f P f \gamma_5 f \]

- Avoids flavour & CPV constraints by construction (MFV).
- Couplings to $WW$ or $ZZ$ loop suppressed.
- Interactions with SM Higgs depend on potential details.

Restrict analysis to couplings of $P$ to fermions

[Discussion restricted to pseudoscalar $P$; analogous results for scalar $S$]
For $m_P \approx 10$ GeV & $\kappa_f = 1$ cross sections of $O(10 \text{nb}, 20 \text{nb})$ at 8 TeV, 13 TeV.

Production via bottom-quark annihilation negligible.
For $|\kappa_P| = O(1)$, total decay width of $P$ below 1 MeV.
Dimuon branching ratios of $2 \cdot 10^{-3}$ ($3 \cdot 10^{-4}$) below (above) $b\bar{b}$ threshold
Mass-mixing of \( P \) with \( \eta_b(n) \)

Since \( P \) & \( \eta_b(n) \) carry the same quantum numbers, the states can mix:

\[
\delta m^2_{P\eta_b(n)} = \kappa_P^b \sqrt{\frac{3}{4\pi\upsilon^2_m}} m_{\eta_b(n)}^3 |R_{\eta_b(n)}(0)|
\]

Effects most pronounced if \( P \) & \( \eta_b(n) \) are mass degenerate.

Interference pattern arising from mass-mixing depends on sign of couplings \( \kappa_P \). To illustrate model dependence consider both cases.

Close to bottom threshold \( P \) decays to \( B^* B \) via P-wave. This suppresses (enhances) dibottom (dimuon) rate of \( P \).
Constraints on universal $\kappa_P$

For $m_P \in [8.6, 11.5]$ GeV recast of LHCb $\Upsilon$ data allows to set first $O(1)$ limits on $|\kappa_P|$. Above 11.5 GeV CMS low-mass dimuon search superior.
Constraints on THDM II

Can also set limits on pseudoscalar $A$ within decoupling limit of THDMII:

$$\mathcal{L} \supset \frac{1}{2} (\partial A)^2 - \frac{1}{2} m_A^2 - \sum_f \frac{m_f}{v} i \kappa_A^f A \bar{f} \gamma_5 f$$

$$\kappa_{e,\mu,\tau,d,s,b}^e = \tan \beta$$

$$\kappa_{u,c,t}^u = \cot \beta$$

LHCb provides best bound for $m_A \in [8.6, 11] \text{ GeV}$. Mass region $[11, 11.5] \text{ GeV}$ remains unconstrained, due to strong mixing effects.
Conclusions & outlook

- Efficient triggering & excellent invariant mass resolution of LHCb allow to test unexplored parameter space in simplified models of spin-0 di-muon resonances
- Dedicated LHCb analysis of full Run I data set is expected to significantly improve shown limits, can be extended to larger invariant masses.
- May also be possible to search for spin-0 resonances in exclusive invariant mass spectra of heavy flavoured hadrons ($D^+D^-$, $B^+B^-$,…)
- Feasibility of di-tau, di-photon searches at LHCb?
Backup
Masses of $\eta_b(n)$ $\chi_b(n)$ states given in units of GeV and corresponding values of radial wave functions at the origin (their derivatives) in units of GeV$^{3/2}$ (GeV$^{5/2}$)