Implications of LHCb measurements and future prospects

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)

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\[
\mathcal{L} \supset -ig_{\text{DM}} a \bar{\chi} \gamma^5 \chi - ig_{\text{SM}} \sum_q \frac{m_q}{v} a \bar{q} \gamma^5 q
\]

\[g_{\text{SM}} = 1, m_\chi = 45 \text{ GeV}\]
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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:

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

\[ gg \to t\bar{t} \]
\[ m_t = 170 \text{ GeV} \]

Dicus et al., hep-ph/9404359
Scalar resonance searches at LHC

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

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

(Far future: \(4t, \; 2t2b\) searches)

Gori et al., 1602.02782
Carena & Liu, 1608.07282
Craig et al., 1605.08744
Goncalves & Lopez-Val, 1607.08614
Scalar resonance searches at LHC

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- $m_a \gtrsim 350\text{GeV}$
- $50\text{GeV} \lesssim m_a \lesssim 350\text{GeV}$: di-photon searches
- $m_a \lesssim 10\text{GeV}$: rare quarkonium, meson decays, …
- $10\text{GeV} \lesssim m_a \lesssim 50\text{GeV}$ region poorly constrained!

(Far future: 4t, 2t)$^2$b searches

Mono-($b,t,...$)-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 on the LHCb experiment.
Bound on $\sigma_{\text{fid}}(pp \to \phi) \cdot \text{Br}(\phi \to \mu^+\mu^-)$

**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
Example SM application

Consider bottomonium pseudoscalar production in NRQCD

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

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

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

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

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

Pseudoscalar $P$ with Higgs-like couplings to fermions

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

- 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 & $\kappa_\perp = 1$ 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) $bb$ threshold.
Mass-mixing of $P$ with $\eta_b(n)$

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

$$\delta m_{P\eta_b(n)}^2 = \kappa_P^b \sqrt{\frac{3}{4\pi v^2} m_{\eta_b(n)}^3} |R_{\eta_b(n)}(0)|$$

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 $P$. 

Drees & Hikasa, PRD 41, 1547 (1990); Baumgart & Katz, 1204.6032
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:

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

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

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

LHCb provides best bound for $m_A \in [8.6, 11]$ GeV. Mass region $[11,11.5]$ 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
Bottomonium parameters

|       | $m_{\eta_b(n)}$ | $|R_{\eta_b(n)}(0)|$ | $m_{\chi_b(n)}$ | $|R'_{\chi_b(n)}(0)|$ |
|-------|----------------|---------------------|----------------|---------------------|
| $n = 1$ | 9.4            | 2.71 ± 0.07         | 9.86           | 1.28 ± 0.11         |
| $n = 2$ | 10.0           | 1.92 ± 0.11         | 10.23          | 1.34 ± 0.15         |
| $n = 3$ | 10.3           | 1.66 ± 0.11         | 10.51          | 1.36 ± 0.20         |
| $n = 4$ | 10.6           | 1.43 ± 0.09         | —              | —                   |
| $n = 5$ | 10.85          | 1.42 ± 0.53         | —              | —                   |
| $n = 6$ | 11.0           | 0.91 ± 0.17         | —              | —                   |

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 $\text{GeV}^{3/2}$ ($\text{GeV}^{5/2}$)