Searches for long lived particles at LHCb

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Outline

- LHCb for long lived particles
- Searches for Majorana neutrinos
- Search for long-lived particles decaying to jet pairs
- Search for hidden-sector bosons in $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays
Flavour as a tool for discovery

Known physics

Energy Frontier
SUSY, extra dim.
Composite Higgs
⇒ LHC, FHC

Intensity Frontier
Hidden Sector
⇒ Fixed target facility

Unknown physics

Energy scale

Interaction strength
Flavour as a tool for discovery

Between the intensity and energy frontiers there is the flavour land which rather than a frontier can be viewed as a tool to jump at the frontiers
The LHCb experiment

Large Hadron Collider as flavour factory

- \( pp \) collisions at 7-8-13 TeV
- Large \( b \)-quark production in the forward region
- Full \( b \)-hadrons spectrum
- \( \mathcal{L} = 3 \cdot 4 \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1} \)
- \( \int \mathcal{L} = 3.0 \text{fb}^{-1} \) in Run I \( \Rightarrow \mathcal{O}(10^{12}) \ b \bar{b} \) pairs

LHCb:

- Specialized B-physics experiment
- Forward single arm spectrometer
- Acceptance: \( 2 < \eta < 5 \)
Excellent vertex and IP resolution

- $\sigma(IP) \simeq 24\,\mu m$ at $p_T = 2$ GeV/c
- $\sigma_{BV} \simeq 16\,\mu m$ in $x, y$

Very good momentum resolution

- $\sigma(p)/p = 0.5\% - 0.8\%$
  for $p \in (0, 100)$ GeV/c
- $\sigma(m_B) \sim 25$ MeV for two body decays

Muon identification

- $\epsilon_\mu = 98\%, \epsilon_{\pi \rightarrow \mu} = 0.6\%, \epsilon_{K \rightarrow \mu} = 0.3\%$
- $\epsilon_{p \rightarrow \mu} = 0.3\%$

Trigger

- $\epsilon_\mu = 90\%$

How long lived?

- Less than 1 meter of decay length for particles reconstructed with long tracks
- Up to about 2 meters for downstream tracks
- Sensitivity to lifetimes of the order of nanoseconds

Example: $K^+ \rightarrow \pi^+\pi^-\pi^+$ decay reconstructed with downstream tracks.
Search for Majorana neutrinos at LHCb: $B^- \rightarrow \pi^+\mu^-\mu^-$

- Search for Majorana neutrinos $B^- \rightarrow \mu^-N(\rightarrow \mu\pi)$
- Short and detached topologies (up to 1000 ps)
- No excess in the $B$ mass: $\mathcal{B}(B^- \rightarrow \pi^+\mu^-\mu^-) < 4.0 \cdot 10^{-9}$ (95%CL)

![Diagram showing the decay process $B^- \rightarrow \pi^+\mu^-\mu^-$]
Search for Majorana neutrinos at LHCb: $B^- \rightarrow \pi^+ \mu^- \mu^-$

- Upper limit with CLs method
- Efficiency varies depending on $\tau_N$
- Different upper limits as a function of $\tau_N$
Search for Majorana neutrinos at LHCb: $B^- \rightarrow \pi^+ \mu^- \mu^-$

- Upper limits on a fourth generation neutrino coupling $|V_{\mu4}|$
- Model dependent limit versus $m_N$

$$B(B^- \rightarrow \pi^+ \mu^- \mu^-) = \frac{G_F^2 f_B^2 f_{\pi}^2 m_B^5}{128 \pi^2 \hbar} |V_{ub}V_{ud}|^2 \tau_B (1 - \frac{m_N^2}{m_B^2}) \frac{m_N}{\Gamma_N} |V_{\mu4}|^4$$

Total width parametrised as:
$$\Gamma_N = f(m_N) \times |V_{\mu4}|^2$$
Search for Majorana neutrinos at LHCb: $D_{(s)}^+ \rightarrow \pi^- \mu^+ \mu^+$

- Search for non-resonant $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^-$ (FCNC)
- and LFV $D_{(s)}^+ \rightarrow \pi^- \mu^+ \mu^+$ decays (Majorana neutrinos?)
- $\mathcal{L} = 1\text{fb}^{-1}$ at $\sqrt{s} = 7$ TeV
- Normalise to $D_{(s)}^+ \rightarrow \phi(\rightarrow \mu\mu)\pi^+$
- No displacement allowed in this case

![Diagram of particle decay processes]
Search for Majorana neutrinos at LHCb: $D^+_s \rightarrow \pi^- \mu^+ \mu^+$

No signal observed, limit at 90%CL:

for FCNC:

\[
\mathcal{B}(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 7.3 \times 10^{-8}
\]

\[
\mathcal{B}(D^+_s \rightarrow \pi^+ \mu^+ \mu^-) < 4.1 \times 10^{-7}
\]

for LFV:

\[
\mathcal{B}(D^+ \rightarrow \pi^- \mu^+ \mu^+) < 2.2 \times 10^{-8}
\]

\[
\mathcal{B}(D^+_s \rightarrow \pi^- \mu^+ \mu^+) < 1.1 \times 10^{-8}
\]

Limits for different $m_{\pi \mu}$ also set
Search for long-lived particles decaying to jet pairs

Motivation

- Some SUSY models with long-lived neutralinos:
  \[ h^0 \rightarrow \chi\chi, \chi \rightarrow 3 \text{quarks} \]

- Some Hidden Valley models
  \[ h^0 \rightarrow \pi_V\pi_V, \text{with } \pi_V \rightarrow b\bar{b} \]
Search for long-lived particles decaying to jet pairs

- Experimentally:
  a pair of jets coming from same vertex, displaced from the primary vertex
  (the second particle is undetected)
- Complementary phase space to other experiments
Search for long-lived particles decaying to jet pairs

- Jets reconstructed with particle flow
- Exploited 0.62 fb$^{-1}$ at 7 TeV
- Search in reconstructed mass and radial distance from the beam
- Limits for different $\pi_V$ masses and lifetimes

\[
\sigma(H) \times B(H \to \pi_V\pi_V) \text{ [pb]}
\]

\[
LHCb
\]

\[
\begin{align*}
\times m_{\pi_V} &= 25 \text{ GeV/c}^2 & \star m_{\pi_V} &= 50 \text{ GeV/c}^2 \\
+ m_{\pi_V} &= 35 \text{ GeV/c}^2 & \diamond m_{\pi_V} &= 35 \text{ GeV/c}^2, \pi_V \to c\bar{c} \\
\circ m_{\pi_V} &= 43 \text{ GeV/c}^2 & \square m_{\pi_V} &= 35 \text{ GeV/c}^2, \pi_V \to s\bar{s}
\end{align*}
\]
Search for hidden-sector bosons in $B^0_d \rightarrow K^* \mu^+ \mu^-$ decays

- Search for $B^0_d \rightarrow K^* \chi$ with $\chi \rightarrow \mu \mu$
- Both prompt and displaced events searched for
- Standard selection
- Narrow resonances vetoed, others handled within profile likelihood
- Scan in mass and lifetime of $\chi$
- Normalization to $B^0_d \rightarrow K^* \mu^+ \mu^-$
- Limits with scan in mass

(JINST 10 (2015) P06002)
Search for hidden-sector bosons in $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays

Limits set assuming spin = 0 for the hidden boson
Limits for different spin assumptions also provided
Search for hidden-sector bosons in $B_{d}^{0} \rightarrow K^{*}\mu^{+}\mu^{-}$ decays

Constrains on an

- Axion model (Freytsis et al. Phys.Rev.D81 034001 2010)
Where do we go from here?

- Data-taking restarted at 13 TeV
- About double cross-section for $b$ and $c$ hadrons
- LHCb will accumulate in Run II about 5 fb$^{-1}$
- LHCb Upgrade will improve the detector and collect higher luminosities (Run III about 15 fb$^{-1}$, for the full dataset $> 50$ fb$^{-1}$ are expected)

- Extrapolation of $B^0_d \rightarrow K^* \chi(\mu^+ \mu^-)$
- Limit on scalar mixing angle
- Addition of downstream $\mu\mu$ pairs
Conclusions and outlook

- LHCb has competitive performances for long-lived particles
- Long lived particles also studied with jets, complementary phase space to GPD
- Searches for Majorana neutrinos and dark bosons put world best limits
- Many new searches on their way with Run I data
- Run II data has improved trigger and larger cross-sections
Additional material