Search for hidden-sector bosons in $B^0 \rightarrow K^{*0} \chi (\rightarrow \mu^+ \mu^-)$ decays

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Introduction

• Lack evidence for dark matter and various cosmic ray anomalies → renewed interest in “hidden sector theories”

• Hidden sector particles singlets wrt Standard Model gauge interactions → very weak interactions
  – Can still get production (and decay) of hidden-sector particle, \( \chi \), by mixing hidden sector particle with some SM “portal particle” e.g. \( H, Z, \gamma, \nu \)

• Previous searches made at a wide range of experiments
  – Stringent constraints on hidden-sector \( \gamma \) and \( \nu \) portals
  – Significantly weaker constraints on axial-vector and scalar portals
The $B^0 \to K^{*0} \chi(\to \mu^+ \mu^-)$ final state lends itself well to searches for $\chi$ bosons with $\chi \to \mu^+ \mu^-$

- $b \to s$ transition mediated by top quark loop – enhanced sensitivity to $\chi$ with large top coupling e.g. via mixing with the Higgs sector
- $K^{*0} \to K^+ \pi^-$ gives entirely charged final state and helps with vertex reconstruction
- Can reduce backgrounds to a low level
- Mass range accessible $2m(\mu) < m(\chi) < m(B^0)-m(K^{*0})$
- Can search for long-lived $\chi$, giving displaced $\mu^+ \mu^-$
Search Strategy

• Blind analysis

• Scan $m_{\text{test}}$ in steps of $\frac{1}{2} \sigma m(\mu^+\mu^-)$

• Constrain $m(K^+\pi^-\mu^+\mu^-)$ to the known $B^0$ mass
  → improves $m(\mu^+\mu^-)$ resoln to 1-7 MeV

• Signal region,
  \[ |m(\mu^+\mu^-) - m(\chi)| < 2\sigma m(\mu^+\mu^-) \]

• Background region $> 3\sigma$ from $m(\chi)$

• Wide resonances have no impact

• Narrow resonances ($\omega$, $\phi$, $J/\psi$, $\psi(2S)$ and $\psi(3770)$) vetoed
Search Strategy

- At each $m_{\text{test}}$ form test statistic, profile likelihood ratio of hypotheses with and without a signal.

- Consider two regions of dimuon lifetime, $\sigma \tau(m_{\text{test}})$ (0.2-1ps)
  - Prompt region: $|\tau(\mu^+\mu^-)| < 3\sigma [\tau(\mu^+\mu^-)]$
  - Displaced region: $|\tau(\mu^+\mu^-)| > 3\sigma [\tau(\mu^+\mu^-)]$

Likelihood formed from product – no assumption made about $\tau(\chi)$

- Fraction of toys that have a minimum local p-value less than value observed in data used to compute global p-value.

[JINST 10 (2015) P06002]
Selection and normalisation

- Use multivariate analysis to reduce backgrounds – uBoost technique gives response that is nearly independent of $\tau(\chi)$ [JINST 8 (2013) P12013]

- Measure $B(B^0 \rightarrow K^0\chi(\rightarrow \mu^+\mu^-))$ relative to $B(B^0 \rightarrow K^0\mu^+\mu^-)$
  - Use prompt region with $1.1 < m^2(\mu^+\mu^-) < 6.0$ GeV$^2$
Unblinded results

- Unblinded $m(\mu^+\mu^-)$ (for candidates in the B mass window)

  - Most significant local excess occurs for $m(\chi) = 253 \text{ MeV}$ – in prompt region 11 candidates are seen with 6.2 expected
  - $p$-value of the no-signal hypothesis is 80% $\rightarrow$ no dark boson!
Branching fraction limits

• Spin of $\chi$ determines angular distribution and hence signal efficiency
  – Set upper limits assuming spin-zero. For $\tau(\chi)<10\text{ps}$: $0.005-0.050$
  – For spin-one, limits would be 10-20% better

• Limits become less stringent for $\tau(\chi)>10\text{ps}$ as $\chi$ would not decay in VELO

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$B(B^0 \rightarrow K^{*0}\chi(\mu^+\mu^-))$

[LHCb]


- Most stringent constraints to date on many theories that predict the existence of additional low-mass bosons
Constraints on models

• Use limits to look at regions excluded for two example models
    • MSSM-like two Higgs doublet model with axion-like particles
    • Limits general but, for ease of presentation, show in limit of large ratio of Higgs-doublet vacuum expectation values, $\tan\beta > 3$, for charged-Higgs masses $m(h) = 1$ and 10 TeV

Constraints on models

• Use limits to look at regions excluded for two example models
    • Hypothesizes that a scalar field $\chi$ was responsible for inflation of the early Universe and may have generated the baryon asymmetry
    • Associated “inflaton” particle expected to have mass $270 < m(\chi) < 1800$ MeV

The Future

- New data has ~double cross-section for b- and c-hadrons
- Can add “downstream” $\mu^+\mu^-$ candidates
- Hope to accumulate 5fb$^{-1}$ during Run-II and then use upgraded detector to accumulate 15fb$^{-1}$ during Run-III
- Extrapolate limit on scalar mixing angle
Other channels

- Previous searches for Majorana neutrinos
  - $B^- \rightarrow \pi^+\mu^+\mu^-$ [Phys. Rev. Lett. 112 (2014) 131802]
  - $D^-_{(s)} \rightarrow \pi^+\mu^+\mu^-$ [Phys. Lett. B 724 (2013) 203]

will be updated – working to improve techniques

- Also investigating our sensitivity to the Hyper CP anomaly: 3 muon events around 214 MeV in $\Sigma^+ \rightarrow p\mu^+\mu^-$

[HyperCP, PRL 94 (2005) 021801]
Conclusions

• Search for dark bosons, $\chi$, in $B^0 \rightarrow K^{*0} \chi(\rightarrow \mu^+ \mu^-)$ decays
  – Sensitive to both prompt and displaced $\chi$
  – No evidence for any dark boson seen
  – Set limits on $B(B^0 \rightarrow K^{*0} \chi(\rightarrow \mu^+ \mu^-))$ at
    
    $<10^{-9}$ level for $\tau=0\text{ps}$
    $<10^{-7}$ level for $\tau=1000\text{ps}$

• Most stringent constraints to date on many theories that predict the existence of additional low-mass bosons

• Searches statistically limited, will improve with new data
Backup