

Searches for low mass dark bosons

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EPS-HEP 2015, Vienna, 22-29 July 2015



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Motivation

- The Higgs discovered in 2012 at LHC is consistent with a SM Higgs boson
 - but it could still have non SM properties (coupling to exotic particles)
- There is a long list of theoretical models that predict the existence of new particles that couple to the SM sector by mixing with the Higgs

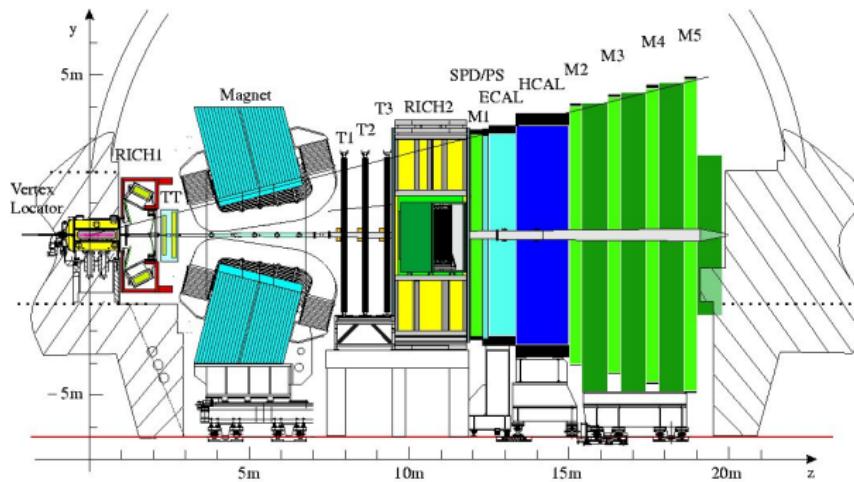


$$\begin{pmatrix} H \\ \chi \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} H' \\ \chi' \end{pmatrix}$$

H -----  ----- χ

- Inflaton, axion-like, dark matter mediator models also predict the new boson to be light.

The LHCb detector



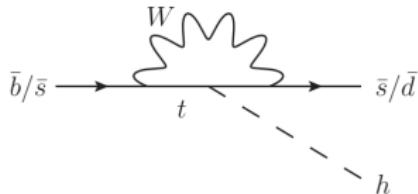
3 fb^{-1} of collected data in 2011 and 2012.

Why at LHCb?

Main production via B meson:

If χ mix with the Higgs and it is light enough

$$\begin{aligned}\Gamma(K \rightarrow \pi\chi) &\propto (m_t^2 |V_{ts}^* V_{td}|)^2 \propto m_t^4 \lambda^5 \\ \Gamma(D \rightarrow \pi\chi) &\propto (m_b^2 |V_{cb}^* V_{ub}|)^2 \propto m_b^4 \lambda^5 \\ \Gamma(B \rightarrow K\chi) &\propto (m_t^2 |V_{ts}^* V_{tb}|)^2 \propto m_t^4 \lambda^2\end{aligned}$$



Advantages of the LHCb detector:

- low p_T trigger \rightarrow low masses accessible
 - single muon, $p_T > 1.76 \text{ GeV}/c$
 - di-muon, $p_{T_1} \times p_{T_2} > (1.6 \text{ GeV}/c)^2$
 - high efficiency for muon trigger ($\sim 90\%$)
- very precise vertex reconstruction (VELO)
 - impact parameter resolution, $\sigma_{IP} = 20 \mu m$
 - lifetime resolution, $\sigma_\tau \sim 0.2 \text{ ps}$ (for $\tau = 100 \text{ ps}$)

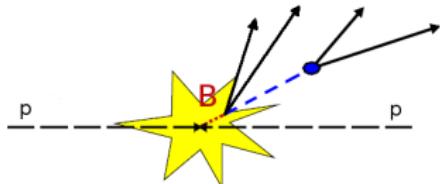
Signal properties

Depending on the coupling to the SM/hidden sector, we can identify two **lifetime** regimes:

[detector resolution
 $\sigma_\tau \sim 0.2$ ps]

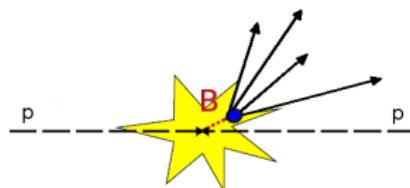
Long lifetime:

- Inflaton [JHEP1005(2010)010]
- Displaced vertex
- Almost background free
- Lower reconstruction efficiency



Short lifetime:

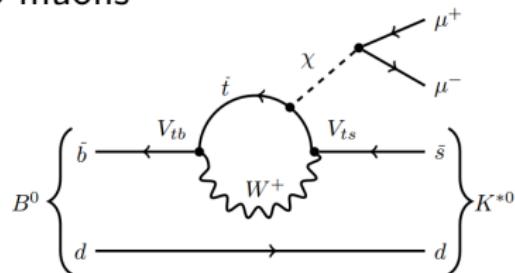
- Dark matter mediator [Phys.Lett.B727(2013)]
- Axion(like) [Phys.Rev.D81(2010)034001]
- Prompt decay
- Contamination from SM background



The decay

- Looking for dark boson decaying into muons

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



- $K^{*0} \rightarrow K^+ \pi^-$:
 - helps to reconstruct the B decay vertex
- $\mathcal{B}(\chi \rightarrow \mu^+ \mu^-)$:
 - dominant till the hadronic threshold ($\chi \rightarrow 2h$, $\chi \rightarrow 3h$)
 - always significant $\mathcal{O}(10^{-2})$ in the full mass range

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

Benchmark models:

1. Inflaton: [arXiv:1403.4638](https://arxiv.org/abs/1403.4638)

- $\tau_\chi = 10^{-8} \div 10^{-10}$ s,
- $m_\chi < \mathcal{O}(1 \text{ GeV})$,
- $\mathcal{B}(B \rightarrow K\chi) \sim 10^{-6}$
- effective coupling to SM particles:
 - $g_Y \frac{m_f}{v_{EW}}$, $g_Y \equiv \sin \theta$

Interesting parameter values,
in the range we can test!

2. Axion portal: [Phys.Rev.D81\(2010\)034001](https://doi.org/10.1103/PhysRevD.81.034001)

- prompt decay
- large allowed mass range
- axion decay constant: $f_\chi \sim 1 - 3 \text{ TeV}$
 - coupling $\propto m_f/f_\chi$

All models predict dark boson with width ~ 0 .

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

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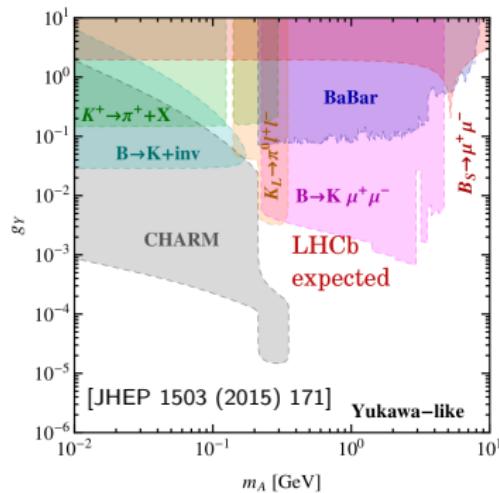
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Existing experimental limit



Similar analysis in BaBar [1] and Belle [2] with $B \rightarrow K\mu\mu$ decay

[1] Phys.Rev.D86(2012)032012

[2] Phys.Rev.Lett.103(2009)171801

Selection

1. Triggered on muons
2. Multivariate selection: $uBDT$ [JINST 8(2013) P12013]
 - o performance independent of mass and lifetime of χ
3. Optimized maximizing Punzi figure-of-merit [arXiv:physics/0308063]

$$P_a = \frac{S}{\frac{5}{2} + \sqrt{B}}$$

with S and B signal and background yields.

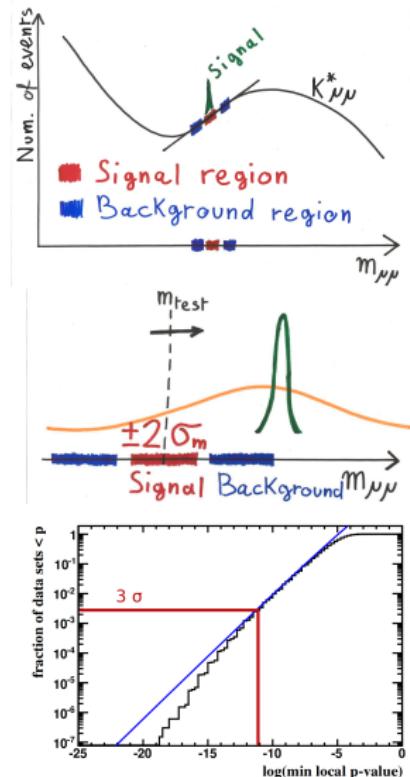
4. Factorize lifetime into two components: $\mathcal{L} = \mathcal{L}^{prompt} \cdot \mathcal{L}^{displaced}$
 - o *prompt*, $\tau < 3\sigma_\tau$
 - irreducible SM background $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
 - o *displaced*, $\tau > 3\sigma_\tau$
 - (almost) background free

Strategy of the search

[M.Williams JINST 10(2015)P06002]

Looking for di-muon resonance:

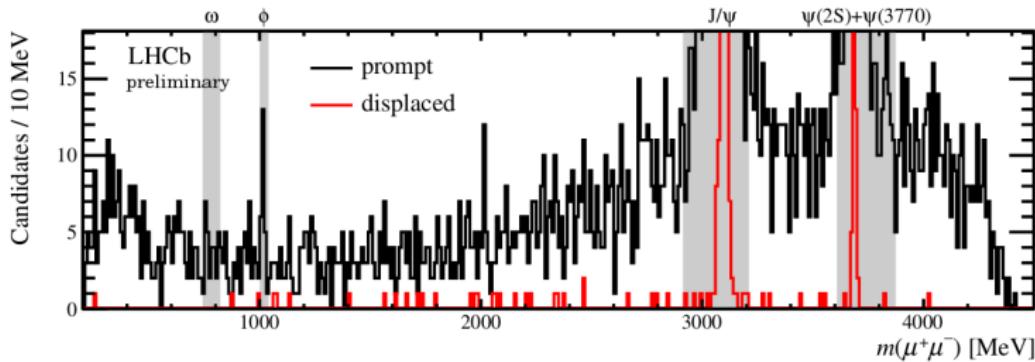
- B^0 mass constrained
- Di-muon mass resolution $\sigma_m = 1 \div 7$ MeV
- Scan m_{test} in steps of $1/2 \sigma_m$
 - wide resonances are safe
 - narrow resonances must be vetoed
- Test statistic performed for each m_{test}
- A global p -value is assigned from the minimum local p -value observed
 - fraction of toys that have a minimum local p -value less than the observed in data
 - takes count of the *Look Elsewhere Effect*



Results

Grey regions correspond to narrow SM di-muon resonances and are vetoed in the analysis

[LHCb-PAPER-2015-036 in preparation]



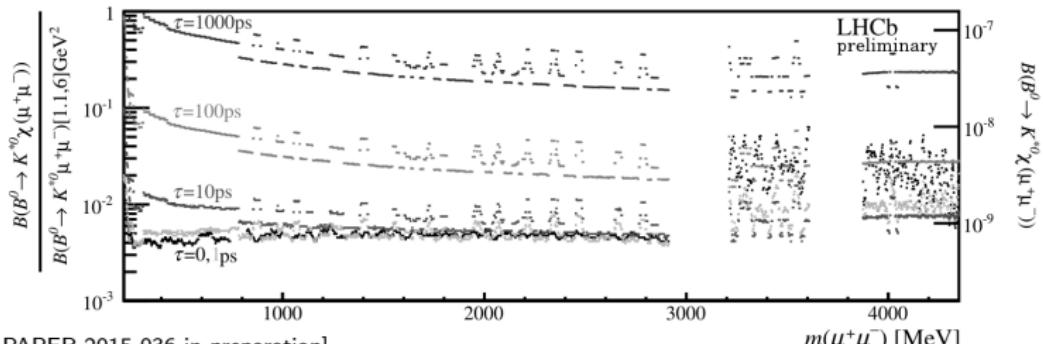
Largest deviation at $m_\chi = 253$ MeV, not statistically relevant:

- local p -value = 0.02

Exclusion limit

No deviation from the background only hypothesis is observed

- We set a 95% CL upper limit as function of mass and lifetime of the new particle (in the LHCb accessible range)
- The new particle is assumed to be a scalar
- Lower lifetimes have better limit due to higher reconstruction efficiency



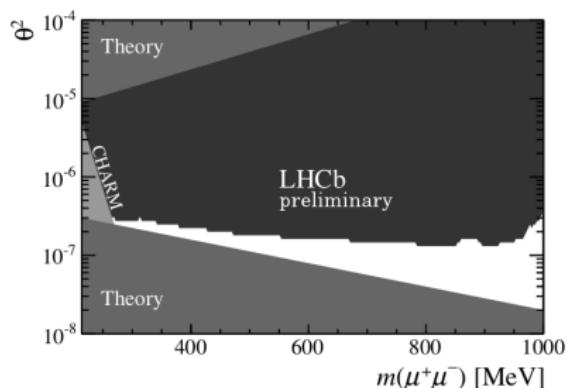
[LHCb-PAPER-2015-036 in preparation]

Exclusion limit: two benchmark models

Interpretation of the result in two specific model:

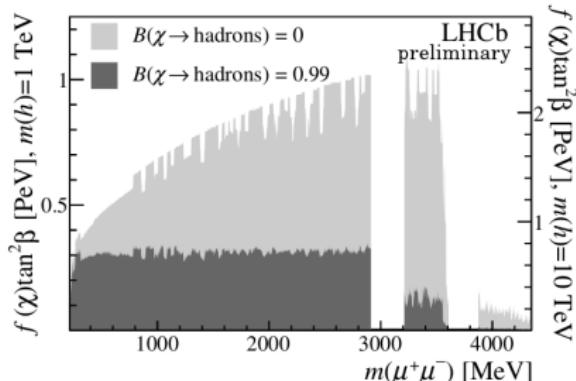
(Specific) inflaton model

[LHCb-PAPER-2015-036 in preparation]



Include 3 sterile neutrinos N_i

Axion portal



MSSM-like two Higgs doublet model.

Conclusion

1. A search for a dark boson in the decay channel $B^0 \rightarrow K^{*0}(\chi \rightarrow \mu^+ \mu^-)$ has been presented
 - o No deviation from the background only hypothesis is observed
2. Results are the most constraining exclusion limit on the process
3. LHCb is able to exclude almost all the theoretical predicted parameter space of a specific Inflaton model

Backup

Strategy

- *signal region* defined as: $| m_{test} - m | < 2\sigma_m$
- *background region* defined as: $3\sigma_m < | m_{test} - m | < (2x + 3)\sigma_m$
- $\mathcal{O}(10\%)$ deviations from local linearity are allowed
 - $x = 5$ below the J/ψ mass
 - $x = 1$ above the J/ψ mass

Trigger

Level		Trigger line	
L0	L0Hadron	L0Muon	LODiMuon
HLT1	Hlt1TrackAllL0	Hlt1TrackMuon	Hlt1DimuonLowMass
HLT2	Hlt2TopoMu2BodyBBDT Hlt2Topo2BodyBBDT Hlt2SingleMuon	Hlt2TopoMu3BodyBBDT Hlt2Topo3BodyBBDT Hlt2DiMuonDetached	Hlt2TopoMu4BodyBBDT Hlt2Topo4BodyBBDT
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Pre-selection

Variable	Cut
$\theta_{\text{dir}}(B^0)$	< 0.03 rad
$\chi^2_{\text{vtx}}(B^0)$	< 15
$\chi^2_{\text{IP}}(B^0)$	< 10
DLL _{Kπ} (K)	> -5
DLL _{Kπ} (π)	< 25
DLL _{Kπ} (K) - DLL _{Kπ} (π)	> 10
$ m(K^+\pi^-) - 895.6 $	< 100 MeV
$FD_T(\chi)$	> 0.1 mm
isMuon(K, π)	False

Selection

	Candidate		Cut	
B	$\chi^2_{\text{vtx}}/\text{ndf}$	<	25	
	χ^2_{IP}	<	50	
	τ	>	0.2	ps
	m	\in	[4800, 5800]	MeV
	p_T	>	1000	MeV
	$\cos \theta_{\text{dir}}$	>	0	
χ	$\chi^2_{\text{vtx}}/\text{ndf}$	<	10	
	χ^2_{FD}	<	25	
	p_T	>	250	MeV
	DOCA	<	0.2	mm
	DOCA χ^2	<	25	
Tracks	$\chi^2_{\text{trk}}/\text{ndf}$	<	3	
	$\min(\chi^2_{\text{IP}})$	>	9	
	P_{gh}	<	0.3	
K, π	p_T	>	250	MeV
	p	>	2000	MeV
	χ^2_{IP}	>	9	
K	ProbNNK	>	0.1	
	ProbNNpi	>	0.2	
μ	p_T	>	100	MeV
	PIDmu	>	-5	
GEC	N_{tracks}	\leq	250	

Multivariate selection

Input variables:

uBDT Variables	
$p_T(B^0)$	$\chi^2_{\text{vtx}}(B^0)$
$\text{FD}(B^0)$	$\chi^2_{\text{IP}}(B^0)$
$\theta_{\text{dir}}(B^0)$	$\text{Iso}(B^0)$
$\chi^2_{\text{IP}}(K^*)$	$\chi^2_{\text{FD}}(K^*)$
$\chi^2_{\text{IP}}(K^+)$	$\chi^2_{\text{IP}}(\pi^-)$
$\min \text{ProbNN}\mu(\mu^\pm)$	

uBDT selection is 85 % efficient on signal

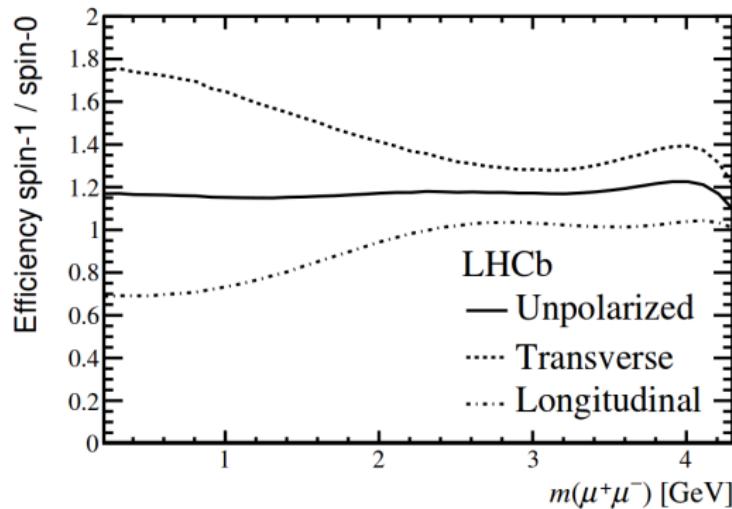
Background rejection

- Narrow SM resonances are vetoed:
 - $\omega, \phi, J/\psi, \psi(2S)$
- Background from particle mis-identification:

Mass	PID
$ m(K^+\pi^- \leftrightarrow K^+K^-) - m_\phi^{PDG} $	< 10 ProbNNpi(π) > 0.3 and ProbNNK(π) < 0.3
$ m(\mu^+\mu^- \leftrightarrow \pi^+\pi^-) - m_{K_S^0}^{PDG} $	< 25
$ m(\mu^+\mu^- \leftrightarrow K^+\pi^-) - m_{D^0}^{PDG} $	< 25 ProbNNmu(μ) > 0.3
$ m(\mu^+\mu^- \leftrightarrow p\pi^-) - m_A^{PDG} $	< 10 ProbNNp(μ) < 0.3
$ m(p_\pi K^- \mu^+\mu^-) - m_{A_b^0}^{PDG} $	< 50 ProbNNp(π) < 0.2

χ spin

Results are presented with the assumption that χ is spin 0



Inflaton benchmark model

Reference: arXiv:1403.4638

- Light inflaton: $0.1 < m_\chi < 1 \text{ GeV}$
- Lifetime $10^{-5} - 10^{-12} \text{ s}$
- 3 sterile neutrinos N_l
 - singlets with respect to the SM gauge group
 - Yukawa-type coupling to inflaton provides Majorana masses
 - the lightest, N_1 , may serve as DM produced by inflaton decays in the early Universe
 - $1 \text{ keV} < M_1 < 1 \text{ MeV}$

Axion-like benchmark model

Reference: Phys. Lett. B727 (2013)

- $\mathcal{L}_{int} = \frac{c_\psi}{f_\chi} \bar{\psi} \gamma_\mu \gamma_5 \psi \partial_\mu \chi$
- effective coupling constant $c_\psi m_\psi / f_\chi$
- The axion arises from spontaneous Peccei-Quinn symmetry breaking in a two Higgs doublet model (2HDM)
 - two Higgs doublet:

$$h_u = \begin{pmatrix} v_u \exp[\frac{i \cot \beta}{\sqrt{2} v_{EW}} A^0] \\ 0 \end{pmatrix}, \quad h_d = \begin{pmatrix} 0 \\ v_d \exp[\frac{i \tan \beta}{\sqrt{2} v_{EW}} A^0] \end{pmatrix}$$

- χ mixes with the CP -odd Higgs A^0

$$\begin{aligned} a_{phys.} &= a \cos \theta - A^0 \sin \theta, \\ A^0_{phys.} &= a \sin \theta + A^0 \cos \theta, \end{aligned} \quad \text{with } \tan \theta = n \frac{v_{EW}}{f_a} \frac{\sin 2\beta}{2}$$