Searches for low mass dark bosons

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Motivation

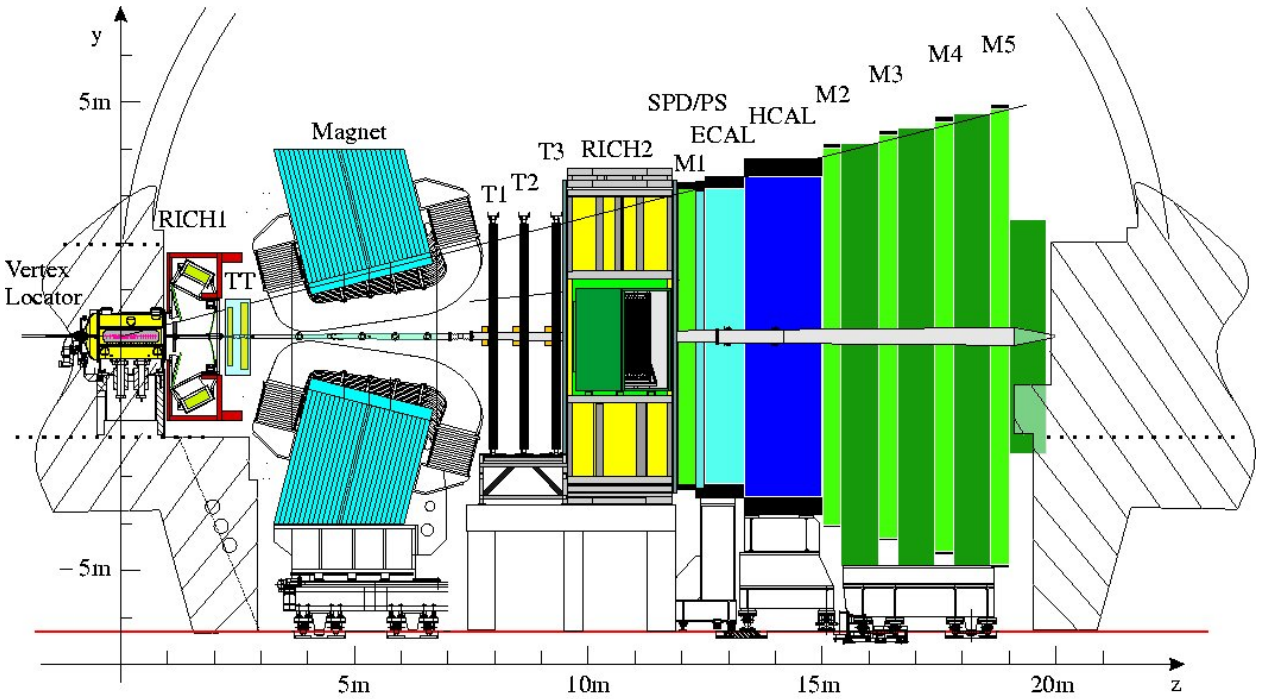
- The Higgs discovered in 2012 at LHC is consistent with a SM Higgs boson
  - but it could still have non SM properties (coupling to exotic particles)

- 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

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

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

The LHCb detector



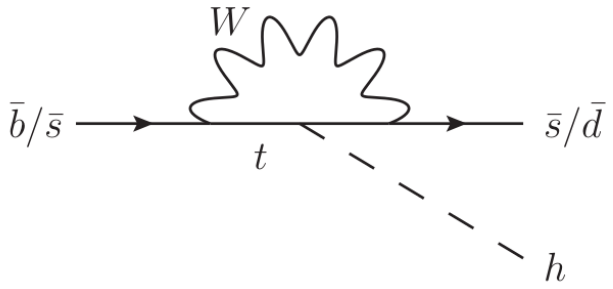
3 fb^{-1} of collected data in 2011 and 2012.

Why at LHCb?

Main production via B meson:

If χ mix with the Higgs and it is light enough

$$\Gamma(K \to \pi\chi) \propto (m_t^2 \mid V_{ts}^* V_{td} \mid)^2 \propto m_t^4 \lambda^5$$
$$\Gamma(D \to \pi\chi) \propto (m_b^2 \mid V_{cb}^* V_{ub} \mid)^2 \propto m_b^4 \lambda^5$$
$$\Gamma(B \to K\chi) \propto (m_t^2 \mid V_{ts}^* V_{tb} \mid)^2 \propto m_t^4 \lambda^2$$



Advantages of the LHCb detector:

- low p_T trigger $\to$ low masses accessible
  - single muon, $p_T > 1.76$ 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, $\sigma_\tau \sim 0.2$ ps (for $\tau = 100$ ps)

Signal properties

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

$$\left[\begin{array}{c}\text{detector resolution}\\ \sigma_\tau \sim 0.2\ \text{ps}\end{array}\right]$$

Long lifetime:

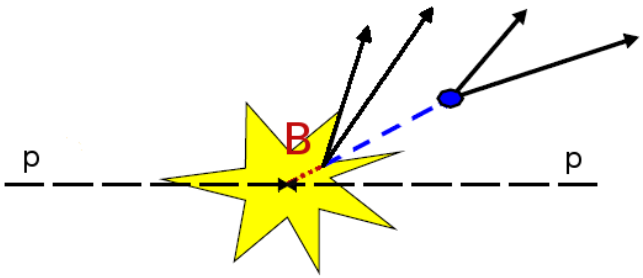
- Inflaton [JHEP1005(2010)010]

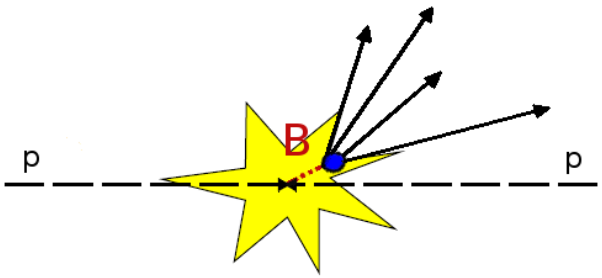
- Displaced vertex
- Almost background free
- Lower reconstruction efficiency

Short lifetime:

- Dark matter mediator [Phys.Lett.B727(2013)]
- Axion(like) [Phys.Rev.D81(2010)034001]

- Prompt decay
- Contamination from SM background

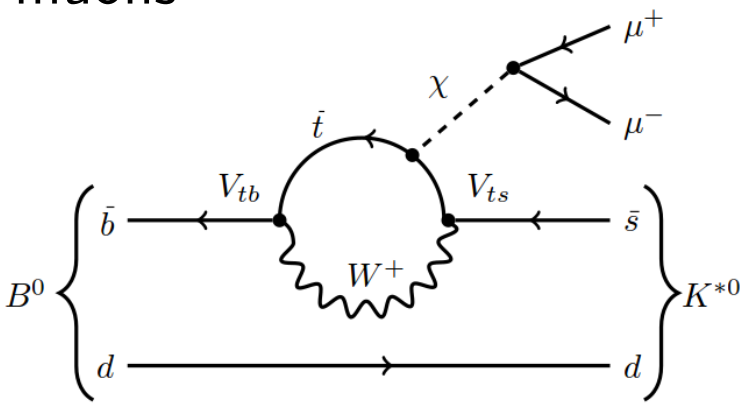




The decay

- Looking for dark boson decaying into muons

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



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

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

Benchmark models:

1. *Inflaton*: arXiv:1403.4638
   - $\tau_\chi = 10^{-8} \div 10^{-10}$ s,
   - $m_\chi < \mathcal{O}(1\text{ GeV})$,
   - $\mathcal{B}(B \to K\chi) \sim 10^{-6}$
   - 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
   - prompt decay
   - large allowed mass range
   - axion decay constant: $f_\chi \sim 1$ - 3 TeV
     - coupling $\propto m_f/f_\chi$

All models predict dark boson with width ~ 0.

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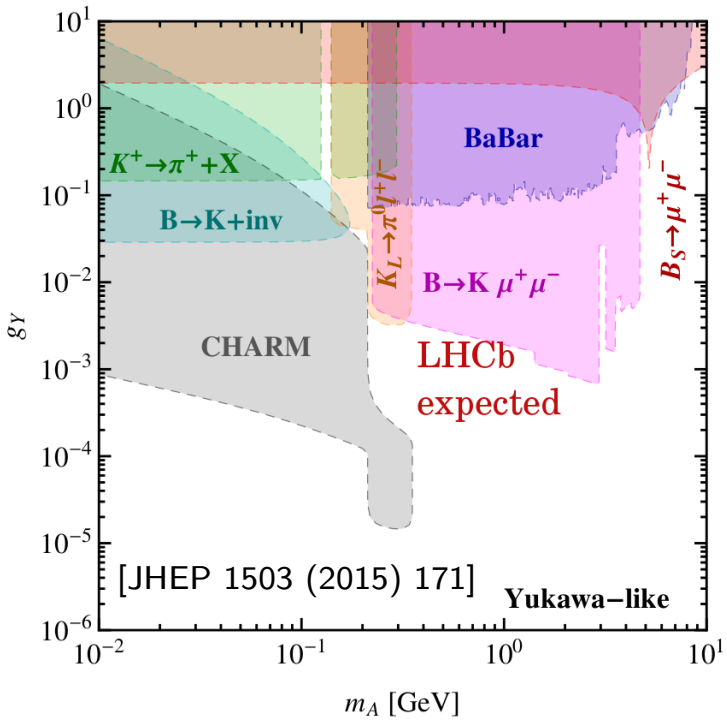
Existing experimental limit



Similar analysis in BaBar [1] and Belle [2] with $B \to K\mu\mu$ 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]
   - 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.

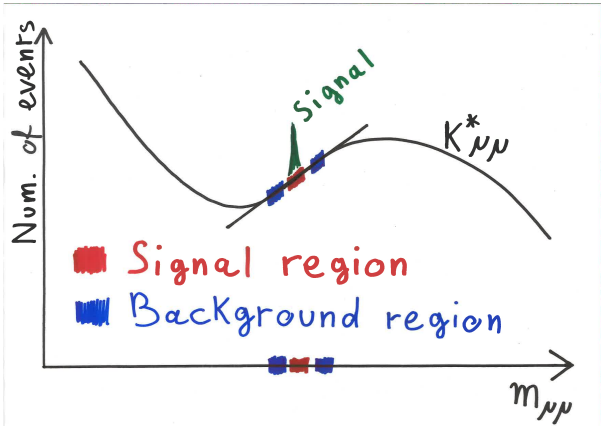
4. Factorize lifetime into two components: $\mathcal{L} = \mathcal{L}^{prompt} \cdot \mathcal{L}^{displaced}$
   - *prompt*, $\tau < 3\sigma_\tau$
     - irreducible SM background $B^0 \to K^{*0}\mu^+\mu^-$
   - *displaced*, $\tau > 3\sigma_\tau$
     - (almost) background free

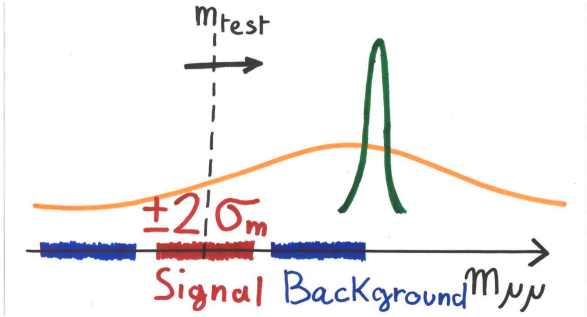
Strategy of the search

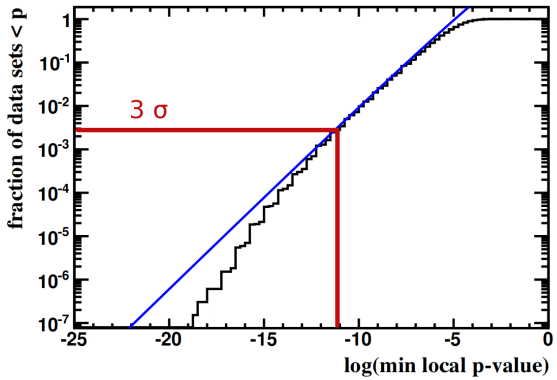
[M.Williams JINST 10(2015)P06002]

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 minumum local p-value observed
  - fraction of toys that have a minumum local p-value less than the observed in data
  - takes account of the *Look Elsewhere Effect*



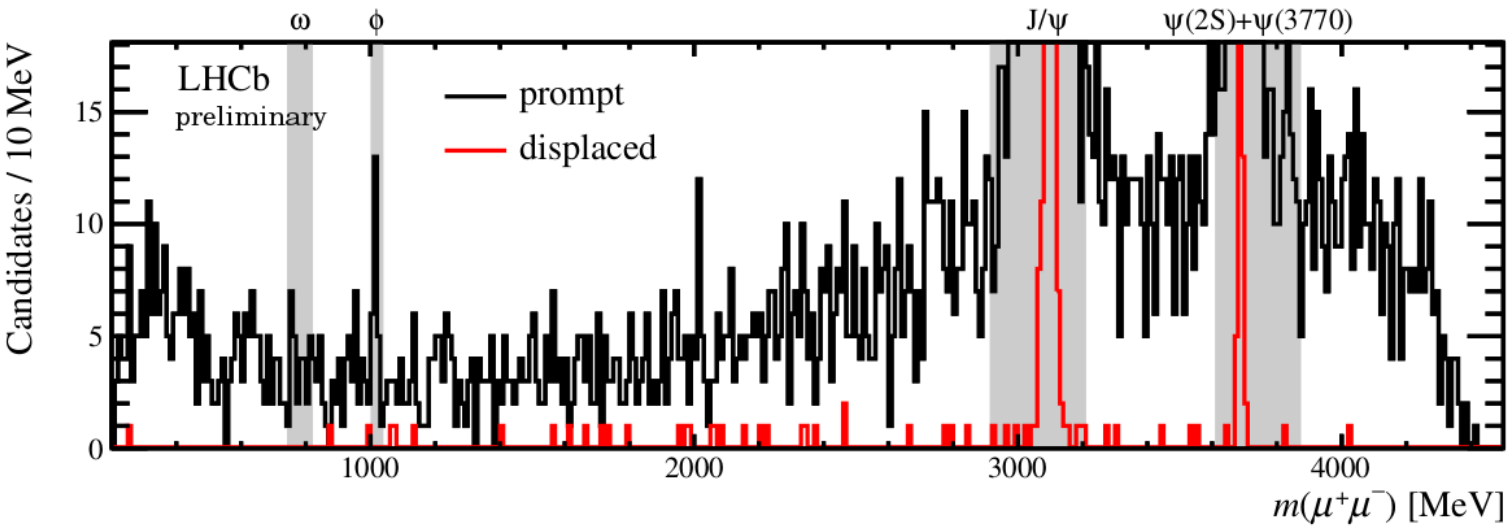




Results

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

[LHCb-PAPER-2015-036 in preparation]



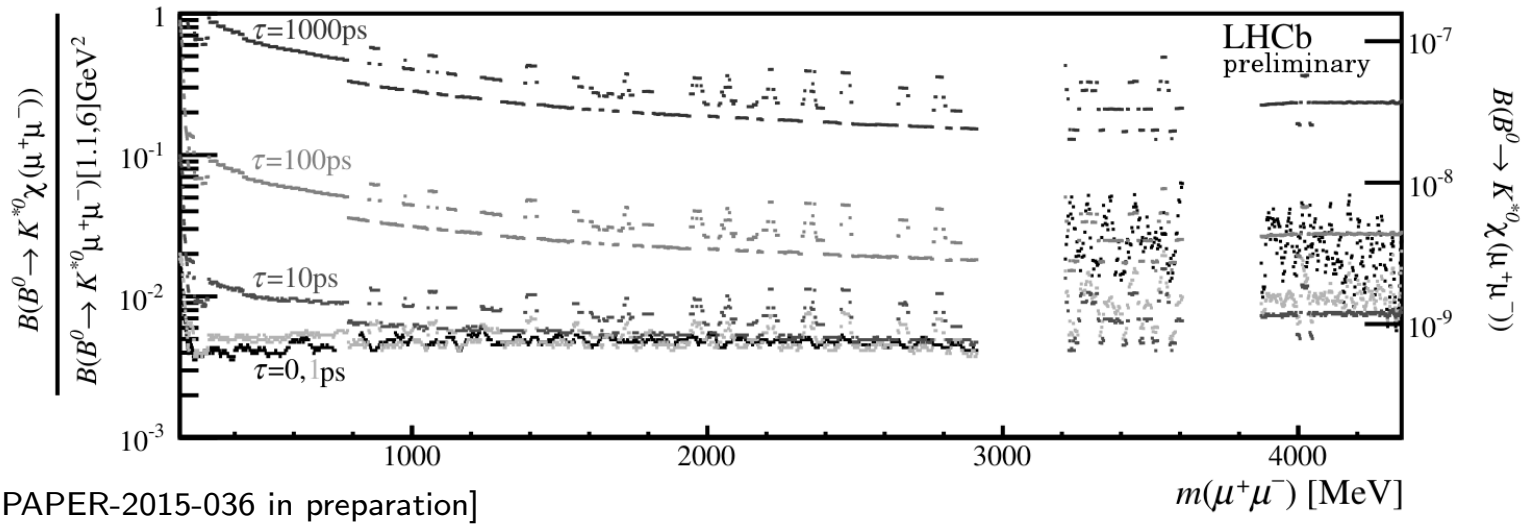
Largest deviation at $m_\chi = 253$ MeV, not statistically relevant:

- 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]

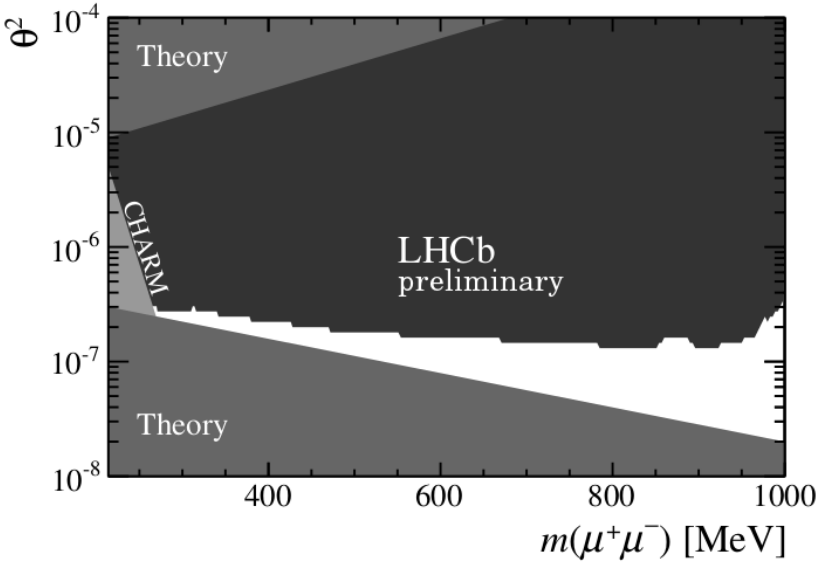
Exclusion limit: two benchmark models

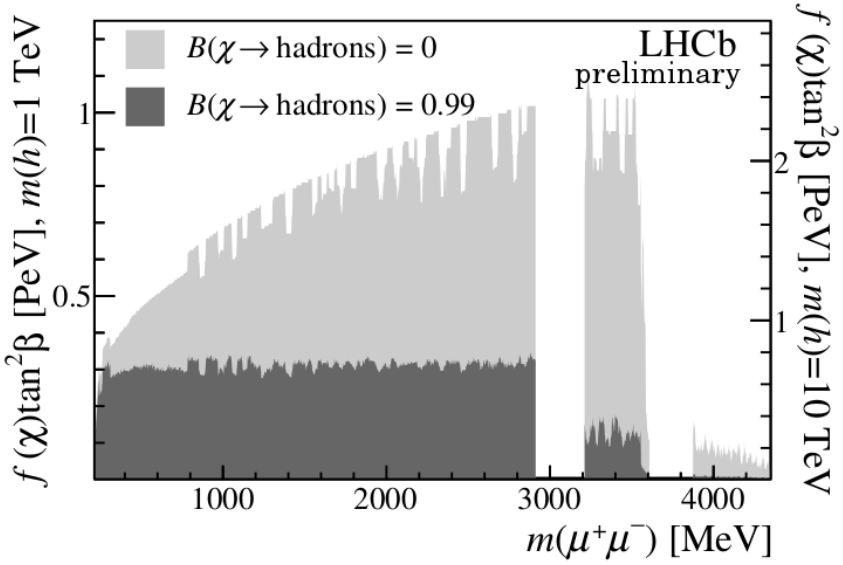
Interpretation of the result in two specific model:

(Specific) inflaton model

Axion portal

[LHCb-PAPER-2015-036 in preparation]





Include 3 sterile neutrinos N_l

MSSM-like two Higgs doublet model.

Conclusion

1. A search for a dark boson in the decay channel $B^0 \to K^{*0}(\chi \to \mu^+\mu^-)$ has been presented
   - 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: $\mid m_{test} - m \mid < 2\sigma_m$
- *background region* defined as: $3\sigma_m < \mid m_{test} - m \mid < (2x + 3)\sigma_m$
- $\mathcal{O}(10\%)$ 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	L0DiMuon
HLT1	Hlt1TrackAllL0	Hlt1TrackMuon	Hlt1DimuonLowMass
HLT2	Hlt2TopoMu2BodyBBDT Hlt2Topo2BodyBBDT Hlt2SingleMuon	Hlt2TopoMu3BodyBBDT Hlt2Topo3BodyBBDT Hlt2DiMuonDetached	Hlt2TopoMu4BodyBBDT Hlt2Topo4BodyBBDT

Pre-selection

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

Selection

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

Multivariate selection

Input variables:

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

uBDT selection is 85 % efficient on signal

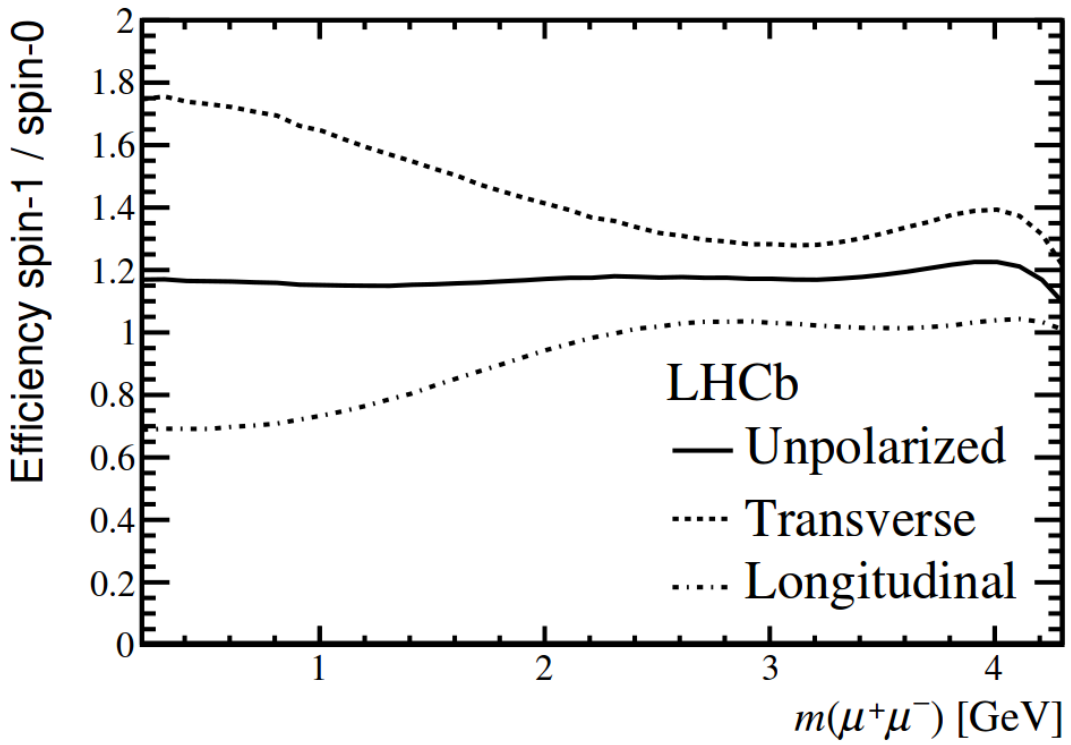
Background rejection

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

Mass		PID
$\left\lvert m(K^+\pi^- \leftrightarrow K^+K^-) - m_{\phi}^{PDG}\right\rvert$	< 10	$\texttt{ProbNNpi}(\pi) > 0.3$ and $\texttt{ProbNNK}(\pi) < 0.3$
$\left\lvert m(\mu^+\mu^- \leftrightarrow \pi^+\pi^-) - m_{K_S^0}^{PDG}\right\rvert$	< 25	
$\left\lvert m(\mu^+\mu^- \leftrightarrow K^+\pi^-) - m_{D^0}^{PDG}\right\rvert$	< 25	$\texttt{ProbNNmu}(\mu) > 0.3$
$\left\lvert m(\mu^+\mu^- \leftrightarrow p\pi^-) - m_{\Lambda}^{PDG}\right\rvert$	< 10	$\texttt{ProbNNp}(\mu) < 0.3$
$\left\lvert m(p_\pi K^-\mu^+\mu^-) - m_{\Lambda_b^0}^{\mathrm{PDG}}\right\rvert$	< 50	$\texttt{ProbNNp}(\pi) < 0.2$

χ spin

Results are presented with the assumption that χ is spin 0



Inflaton benchmark model

Reference: arXiv:1403.4638

- Light inflaton: $0.1 < m_\chi < 1$ GeV
- Lifetime 10^{-5} - 10^{-12} s
- 3 sterile neutrinos N_I
  - siglets 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 keV $< M_1 <$ 1 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 simmetry breaking in a two Higgs doublet model (2HDM)
  - two Higgs doublet:

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

- χ mixes with the CP-odd Higgs A^0

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