Search for long-lived scalar particles in B decays at LHCb

A. Mauri
on the behalf of the LHCb collaboration

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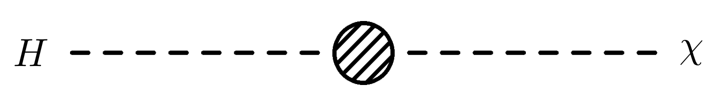
Motivation

- 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

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



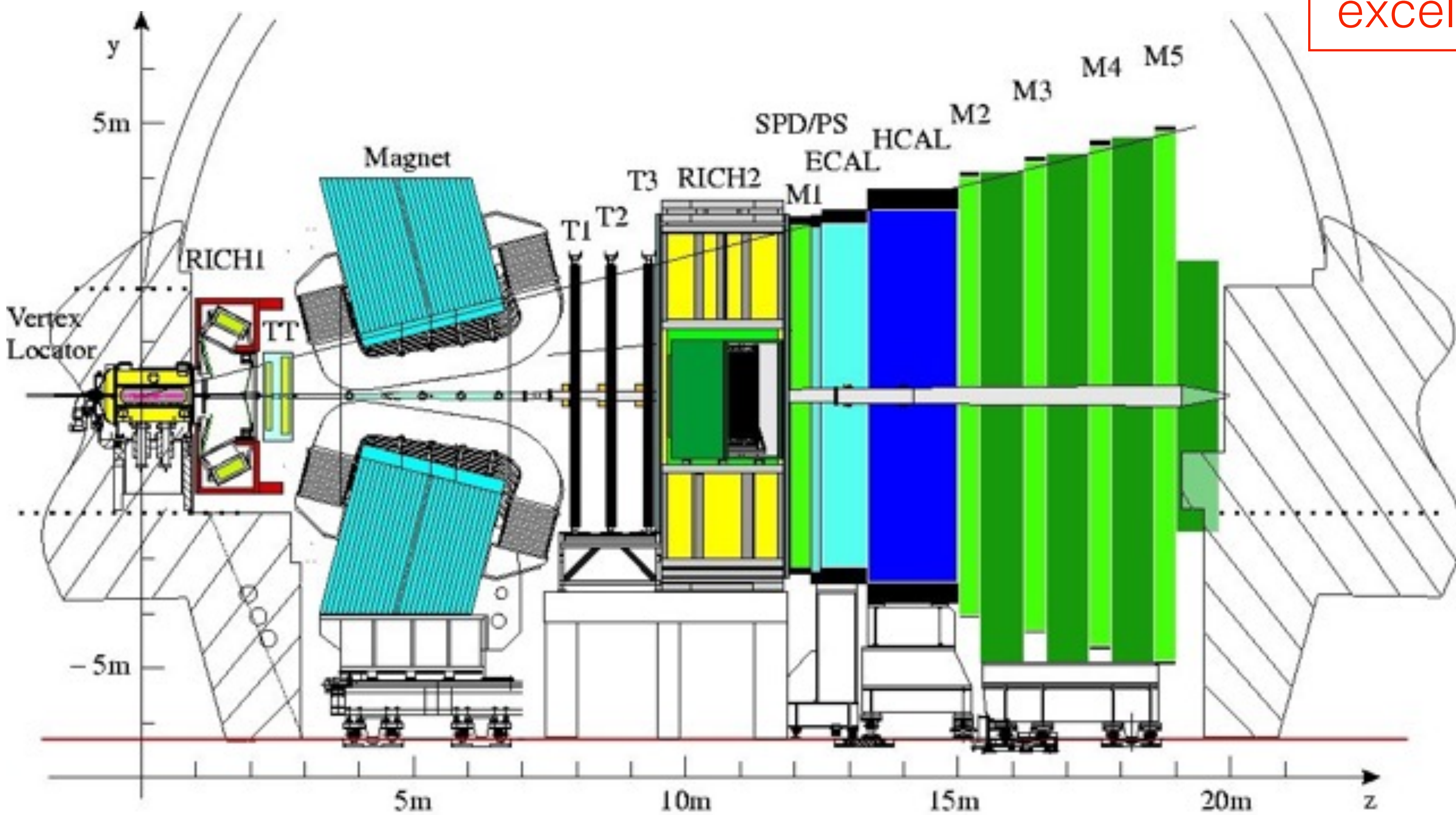
- Inflaton, axion-like, dark matter mediator models also predict the new boson to be light

The LHCb detector

LHCb is a forward spectrometer at LHC

- ✳ Pseudorapidity range: $2 < \eta < 5$
- ✳ focused on the study of b and c decays

excellent vertex resolution
excellent momentum resolution
excellent particle identification
!



[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

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

Why at LHCb?

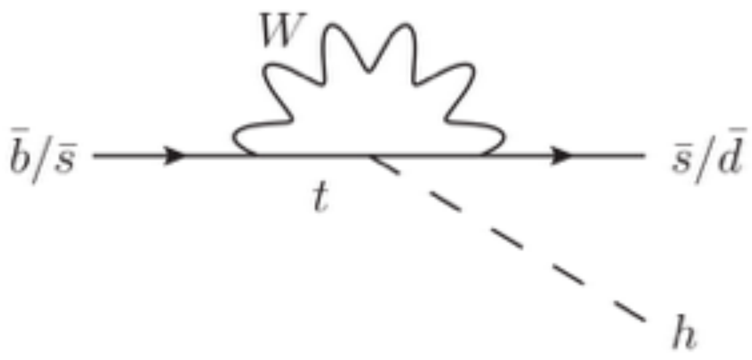
- Main production via B meson:
  - if χ mixes with the Higgs and it is light enough

$$\Gamma(K \to \pi\chi) \propto (m_t^2 \mid V_{ts}^* V_{td} \mid)^2 \propto m_t^4 \lambda^5$$

$$\Gamma(D \to \pi\chi) \propto (m_b^2 \mid V_{cb}^* V_{ub} \mid)^2 \propto m_b^4 \lambda^5$$

$$\boxed{\Gamma(B \to K\chi) \propto (m_t^2 \mid V_{ts}^* V_{tb} \mid)^2 \propto m_t^4 \lambda^2}$$

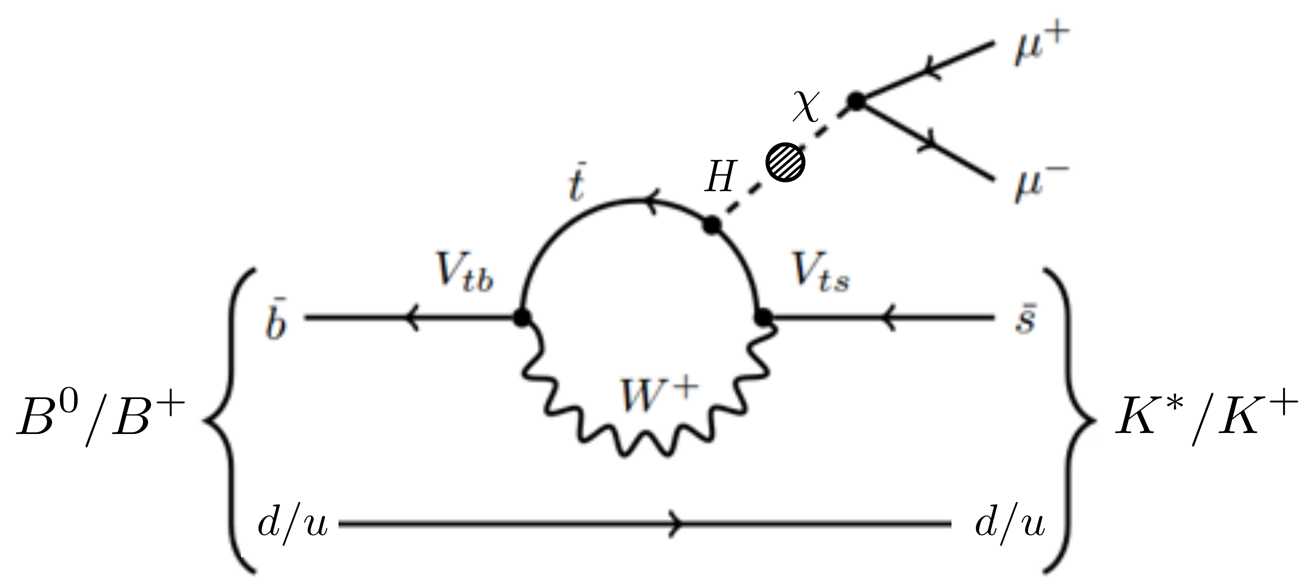
→ $b \to s$ transitions are the favourite mode



- Advantages of the LHCb detector:
  - low p_T trigger → 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 (~90%)
  - very precise vertex reconstruction (VELO)
    - impact parameter resolution, $\sigma_{IP} = 20\ \mu m$
    - lifetime resolution, $\sigma_T \sim 0.1$ ps

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

- Looking for a new scalar particle decaying into muons
  - $B^0 \to K^{*0}\chi(\to \mu^+\mu^-)$ [PRL 115(2015)121802]
  - $B^+ \to K^+\chi(\to \mu^+\mu^-)$ → more sensitive to scalar particle [PRD 95(2017)071101]



- $\mathcal{B}(\chi \to \mu^+\mu^-)$:
  - dominant up to the hadronic threshold ($\chi \to 2h$, $\chi \to 3h$)
  - always significant $O(10^{-2})$ in the full mass range

Signal properties

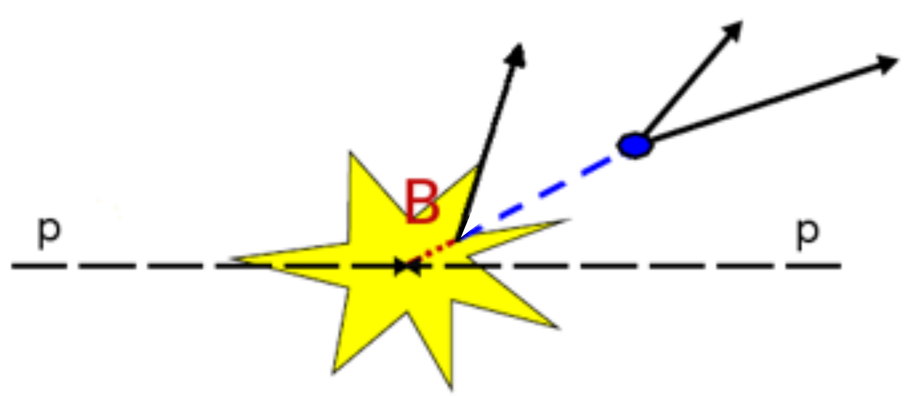
* Depending on coupling to the SM, we can identify two **lifetime regimes**:

detector resolution
$0.1 \div 0.2$ ps

<u>Long lifetime:</u>

- Inflaton [JHEP1005(2010)010]

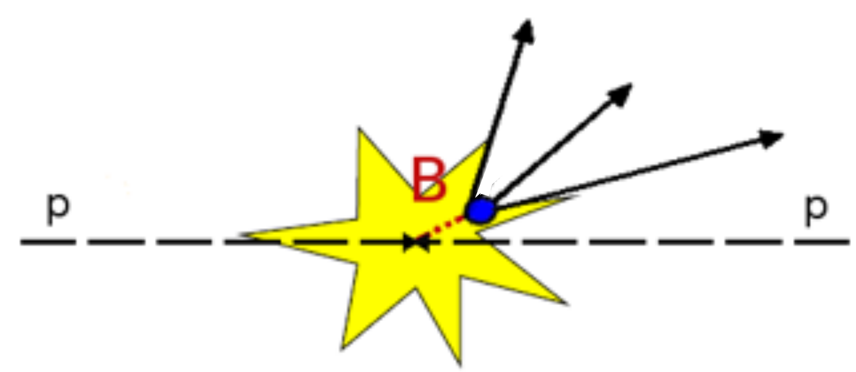
- Displaced vertex
- Almost background free
- Lower reconstruction efficiency



<u>Short lifetime:</u>

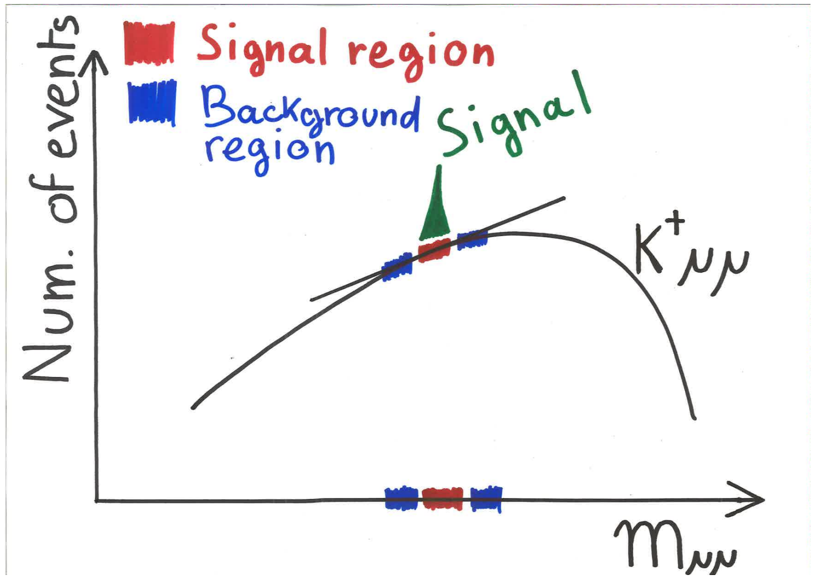
- Dark matter mediator [Phys.Lett.B727(2013)]
- Axion-like [Phys.Rev.D81(2010)034001]

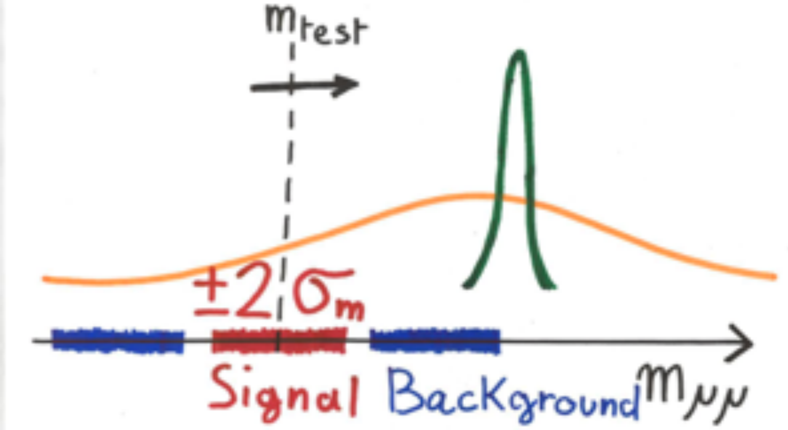
- Prompt decay
- Contamination from SM background



Overview of the strategy

- Unknown mass and lifetime: **2D search** (m, τ)
- Peak search in the *dimuon mass* distribution
  - step of $\frac{1}{2}\sigma_m$
  - signal region: $\pm 2\sigma(m_\chi)$
  - background region:
    - signal sideband
    - assume local-linearity
  - SM resonances must be vetoed
    - ϕ, J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4160)$ vetoed!

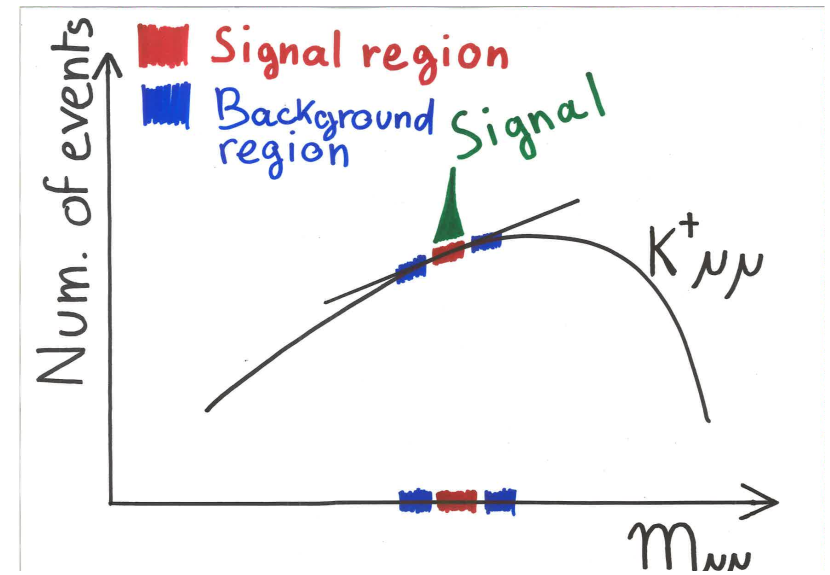




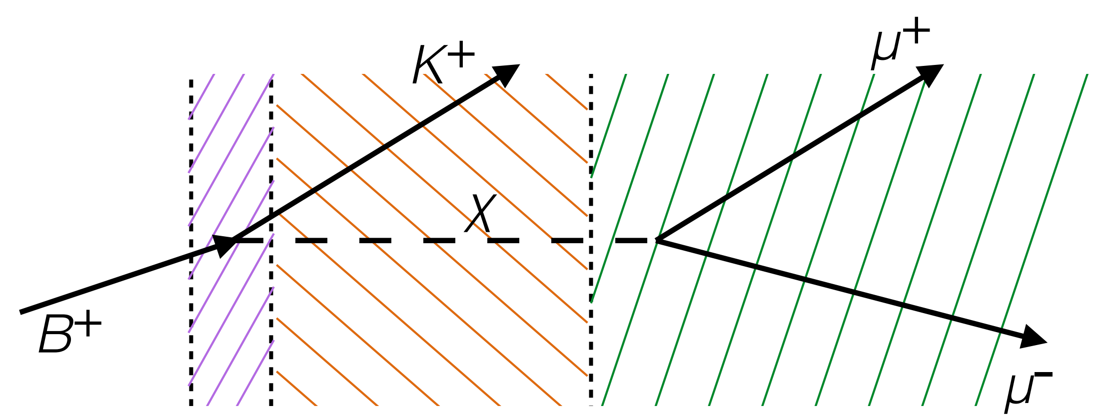
Strategy reference [M. Williams, JINST 10 (2015) P06002]

Overview of the strategy (II)

- Unknown mass and lifetime: **2D search** (m, τ)
- Peak search in the *dimuon mass* distribution
  - step of $\frac{1}{2}\sigma_m$
  - signal region: $\pm 2\sigma(m_\chi)$
  - background region:
    - signal sideband
    - assume local-linearity
  - SM resonances must be vetoed
    - ϕ, J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4160)$ vetoed!



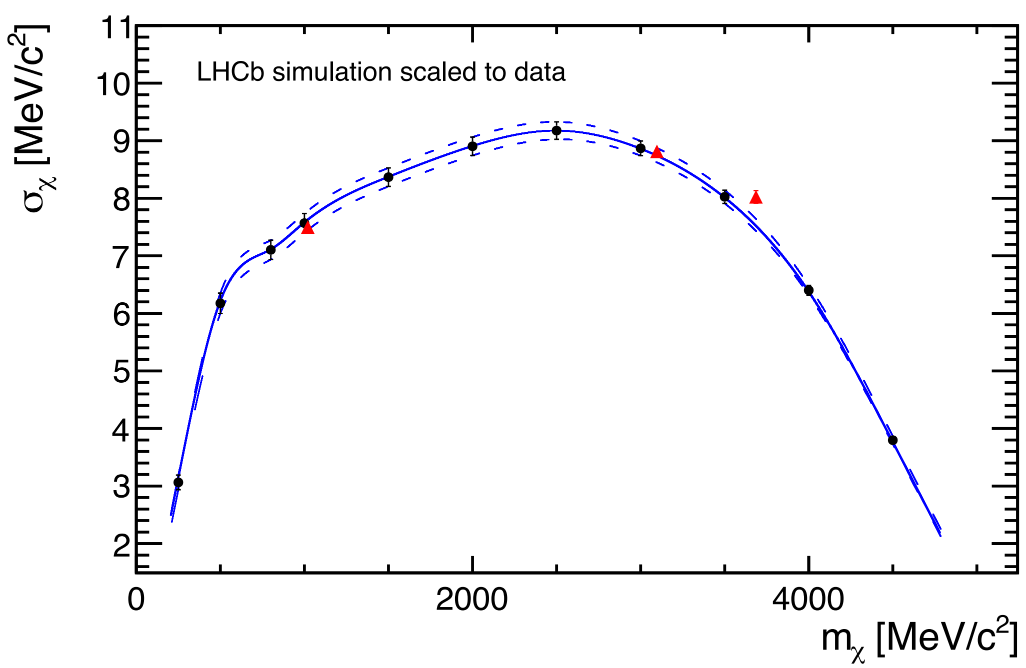
- We define 3 bins of *time of decay*
  - prompt: | t | < 1 ps
  - displaced: 1< t < 10 ps
  - “zero background” search: t > 10 ps
    - O(1) expected event



- Upper limit set with the CLs method, as function of mass and lifetime

Selection & background

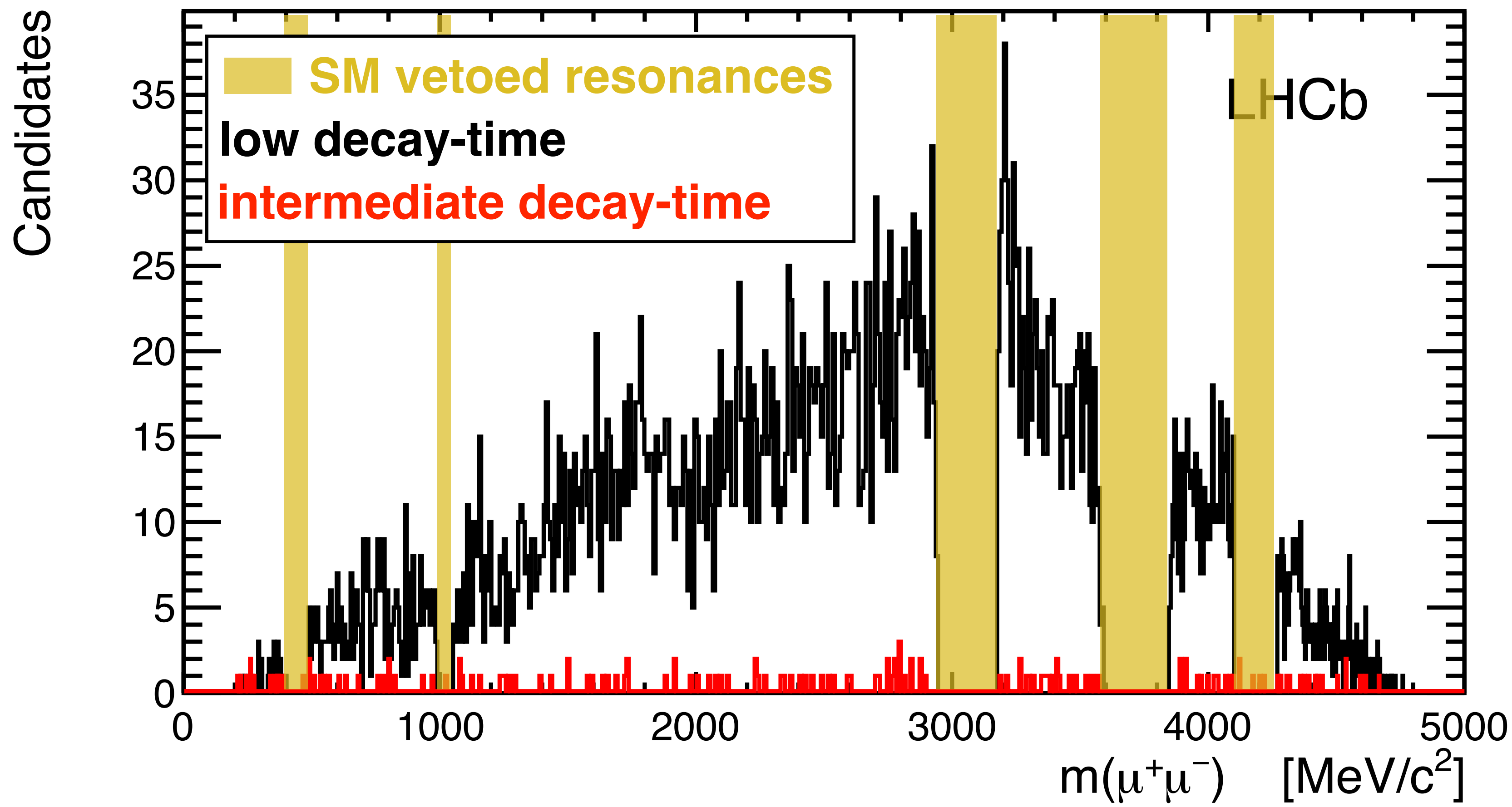
- Trigger on muons
- Multivariate selection (MVA):
  - High rejection of combinatorial background
- Main background sources:
  - SM $B^+ \to K^+\mu^+\mu^-$ → *prompt* affect only the *low decay-time*
    - $\mathcal{O}(5000)$ expected events
  - combinatorial background → can be *displaced*
    - $\mathcal{O}(1000)$ expected events
- B candidates selected within 50 MeV around the B mass
  - dimuon mass resolution between 3 and 9 MeV



[PRD 95(2017)071101]

Result: di-muon mass distribution

[PRD 95(2017)071101]



binning
$\sim 1\,\sigma(m_\chi)$

Zero events observed in the long decay-time region!

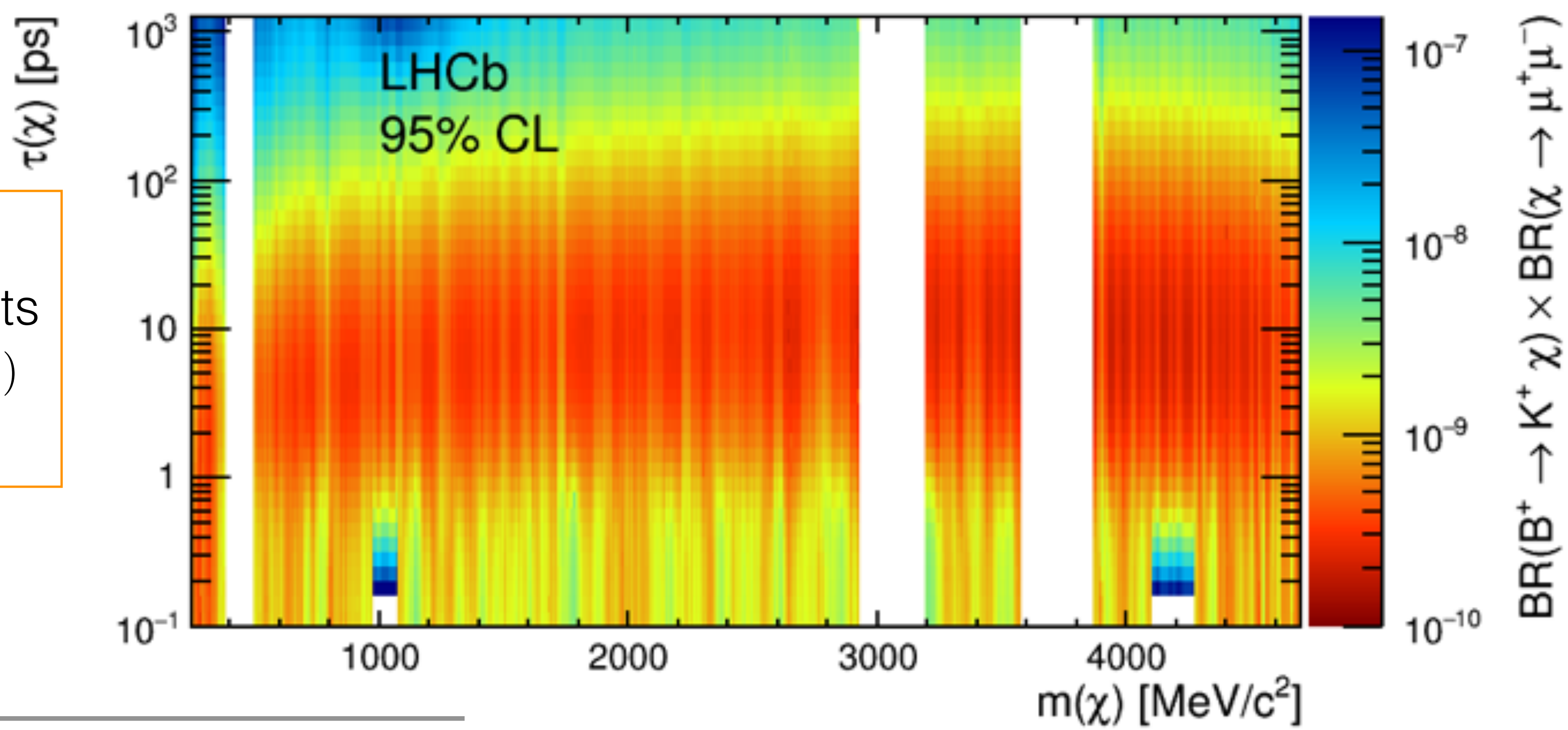
No statistically significant excess are observed → we set excluded limits!

95% CL excluded BR

- We set a 95% CL upper limit as a function of the mass and lifetime
- Limits are between 2 x10^{-10} and 10^{-7}
- Most sensitive limit for lifetime ~ 10 ps
  - For higher lifetimes candidates start to escape from the detector
  - Lower lifetimes are affected by higher background contamination
- The precision on the upper limits is dominated by the statistical uncertainties

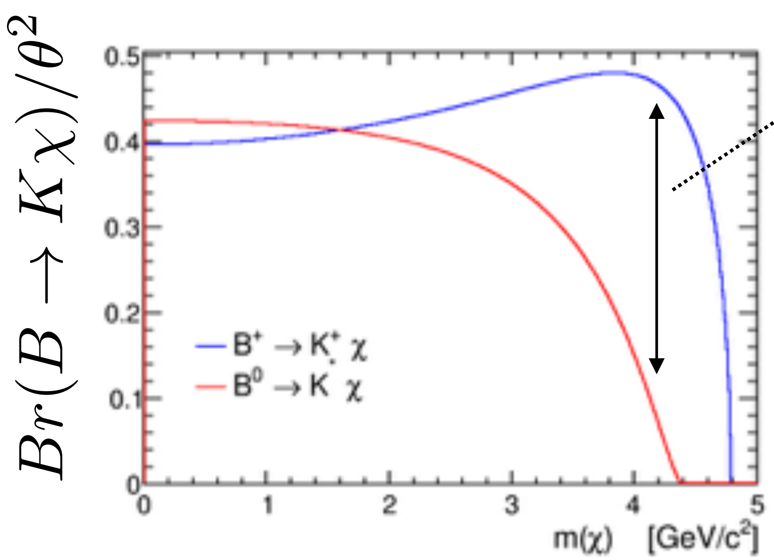
Up to a factor of 20 better than previous limits from $B^0 \to K^{*0}\chi(\to \mu^+\mu^-)$ [PRL 115(2015)121802]

[PRD 95(2017)071101]



Interpretation of the result: the inflaton model

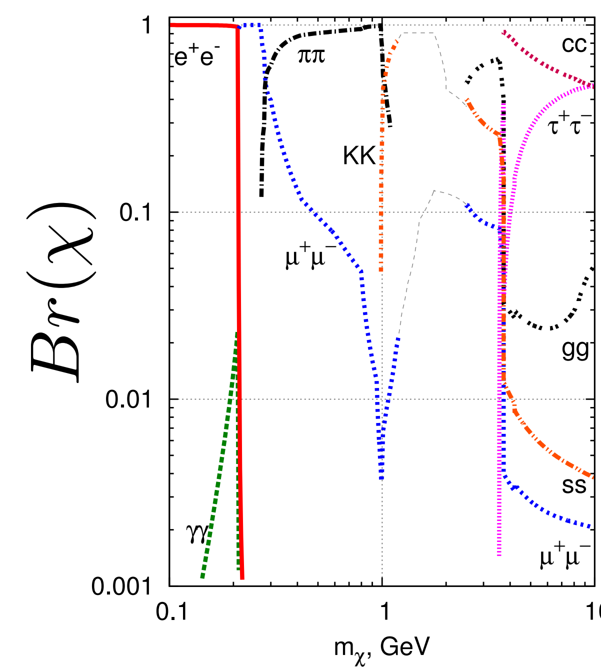
BR of *B*-meson into inflaton:



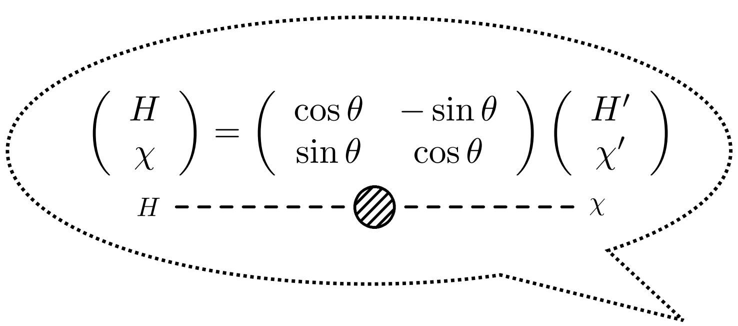
$B^+ \to K^+\chi$ is more sensitive to new scalar particle

Batell, Pospelov, Ritz
[PRD 83, 054005 (2011)]

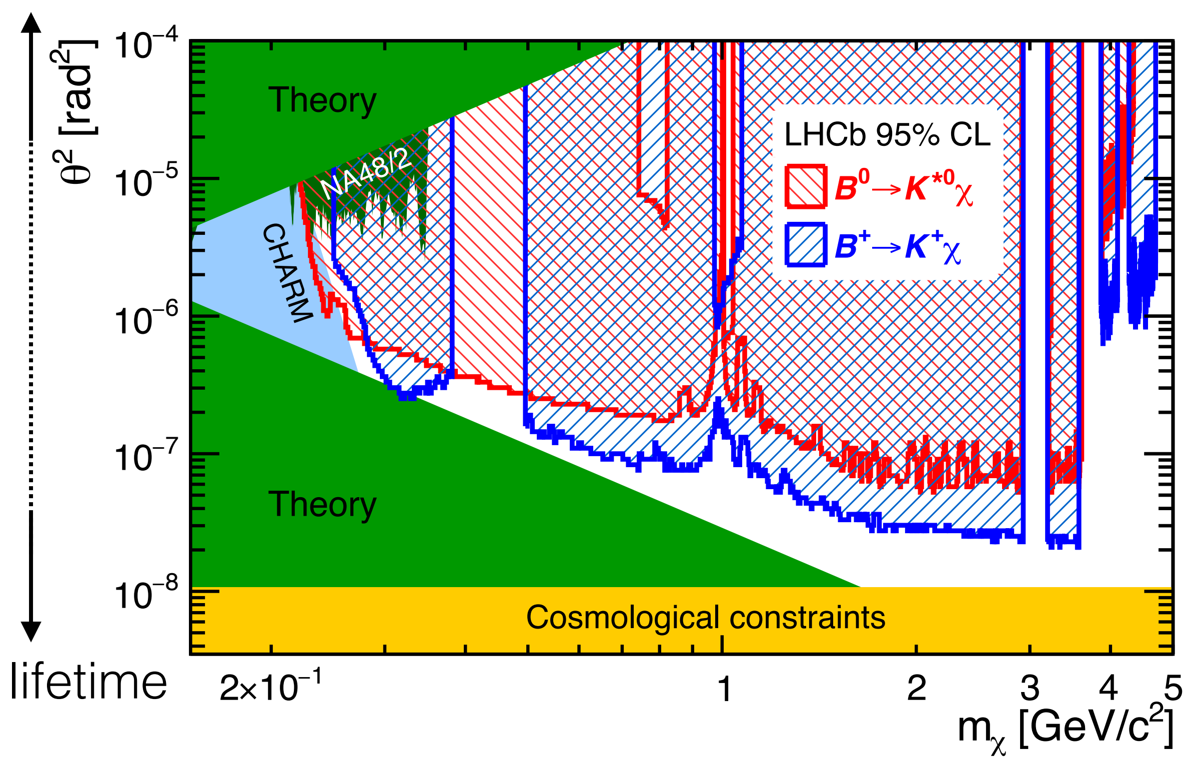
BR of the inflaton into muons:



Bezrukov, Gorbunov
[JHEP 07 (2013) 140]



- We put a limit on the <u>mixing angle</u> as a function of the mass
- Excluded region improved and close to completely excluded the allowed parameter space



[PRD 95(2017)071101]

Conclusion (I)

1. A search for an hypothetical new scalar particle in the decay $B^+ \to K^+\chi(\to \mu^+\mu^-)$ has been presented
2. No deviation from the background only hypothesis is observed
3. Upper limits set on $\mathcal{B}(B^+ \to K^+\chi) \times \mathcal{B}(\chi \to \mu^+\mu^-)$ between 2 x10^{-10} and10^{-7} as function of mass and lifetime
   - Limits supersede previous search from LHCb
4. Interpretation of the result in term of the inflaton model
   - LHCb is able to exclude almost all the allowed parameter space for a light inflaton

Thank you!

backup

Background

1. SM di-muon resonances
   - ϕ, J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4160)$: vetoed!
2. SM $B^+ \to K^+\mu^+\mu^-$
   - Irreducible, same final state and topology
   - Prompt!
   - *O(5k)* events
3. Combinatorial background
   - Can be displaced!
4. Background from $B^+ \to D^0 X$
   - $D^0 \to K\pi$ ⟶ removed with additional PID requirement
   - $D^0 \to \pi^+\pi^-, K^+K^-$ ⟶ negligible
5. Other B decays (negligible)
   - $B^+ \to 3h\,(K^+K^-K^+,\ K^+K^-\pi^+,\ K^+\pi^-\pi^+,\ \pi^+\pi^-\pi^+)$
   - $B^+ \to \pi^+\mu^+\mu^-$
   - $B^0 \to K^*\mu^+\mu^-$
6. $\Lambda \to p\pi$, $K^0_S \to \pi^+\pi^-$: vetoed!

Background summary

Background	Variable	Mass region (MeV/c^2)	Cut
$\phi \to \mu^+\mu^-$	$m_{\mu^+\mu^-}$	[985, 1055]	vetoed-1st bin
$J/\psi \to \mu^+\mu^-$	$m_{\mu^+\mu^-}$	[2946, 3176]	vetoed
$\psi(2S)$, $\psi(3770) \to \mu^+\mu^-$	$m_{\mu^+\mu^-}$	[3586, 3850]	vetoed
$\psi(4160) \to \mu^+\mu^-$	$m_{\mu^+\mu^-}$	[4103, 4270]	vetoed-1st bin
$J/\psi \to \mu^+\mu^-$ with $K^+ \leftrightarrow \mu^+$ swap	$m_{(K\mu\leftrightarrow\mu\mu)}$	[3000, 3200]	isMuon(K^+)=0
$B^+ \to D^0(\to K\pi)X$	$m_{(\mu\mu\leftrightarrow K\pi)}$	[1840, 1890]	ProbNNmu(μ) > 0.4
$K^0_S \to \pi^+\pi^-$	$m_{(\mu\mu\leftrightarrow\pi\pi)}$	[443, 523]	vetoed
$\Lambda^0 \to p\pi$	$m_{(\mu\mu\leftrightarrow p\pi)}$	[1090, 1120]	vetoed

Decay-time binning

- 3 bins of time of decay:
  - 1st bin:
    - **prompt:** | t | < 1 ps
      - Contain all the $B^+ \to K^+\mu^+\mu^-$ events
      - O(5000) expected events
  - 2nd bin:
    - **displaced** di-muon candidates: 1< t < 10 ps
      - low (combinatorial) background
      - O(1000) expected events
  - 3rd bin:
    - **“zero background”** search: t > 10 ps
      - O(1) expected event

detector resolution ~0.2 ps

High background & high efficiency — Sensitive to short lifetime

Low background & low efficiency — Sensitive to long lifetime

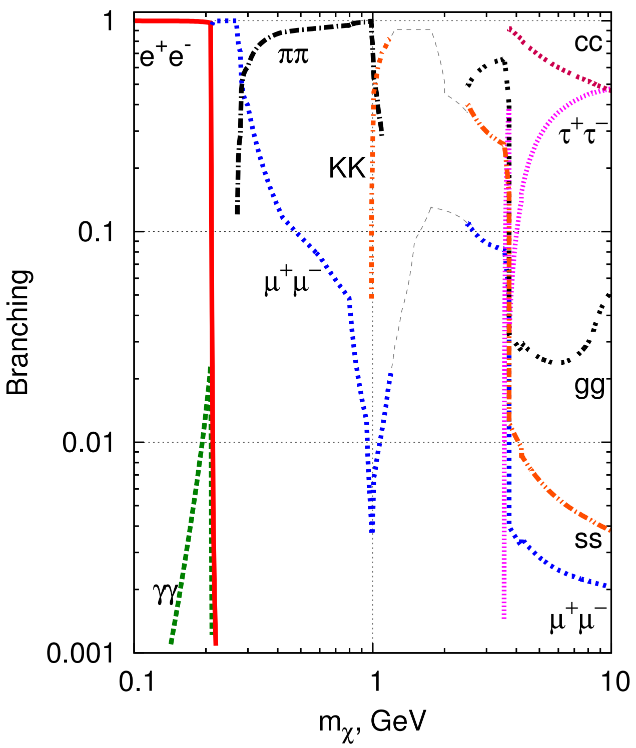
low efficiency → events start to escape from the detector

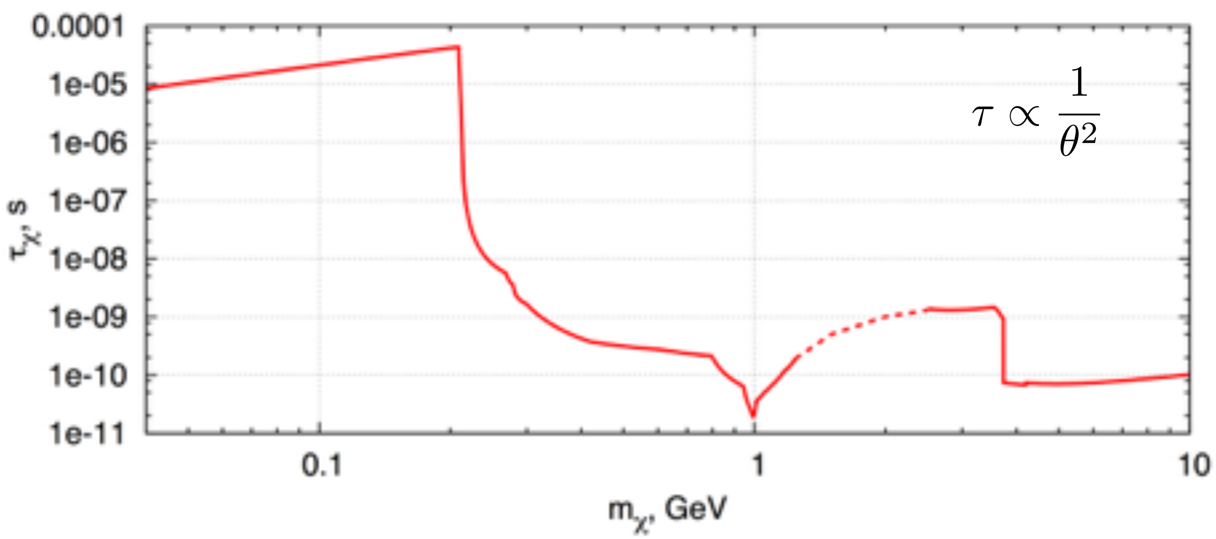
- Bins combined afterwards into a single Likelihood $\mathcal{L} = \prod_{bins} \mathcal{L}_i$

Inflaton model

Interpretation of the result in the inflaton model.

- Branching ratio of the inflaton into muons:
  - between 1 and ~1%
- Lifetime:
  - varies of several order of magnitude
  - scale as $\tau \propto \frac{1}{\theta^2}$





[Bezrukov, *Light inflaton after LHC8 and WMAP9 results*, JHEP 07 (2013) 140]

Systematics

- Sources:
  - signal resolution
  - signal efficiency (MC size)
  - background mass-shape mis-modelling
  - Normalization branching ratio
- The impact of these uncertainties on the excluded limit is found to be minimal (on average it is enhanced by only 2 %).

Source	Uncertainty
Signal resolution	$(1.5 \div 2)\%$
MC size	$(2 \div 6)\%$
MC lifetime reweighting	$(0 \div {}^{+0}_{-20})\%$
Background mass shape mismodelling	$0.08 \times$ stat. err.
Normalization branching ratio	3 %