# Sterile neutrino and other long lived particle searches at LHCb

Marcin Chrząszcz
mchrzasz@cern.ch

University of Zurich[UZH]

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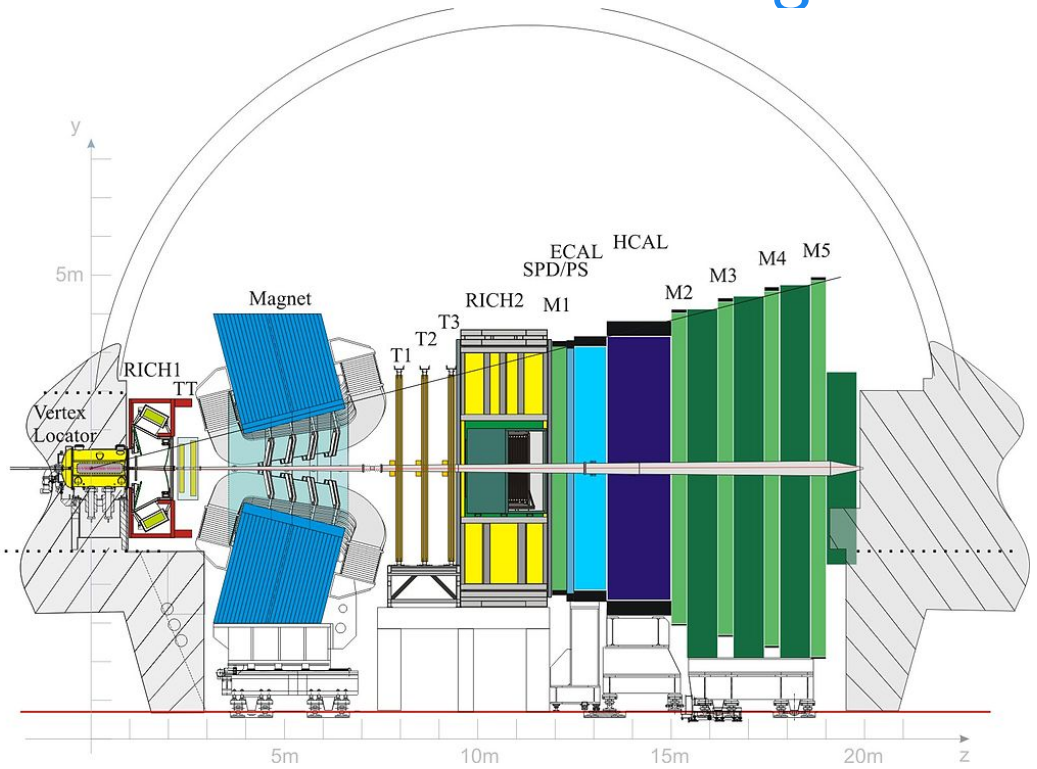
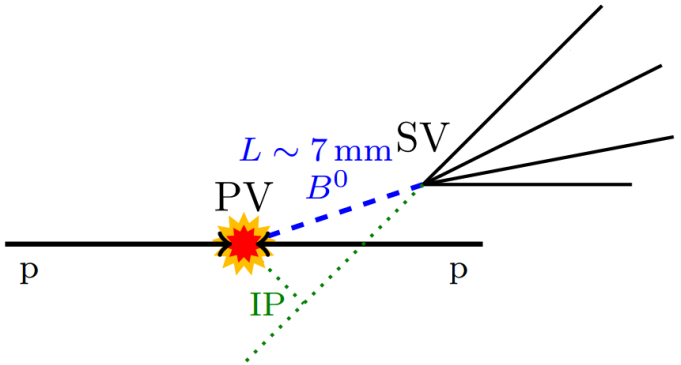
# Outline

- LHCb detector and operations.
- Majorana neutrino search.
- Inflaton search in $B \to K^* \chi(\mu\mu)$.
- Hidden valley searches.

# LHCb detector - tracking

*Int. J. Mod. Phys. A30 (2015) 1530022*

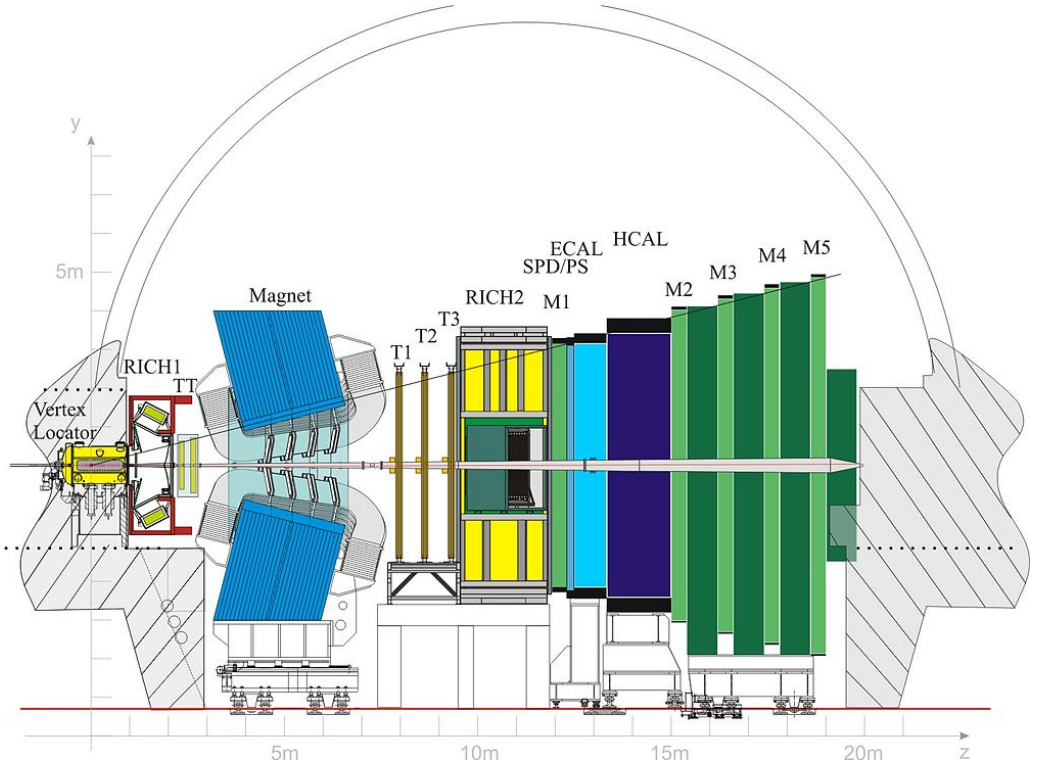


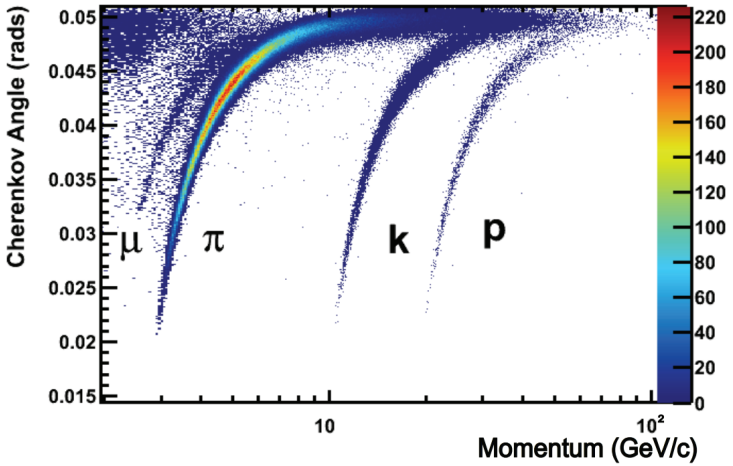




- Excellent Impact Parameter (IP) resolution ($20\ \mu\mathrm{m}$).
  $\Rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim\ 40\ \mathrm{fs}$.
  $\Rightarrow$ Good separation of primary and secondary vertices.
- Excellent momentum ($\delta p/p \sim 0.5 - 1.0\%$) and inv. mass resolution.
  $\Rightarrow$ Low combinatorial background.

# LHCb detector - PID

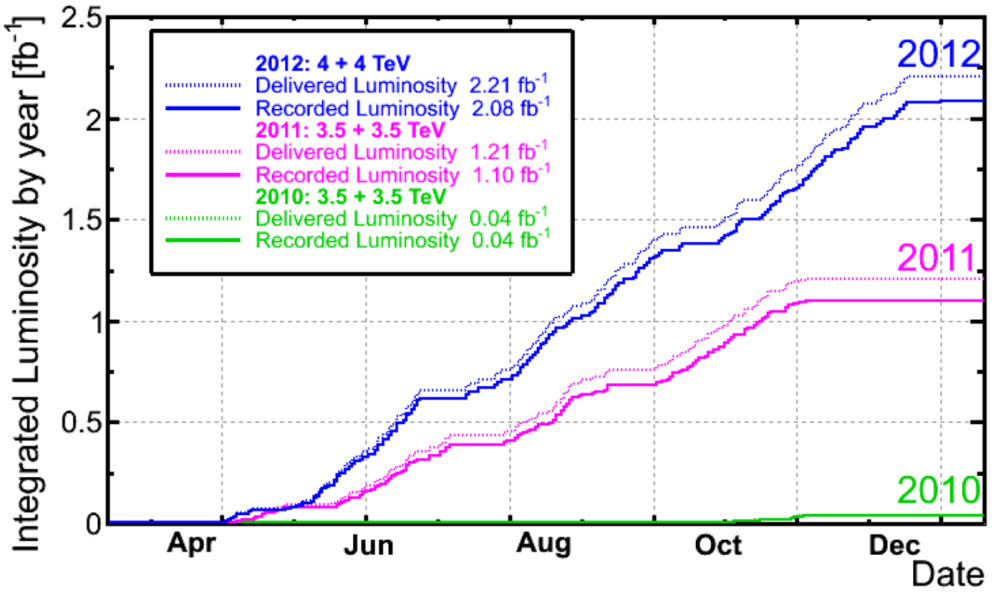
*Int. J. Mod. Phys. A30 (2015) 1530022*

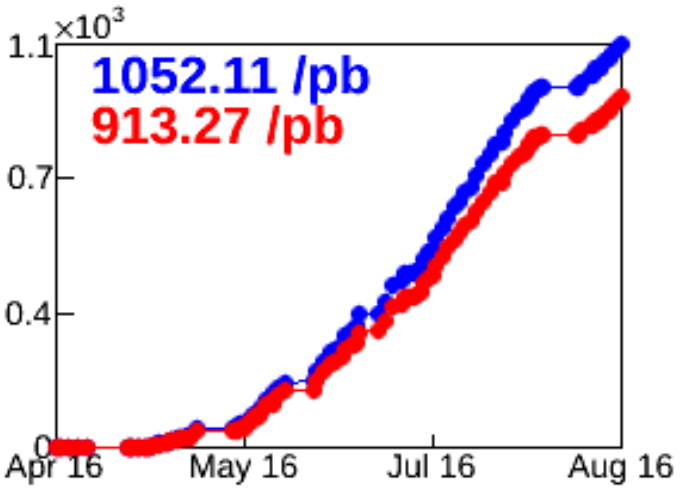



- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
- Good $K-\pi$ separation via RICH detectors, $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$.
  $\Rightarrow$ Reject peaking backgrounds.
- High trigger efficiencies, low momentum thresholds. Muons: $p_T > 1.76\mathrm{GeV}$ at L0, $p_T > 1.0\mathrm{GeV}$ at HLT1, $B \to J/\psi X$: Trigger $\sim 90\%$.

# Data taken by LHCb

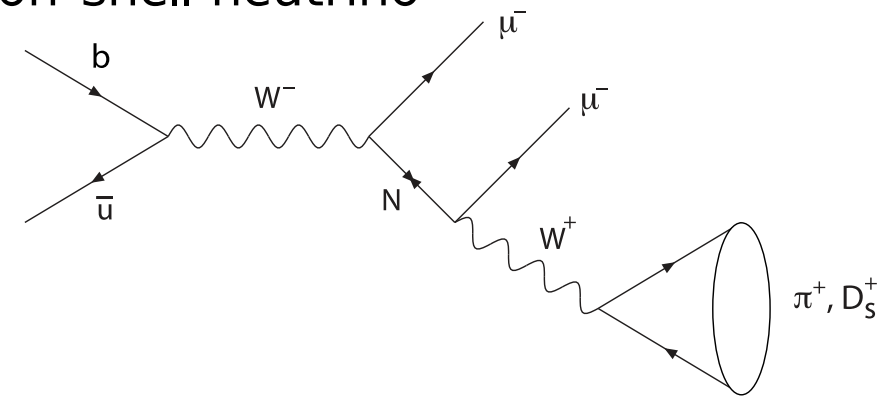


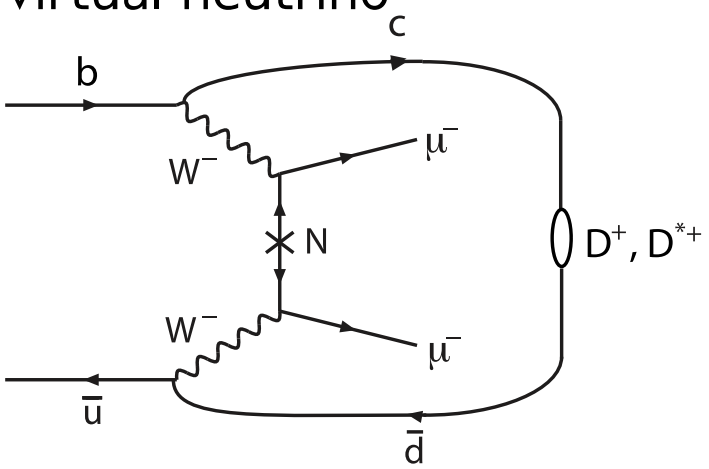

- In 2011 and 2012 LHCb has gathered $3\ \mathrm{fb}^{-1}$ of $pp$ collisions.
- Got $1\ \mathrm{fb}^{-1}$ in 2016 already!
- The cross section are now two times bigger compared to Run1.

# Majorana neutrinos in bottom decays

on-shell neutrino




virtual neutrino

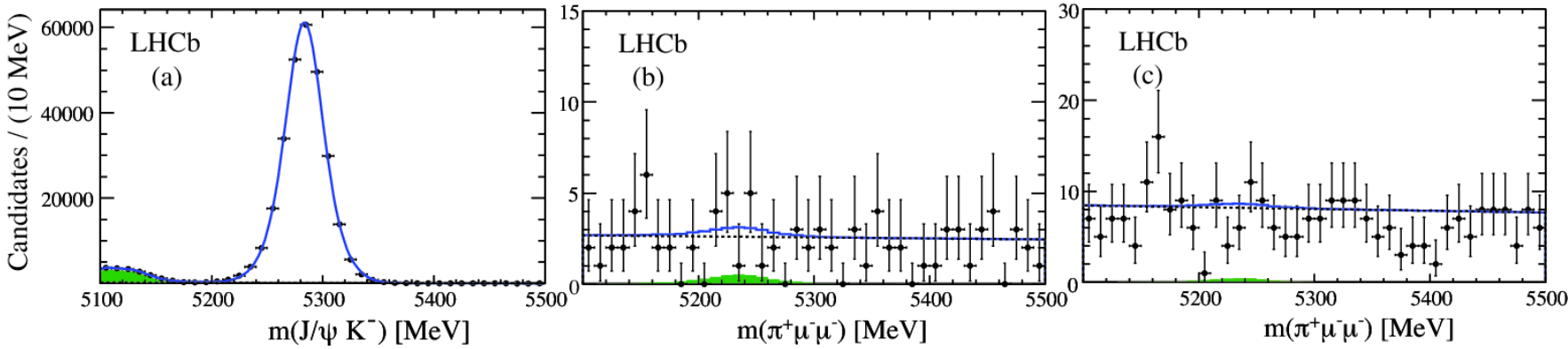


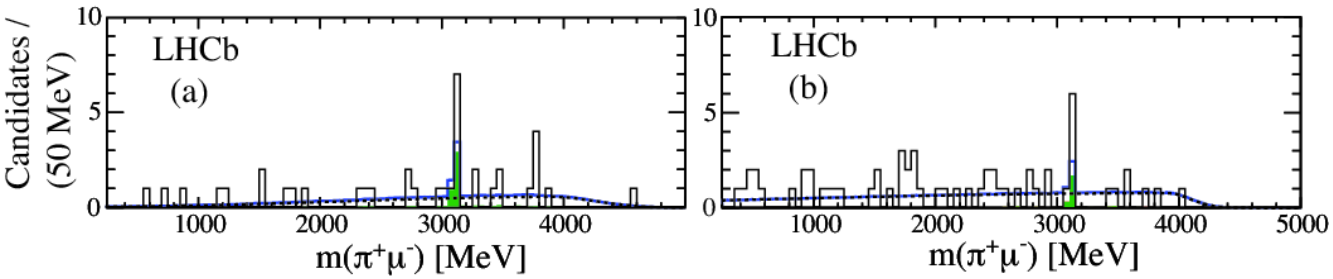

- resonant production in accessible mass range
- rates depend on Majorana neutrino–lepton coupling $|V_{\mu 4}|$ (e.g. arXiv:0901.3589)
- $m_4 = m_{\ell^-,\pi^+}$
- $m_\mu + m_\pi < m_4 < m_B - m_\mu$

Diagram without mass restriction
Cabibbo favoured for $B \to D$
Analogous to double $\beta$ decay.

# On-shell Majorana neutrinos

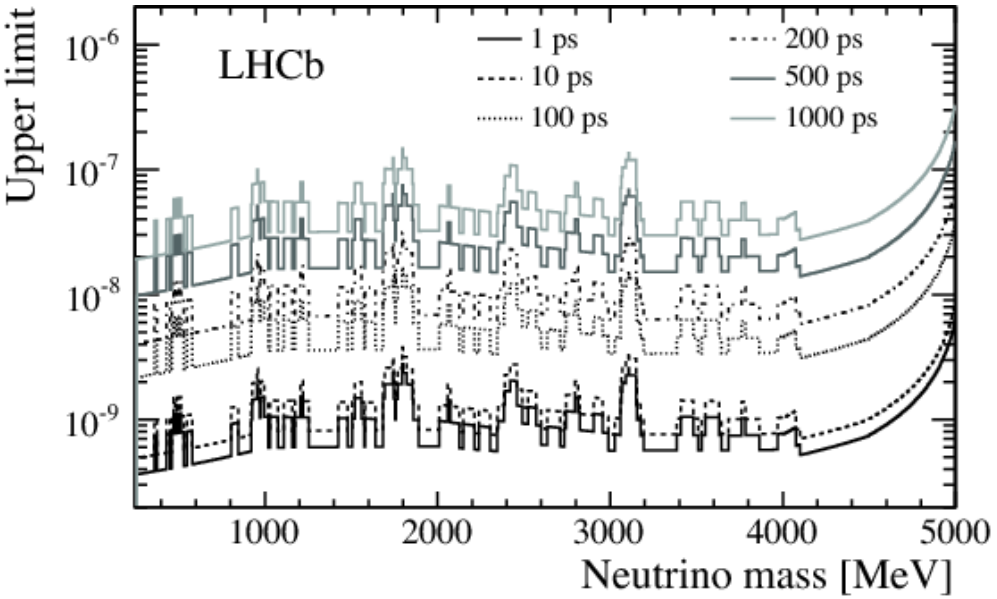
- $B^- \to \pi^+ \mu^- \mu^-$ searched with full data set $3\ \mathrm{fb}^{-1}$.
- Searches performed for two scenarios:
  - Short life-time neutrinos: $\tau_4 < 1ps$
  - Long life-time neutrinos: $\tau_4 \in (1, 1000)ps$

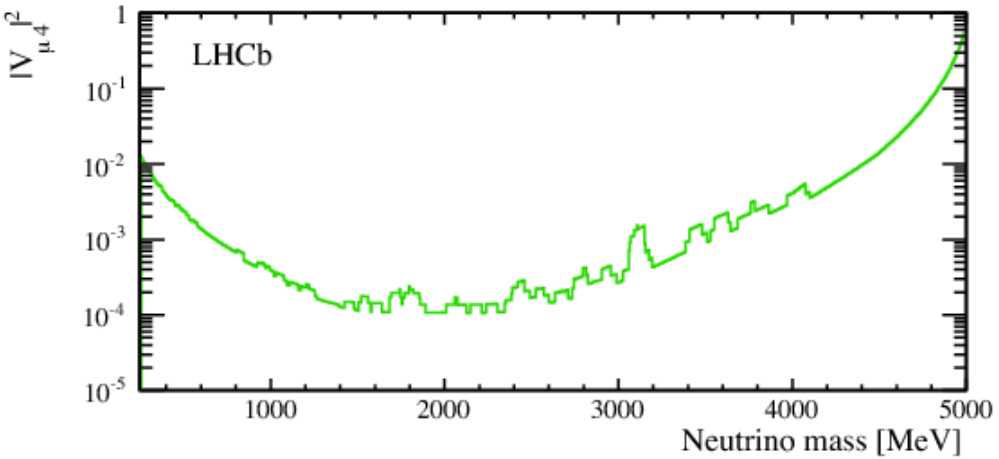



Phys. Rev. Lett. 112, 131802

# On-shell Majorana neutrinos



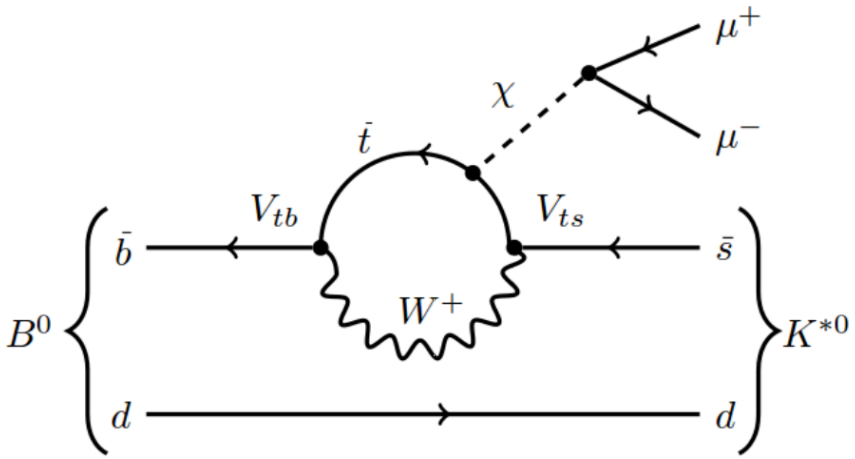

- In absence of signal UL. were set.
- $Br(B^- \to \pi^+ \mu^- \mu^-)$ in range $10^{-9}$.
- Limits also set for the coupling $|V_{\mu 4}|^2$

$$Br(B^- \to \pi^+ \mu^- \mu^-) = \frac{G_f^4 f_B^2 f_\pi^2}{128\pi\hbar} \tau_B m_B^5 |V_{ub}V_{ud}|^2 |V_{\mu 4}|^4 (1 - \frac{m_4^2}{m_B^2}) \frac{m_4}{\Gamma_{N_4}}$$

# $B \to K^* \chi(\mu\mu)$ search

- Search for displaced di-muon vertex coming form $B$ meson.

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




- If $\chi$ mixes with the Higgs and it is light:
  - $\Gamma(K \to \pi\chi) \propto m_t^4 \lambda^5$
  - $\Gamma(D \to \pi\chi) \propto m_b^4 \lambda^5$
  - $\Gamma(B \to K\chi) \propto m_t^4 \lambda^2$
- In addition; $K^* \to K^+ \pi^-$ helps in vertex reconstruction.
- High $\mathcal{B}(\chi \to \mu^- \mu^+)$.

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

Benchmark models:

1. *Inflaton*: arXiv:1403.4638
   - $\tau_\chi = 10^{-8} \div 10^{-10}$ s,
   - $m_\chi < \mathcal{O}$(1 GeV),
   - $\mathcal{B}(B \to K\chi) \sim 10^{-6}$

2. *Axion portal*: Phys.Rev.D81(2010)034001
   - prompt decay are favourite
   - axion decay constant: $f_\chi \sim$ 1 - 3 TeV
   - $\mathcal{B}(\chi \to \mu\mu)$:
     - is dominant for $360 < m_\chi < 800$ MeV
     - $\sim \mathcal{O}(10^{-2})$ for 800 MeV $< m_\chi < 2m_\tau$

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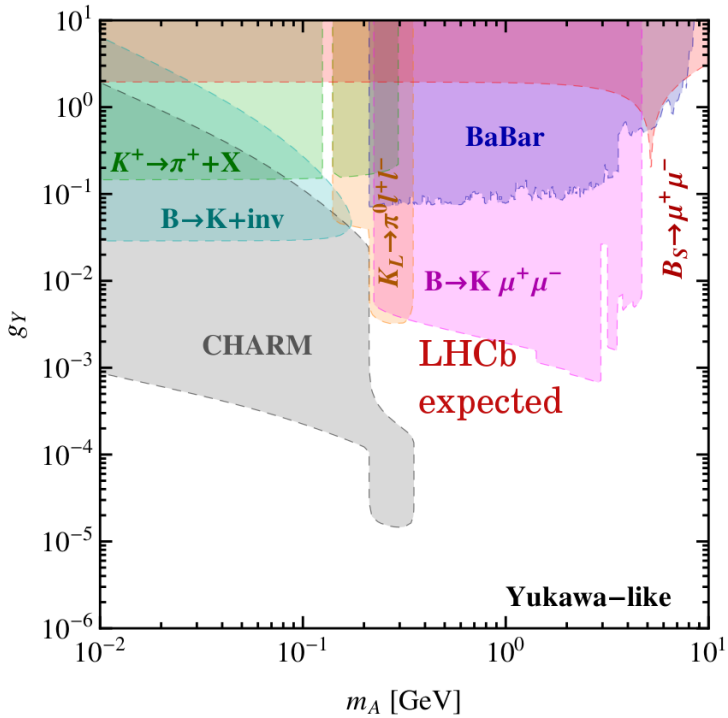
Existing experimental limit

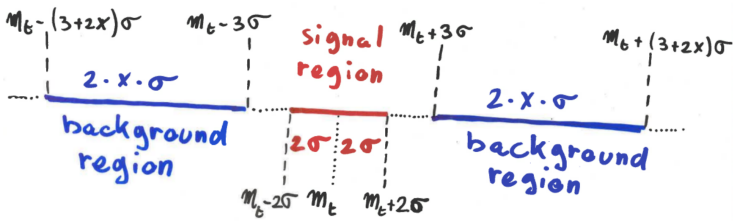



[JHEP 1503 (2015) 171]

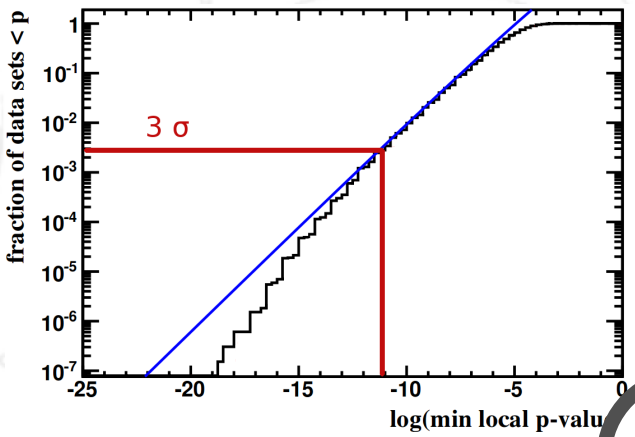
# $B^0 \to K^{*0}(\chi \to \mu^+\mu^-)$: strategy of the search

- Looking for di-muon resonance: [JINST 10(2015)P06002]
  - scan in step of $1/2\ \sigma_m(\chi)$

- Definition of search regions:
  - *signal*: $\mid m_{test} - m \mid < 2\sigma_m$
  - *background*: $3\sigma_m < \mid m_{test} - m \mid < (2x+3)\sigma_m$




- Background evaluation assume local linearity:
  - wide resonances are safe (small deviation from local linearity)
  - narrow resonances must be vetoed
  - $\mathcal{O}(10\%)$ deviations are allowed
    - $x = 5$ below the $J/\psi$ mass
    - $x = 1$ above the $J/\psi$ mass
- A global $p$-value is assigned from the minumum local $p$-value observed



Phys. Rev. Lett. 115, 161802 (2015)

- Trigger on muons.
- Multivariate selection: $\mu\mathrm{BDT}$ JINST 8(2013)
  - $\mu\mathrm{BDT}$ ensures flat efficiency in lifetime of $\chi$.
- Optimized on Punzi figure-of-merit:

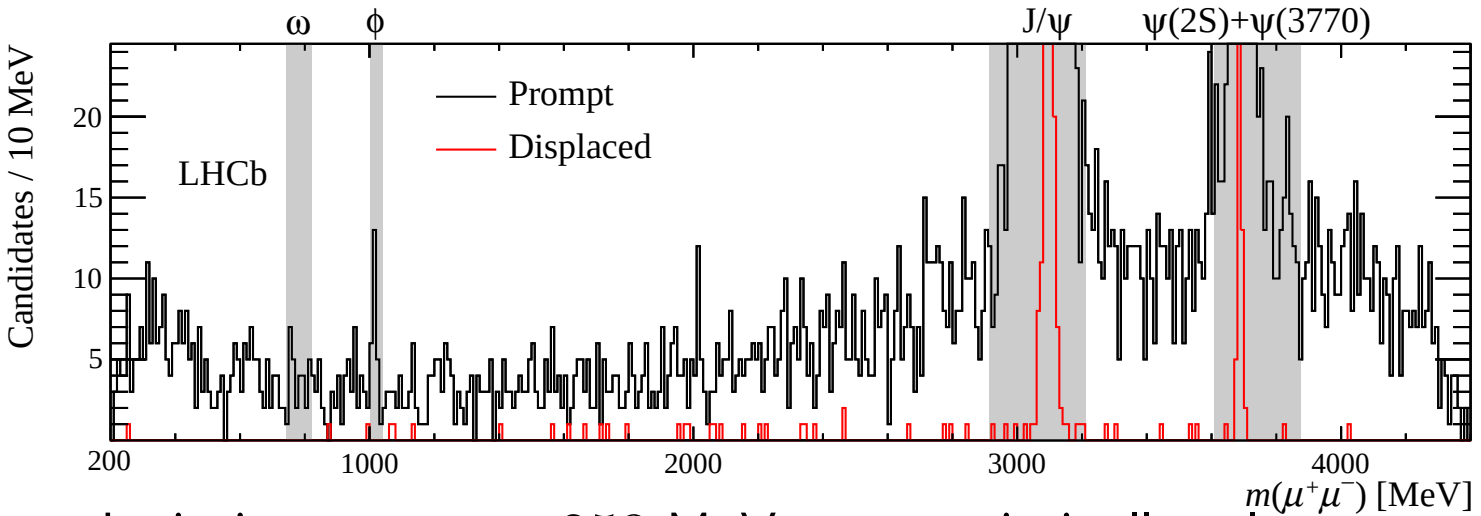
$$P_a = \frac{S}{\frac{5}{2} + \sqrt{B}},$$

  with $S$ and $B$ are signal and background yields.
- Factorize lifetime into two components: $\mathcal{L} = \mathcal{L}^{\mathrm{prompt}} \bigotimes \mathcal{L}^{\mathrm{displaced}}$
  - Prompt: $\tau < 3\sigma_\tau$
    $\mapsto$ SM background of $B^0 \to K^* \mu^- \mu^+$
  - Displaced: $\tau > 3\sigma_\tau$
    $\mapsto$ Almost background free.

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

*Phys. Rev. Lett. 115, 161802 (2015)*

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




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

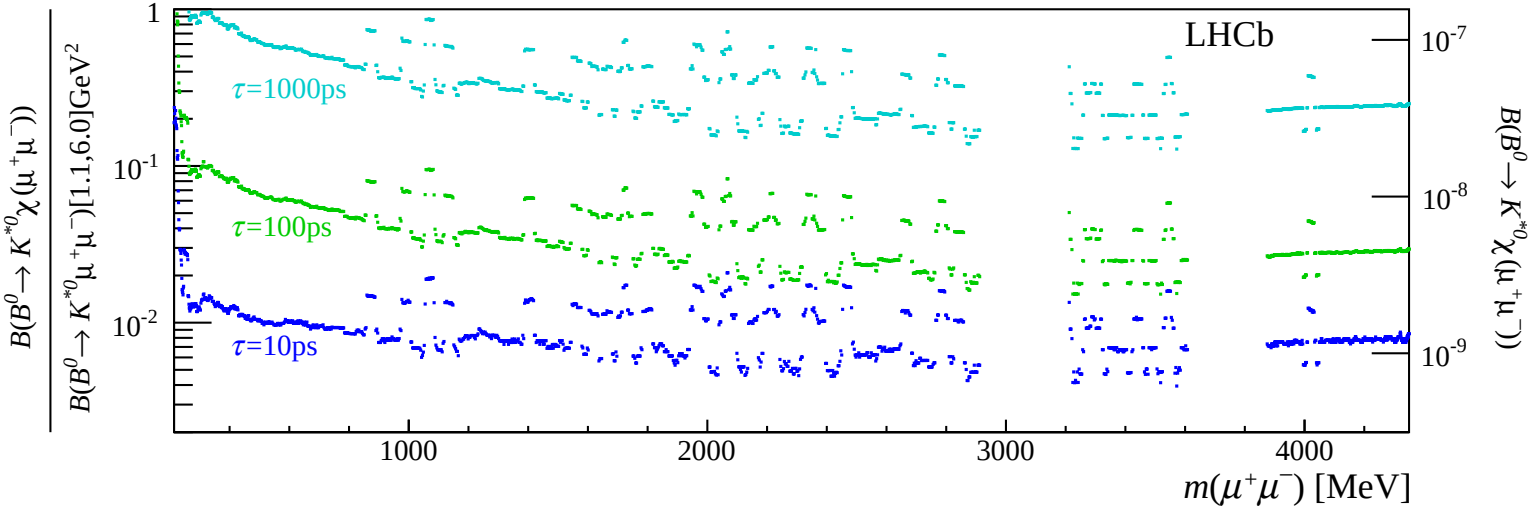
- local $p$-value = 0.02

# Exclusion limit

*Phys. Rev. Lett. 115, 161802 (2015)*

No deviation from the standard model is observed

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

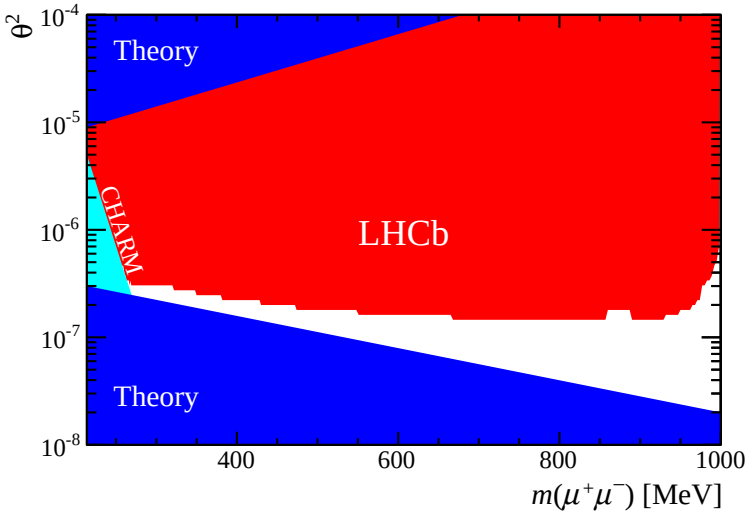


# The two benchmark models

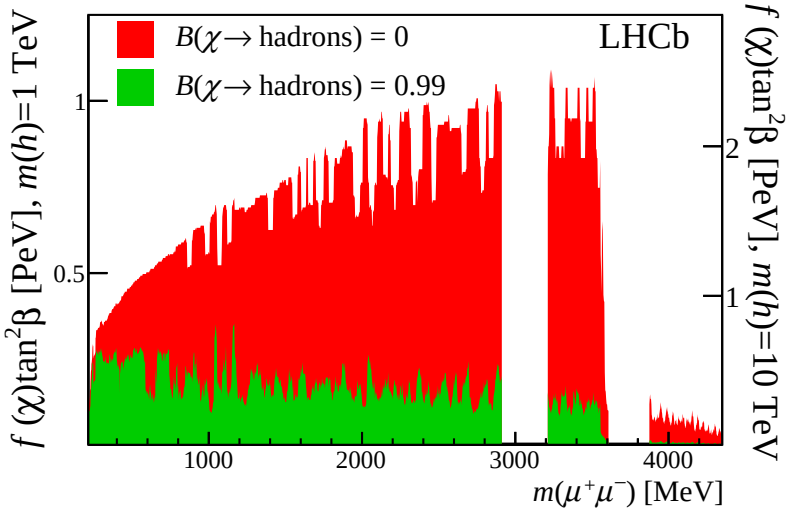
*Phys. Rev. Lett. 115, 161802 (2015)*

Interpretation of the result in two specific model:

## Inflaton model




## Axion portal




1. Able to exclude the large part of inflaton parameter space
2. Two exclusion limits are shown in the interpretation of the axion portal
   - $\chi$ dominantly decaying into muons
   - $\mathcal{B}(\chi \to \mu\mu) \sim \mathcal{O}(10^{-2})$ (when $\chi \to 3\pi$ becomes dominant)

# Hidden valley searches

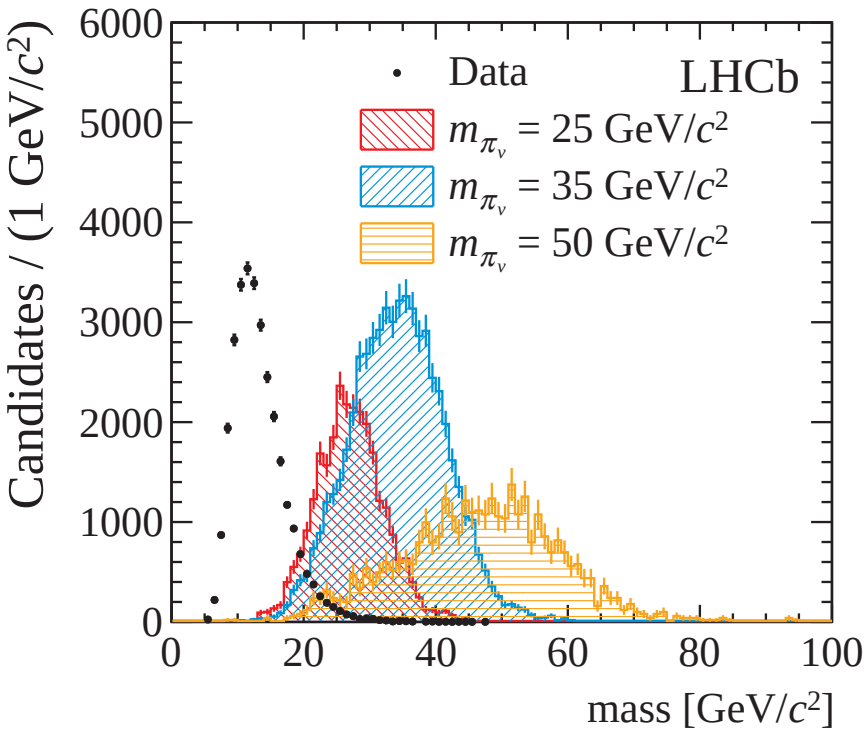
*Eur. Phys. J. C 75 (2015) 152*

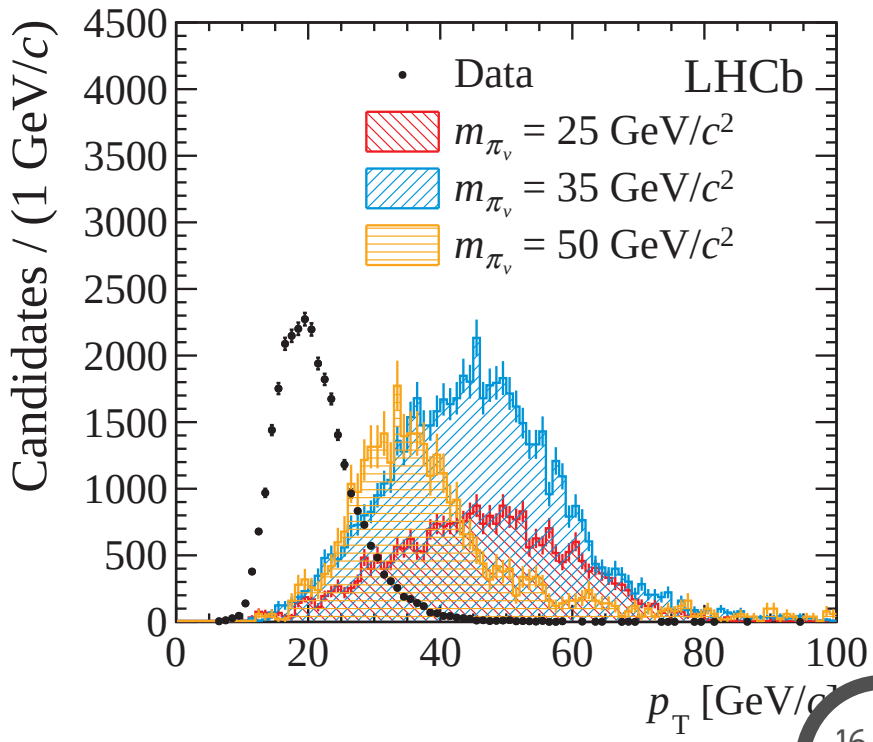
- A possible extensions of the SM are models where the new particles have a small couplings to the SM particles.
- Such models are:
  - Lightest SUSY
  - B/LNV
  - Gravity mediated SUSY
  - Hidden Valleys
- LHCb have performed a search for $\pi_\nu$ particles that are pair produced from Higgs like SM particle.
- They have a long lifetime and decay to pair of jets.

# Analysis strategy

*Eur. Phys. J. C 75 (2015) 152*

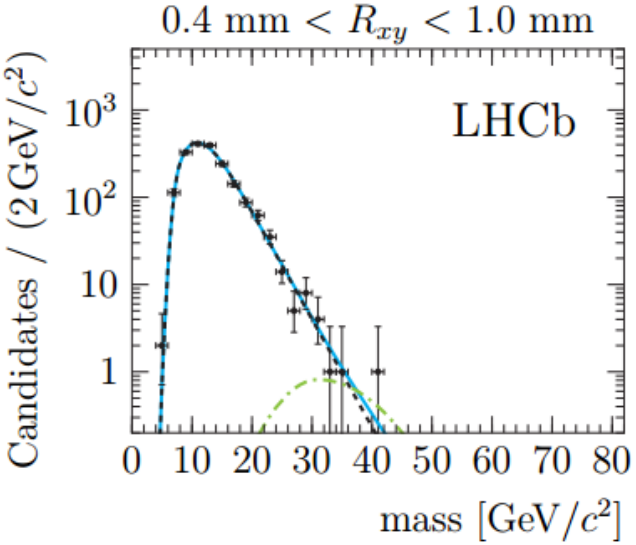
- Efficient trigger for long living particles.
- Reconstruction of two jets.
- MVA used for vertex search.
- Search performed in different regions of displaced vertexes ($R_{xy}$).
  - $0.4 < R_{xy} < 4$ mm, removes heavy flavour and material interaction backgrounds.

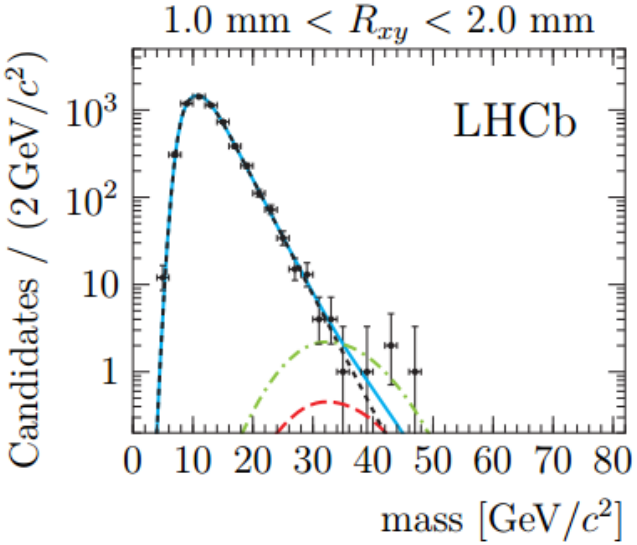


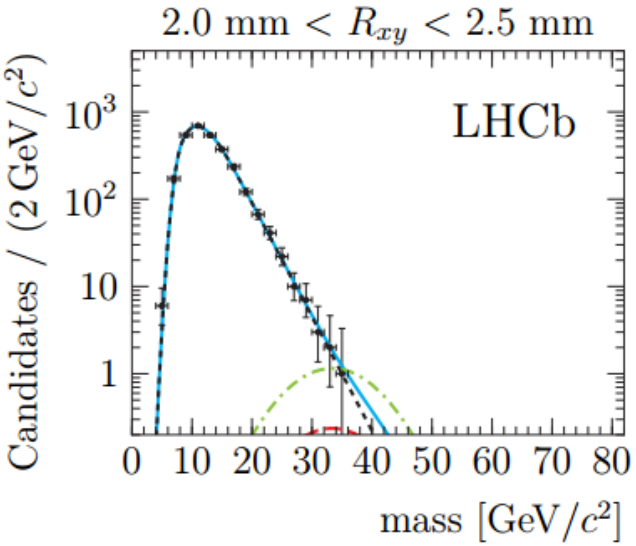



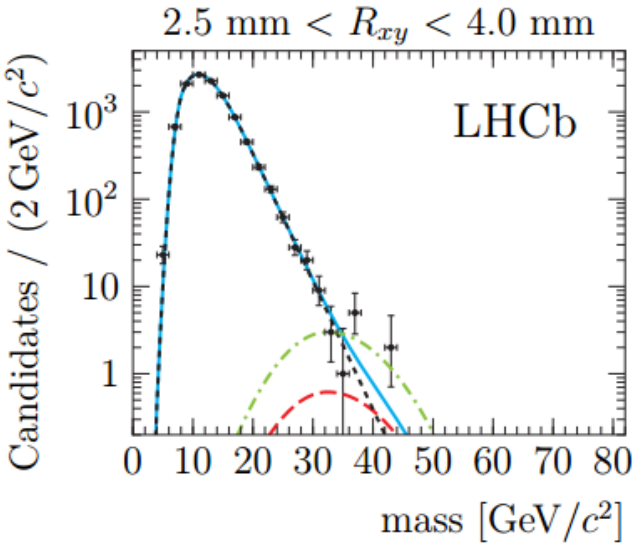
# Di-jet distribution

*Eur. Phys. J. C 75 (2015) 152*



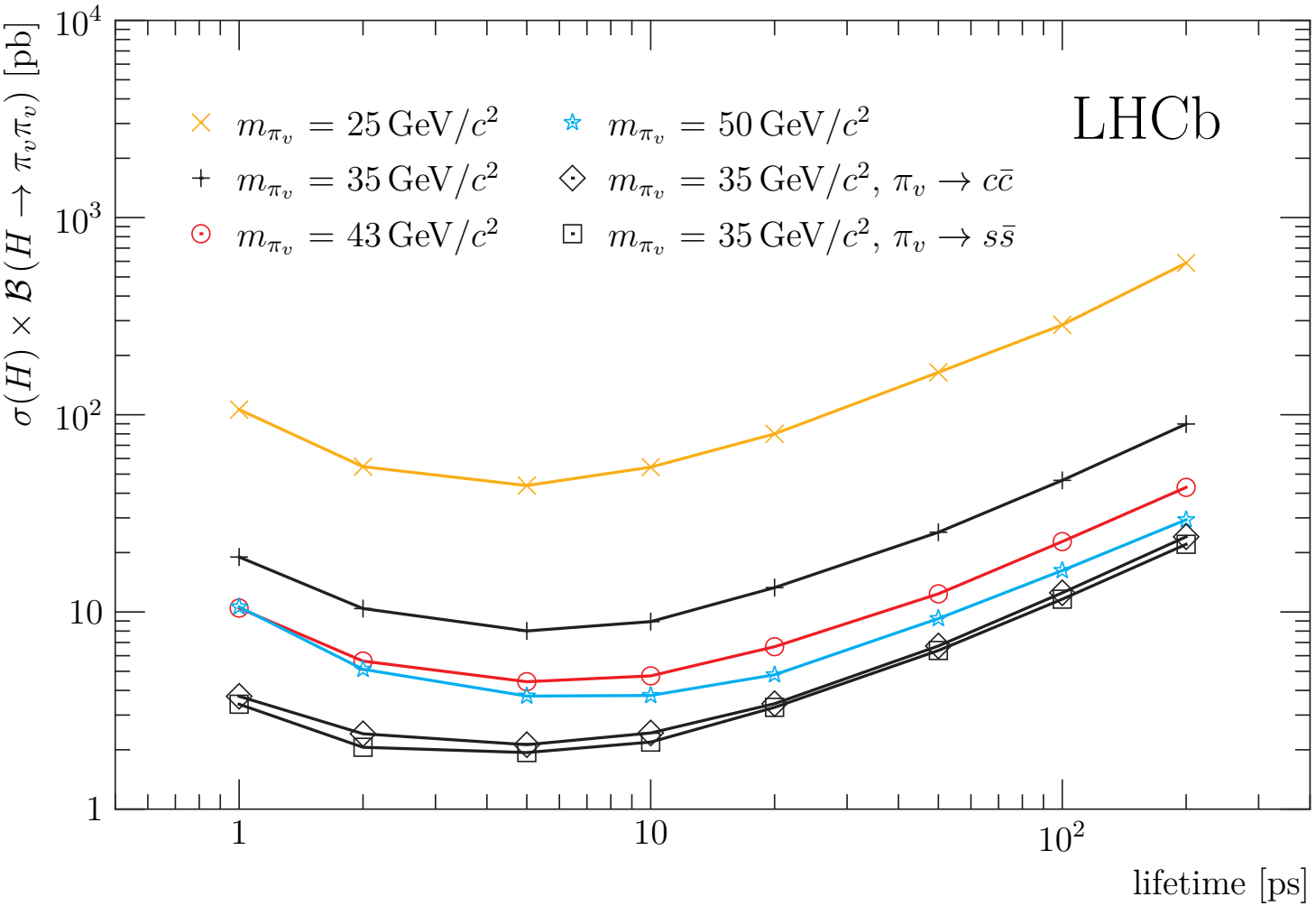




- Signal component fit result, Background component

# Results

*Eur. Phys. J. C 75 (2015) 152*



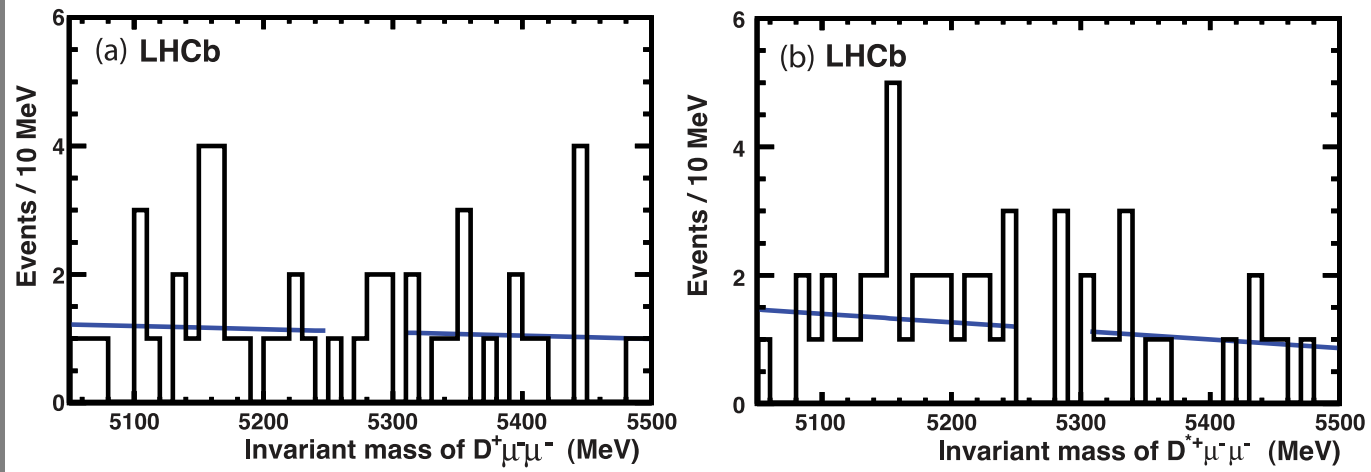
# Conclusion

1. Three examples of displaced vertex searches for new physics have been presented, using the Run I LHCb data set
   - very clear new physics signature, SM background highly suppressed
   - more channels are going to be studied
2. Results are the most up-to-date exclusion limit on the processes
3. LHCb is able to exclude almost all the theoretical predicted parameter space of a specific Inflaton model

# Backup

# Virtual Majorana neutrinos

$B^- \to D^+ \mu^- \mu^-$ $B^- \to D^{*+} \mu^- \mu^-$




$\mathcal{B}(B^- \to D^+ \mu^- \mu^-) < 6.9 \times 10^{-7}$
@ 95 % CL
Based on $0.41\ \mathrm{fb}^{-1}$ $7\ \mathrm{TeV}$ data.

$\mathcal{B}(B^- \to D^{*+} \mu^- \mu^-) < 2.4 \times 10^{-6}$
@ 95 % CL

Phys. Rev.D85 (2012) 112004

# Long living charged particles like $\widetilde{\tau}$

$\Rrightarrow$ Long living particles can also be produced in the PV.

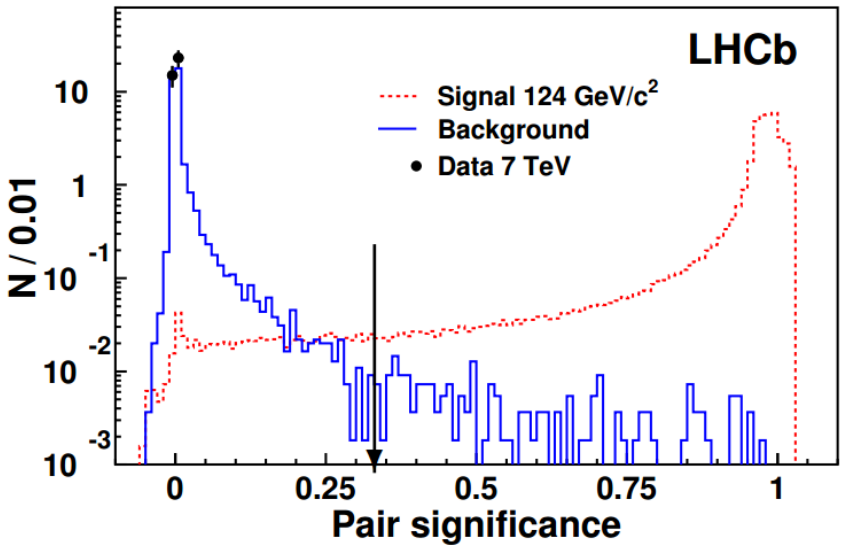
- This kind of particles would be produce in relatively low velocities and could be identified by their time -of-flight, $dE/dx$ or in Cherenkov detectors.

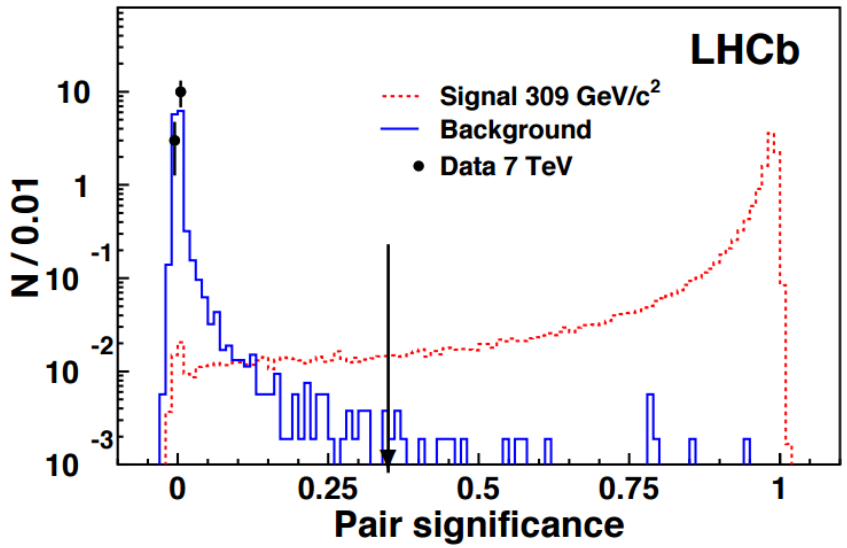
$\Rrightarrow$ LHCb performed a search for long living $\widetilde{\tau}$ particles.
$\Rrightarrow$ $\widetilde{\tau}^{+}\widetilde{\tau}^{-}$ produced by Drell-Yan process.

# $\widetilde{\tau}$ analysis strategy

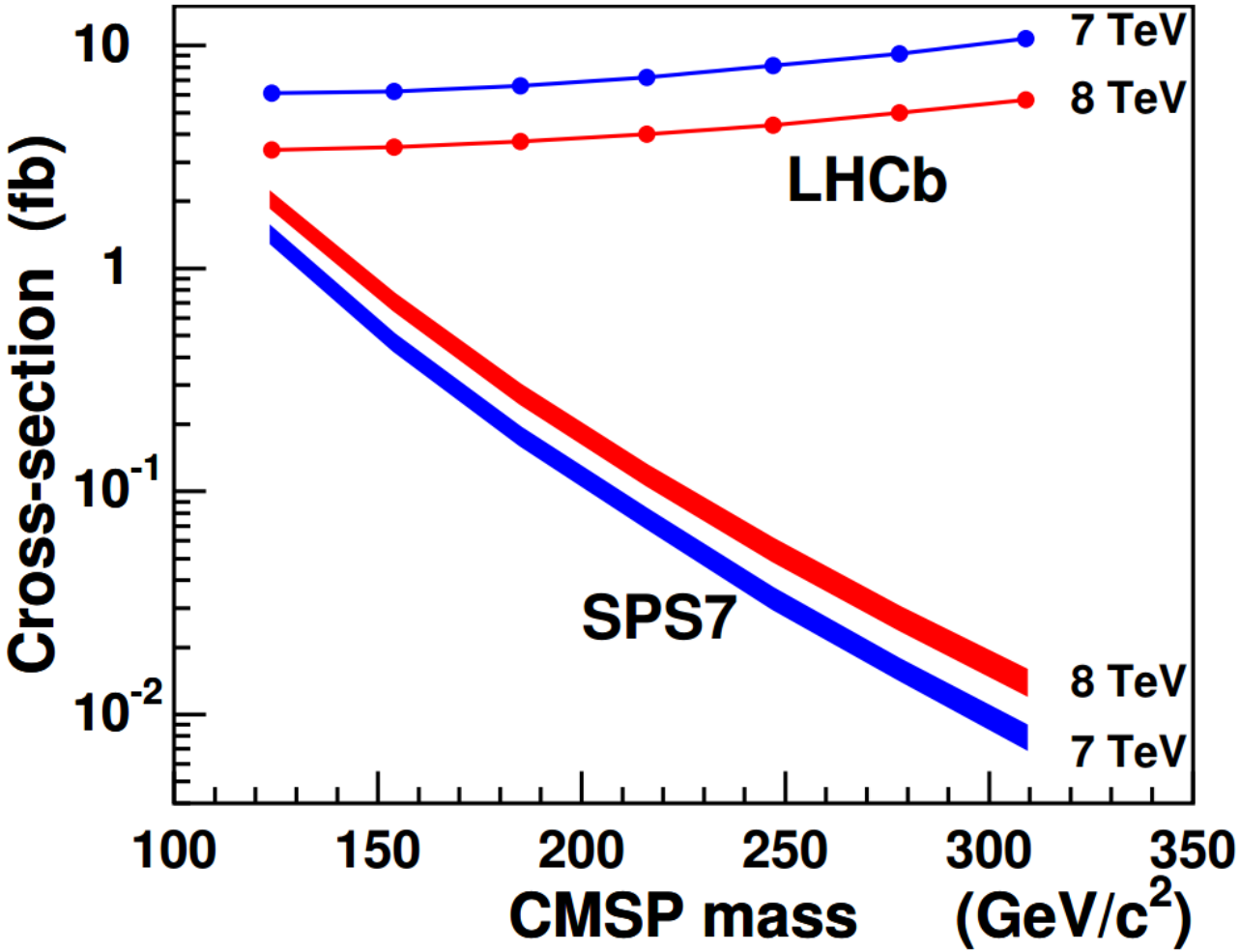
$\Rrightarrow$ Search performed $\widetilde{\tau}$ in mass range of $124 - 309$ GeV.

$\Rrightarrow$ After the loose preselection to reduce normal Drell-Yan production.




$\Rrightarrow$ After the preselection an Neural Net is trained based on Cherenkov detectors to calculate to further suppress the remaining background.

# $\tilde{\tau}$ results

- No significant signal yield has been observed.
- $95\ \%$ upper limit has been set.