

Search for long-lived particles at LHCb

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Outline

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2 Updated search for long-lived particles decaying to jet pairs

arXiv:1705.07332, submitted to Eur.Phys.J. C in May 2017

3 Search for Higgs-like bosons decaying into long-lived exotic particles

Eur.Phys.J. C (2016) 76:664, arXiv:1609.03124

4 Search for massive long-lived particles decaying semileptonically in the LHCb detector

Eur.Phys.J. C (2017) 77:224, arXiv:1612.00945

5 Summary

Introduction

- ▶ 3 LHCb searches for long-lived particles that decay with detectable displaced vertices
- ▶ another LHCb search (A.Mauri, LLPs in B decays) in “Dark Matter” session

Examples of long-lived particles in New Physics models

Hidden sector particles decaying to ordinary matter via feeble portal interaction

- ▶ e.g., “Hidden valley” massive long-lived scalar π_V decaying to $b\bar{b}$ (2 jets) in hidden sector models feebly interacting with ordinary matter via Higgs portal
- ▶ M.J.Strassler and K.M.Zurek, PLB 651 (2007) 374; M.J.Strassler and K.M.Zurek, PLB 661 (2008) 263; S.Chang, R.Dermisek, J.F.Gunion, and N.Weiner, Ann.Rev.Nucl.Part.Sci. 58 (2008) 75; N.Craig, A.Katz, M.Strassler, and R.Sundrum, JHEP 07 (2015) 105; D.Curtin and C.B.Verhaaren, JHEP 12 (2015) 072

mSUGRA LSP decaying via feeble baryon-number-violating interaction

- ▶ D.E.Kaplan & K.Rehermann, JHEP 10 (2007) 056; P.W. Graham, D.E.Kaplan, S.Rajendran, P.Saraswat, JHEP 07 (2012) 149

mSUGRA LSP decaying via feeble R-parity-violating interaction

- ▶ B.C.Allanach, A.Dedes, and H.K.Dreiner, PRD 69 (2004) 115002

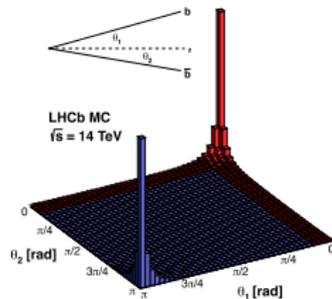
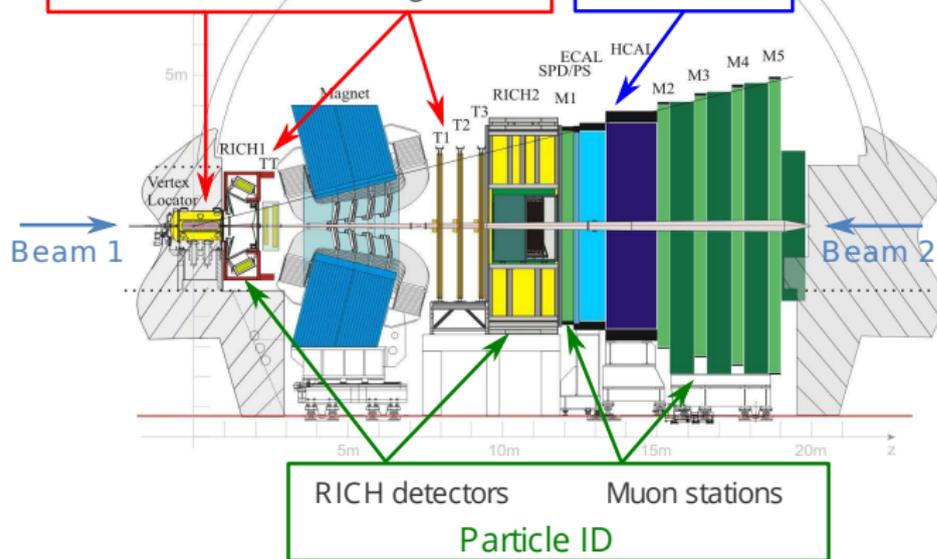
LHCb detector

Momentum & Vertices

Vertex locator Tracking stations

Energy

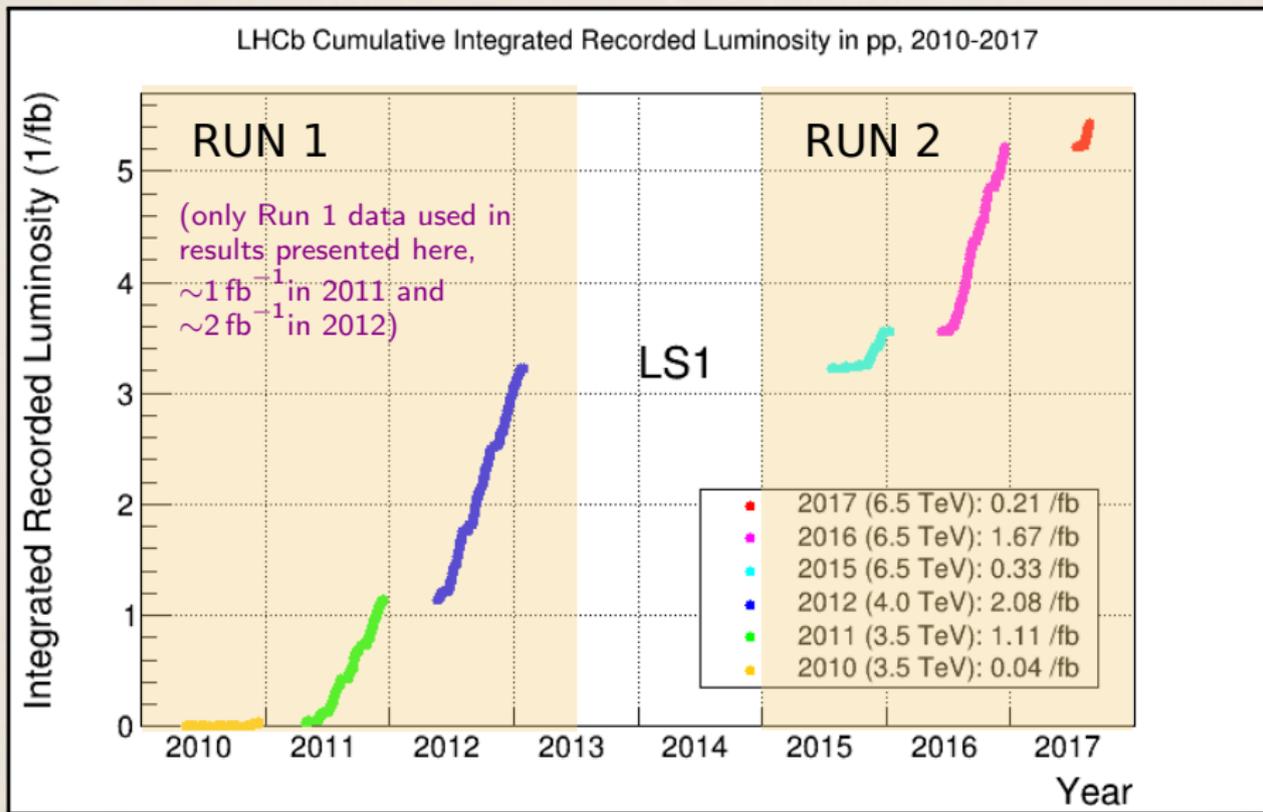
Calorimeters



25% of $b\bar{b}$ pairs in LHCb acceptance

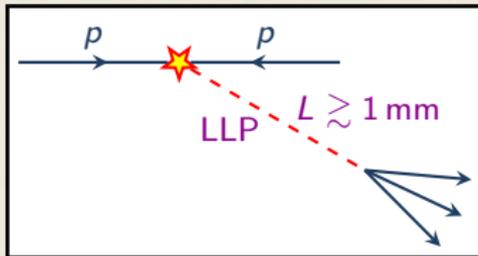
- ▶ Int.J.Mod.Phys. A 30, 1530022 (2015)
- ▶ single arm spectrometer focused on forward b hadrons studies

LHCb accumulated luminosity



Long-lived particles at LHCb

- ▶ the following searches look for particles with a lifetime
 - ▶ long enough to give decay vertices with measurable radial displacement from beams
 - ▶ short enough to decay in LHCb detector, to permit reconstruction of decay vertex



- ▶ LLPs detectable at LHCb have
 - ▶ lifetime $\gtrsim 1$ ps
 - ▶ narrow widths

Long-lived particles at LHCb

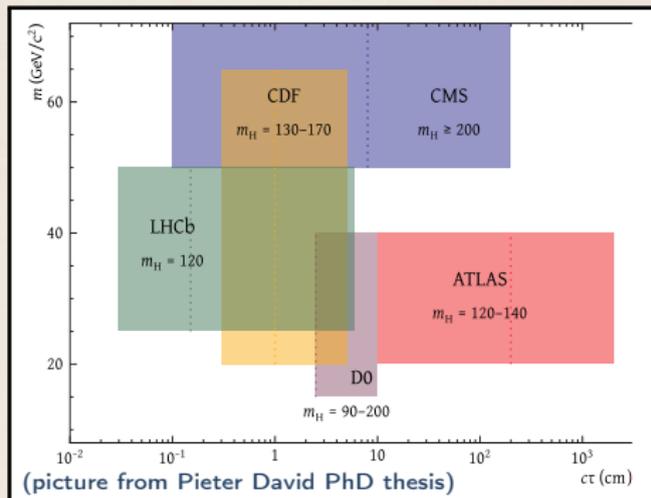
LHCb vertexing

- ▶ $\lesssim 20$ cm along the beam using vertex locator (VELO)
 - ▶ fires trigger
- ▶ $\lesssim 200$ cm along the beam using trigger tracker (TT)
 - ▶ worse vertex and p resolution

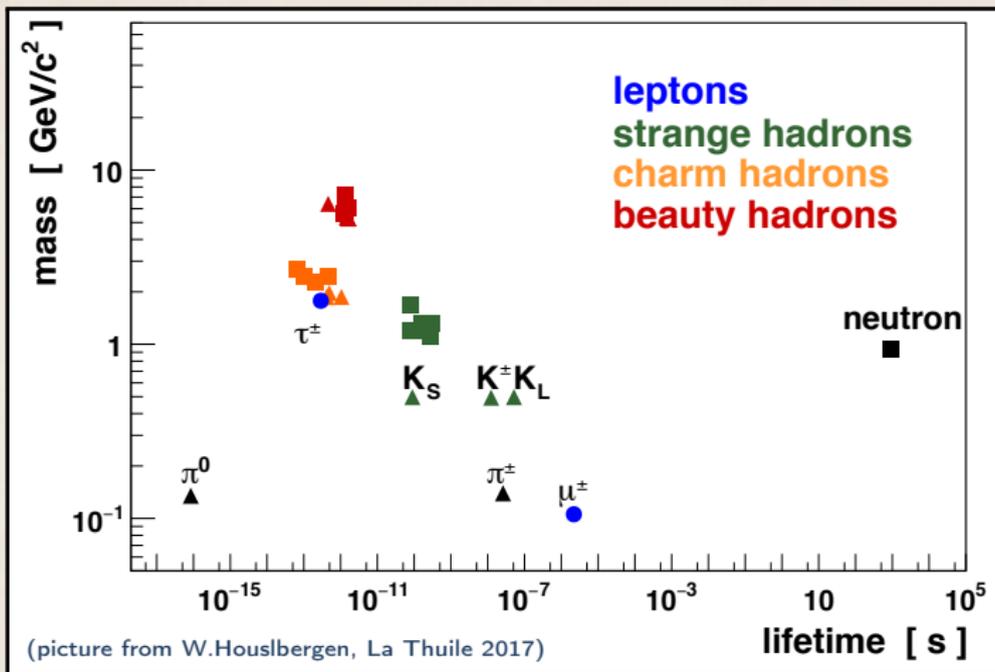
LHCb complementary to ATLAS & CMS

- ▶ shorter lifetimes, down to ~ 1 ps
- ▶ lighter masses (down to ~ 25 GeV dijets)

regions with (subset of) published limits for the LLP \rightarrow dijet analyses



Long-lived particles in the Standard Model

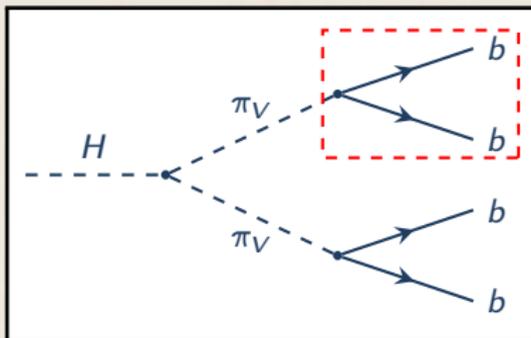


- ▶ backgrounds for searches presented here
- ▶ backgrounds typically very low for LLPs not matching SM particles

Updated search for long-lived particles decaying to jet pairs
arXiv:1705.07332, submitted to Eur.Phys.J. C in May 2017

Updated search for long-lived particles decaying to jet pairs

- ▶ search for $H \rightarrow \pi_V \pi_V$, $\pi_V \rightarrow 2$ jets with displaced vertex
 require detection of just one π_V : much larger acceptance but higher background



▶ dataset:

\sqrt{s} [TeV]	integrated luminosity [fb ⁻¹]
7	0.62
8	1.38

(limited by availability of required triggers)

- ▶ updates previous search on 0.62 fb⁻¹ of data at $\sqrt{s} = 7$ TeV

backgrounds and selection

main background sources

- ▶ displaced vertices from heavy-flavour decays
- ▶ interactions of particles with detector material

selection

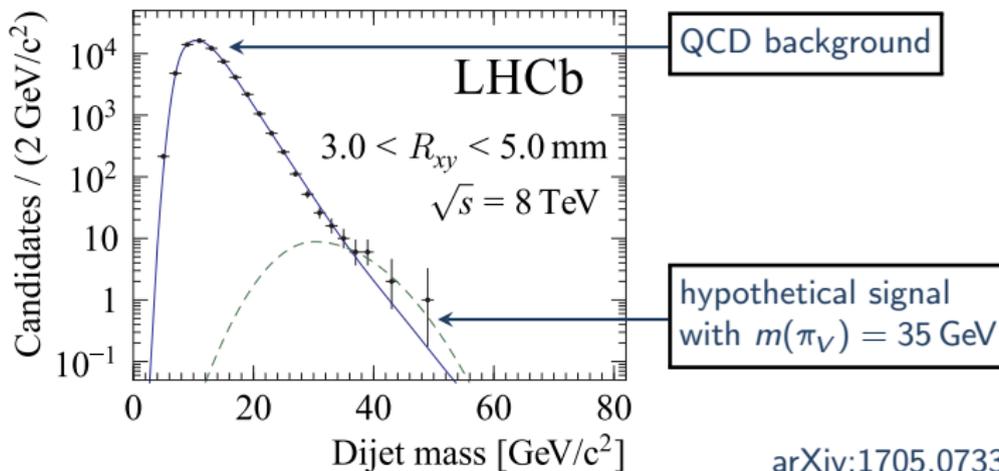
- ▶ rely inclusive trigger on displaced vertex
- ▶ one high-track-multiplicity vertex with significant radial distance R_{xy} w.r.t. beams line
- ▶ discard vertices located on detector material
- ▶ two jets (made of tracks neutral objects) with tracks associated to displaced vertex
- ▶ dijet candidate momentum must be aligned with displacement vector from one reconstructed primary vertex to displaced vertex
- ▶ kinematic separation of jets in pseudorapidity-azimuth $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 2.2$ (suppresses background from two back-to-back Standard Model background dijets)

fit signal + background

- ▶ fit signal + background dijet mass distributions in 6 bins of vertex displacement R_{xy}

signal model

- ▶ signal shape from simulation (PYTHIA8 tuned for LHCb, GEANT4)
 - ▶ simulated 4 π_V masses from 25 to 50 GeV
 - ▶ simulated 2 lifetimes which by re-weighting allow probing 2 – 500 ps



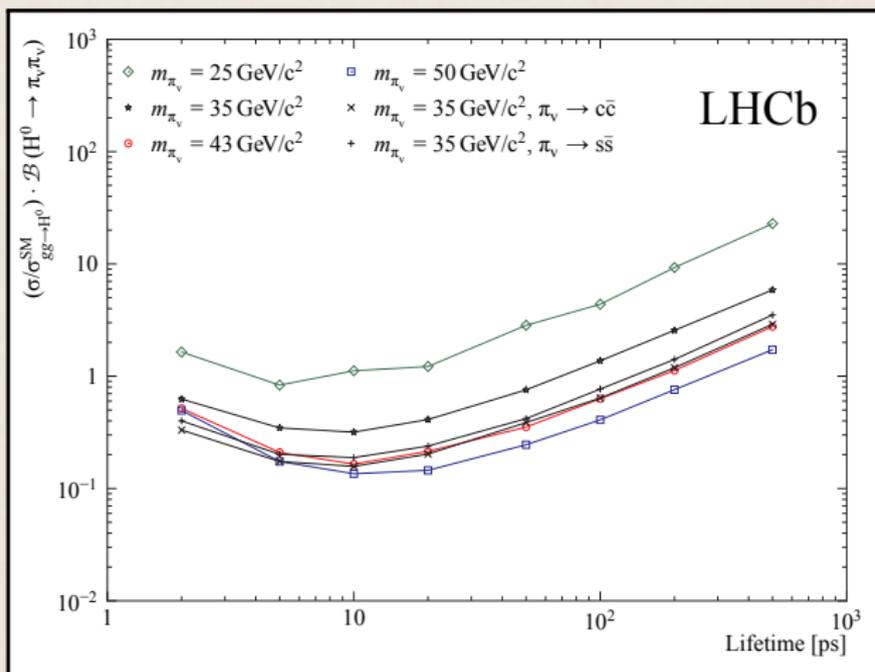
fit signal + background

backgrounds models

- ▶ combination of tracks from heavy-flavour decay or mat. interaction and primary vertex
 - ▶ modeled with bifurcated Gaussian convoluted with exponential
 - ▶ all parameters floated in fit
- ▶ Standard Model back-to-back dijets
 - ▶ less steeply falling mass spectrum
 - ▶ **fit bkg shape from data events failing the jet kinematic separation cut**
 - ▶ only normalization is floated in fit

Results, arXiv:1705.07332, submitted to Eur.Phys.J. C in May 2017

- ▶ no excess found, 95% CL upper limits set as function of π_V mass and lifetime with CLs
- ▶ w.r.t. similar ATLAS and CMS searches, more sensitive at small masses and lifetimes

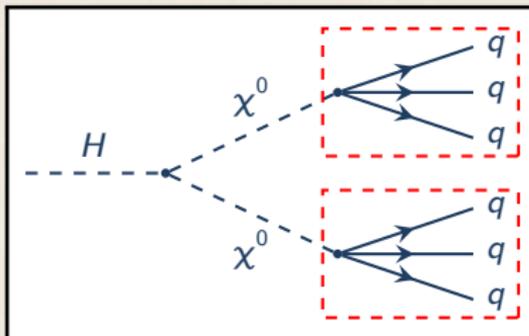


Search for Higgs-like bosons decaying into long-lived exotic particles

Eur.Phys.J. C (2016) 76:664, arXiv:1609.03124

Search for Higgs-like bosons decaying into long-lived exotic particles

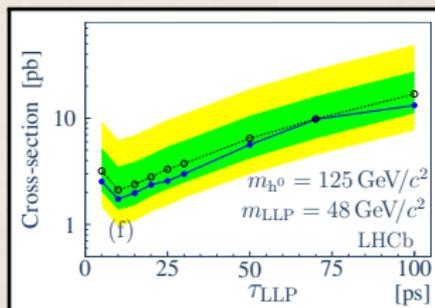
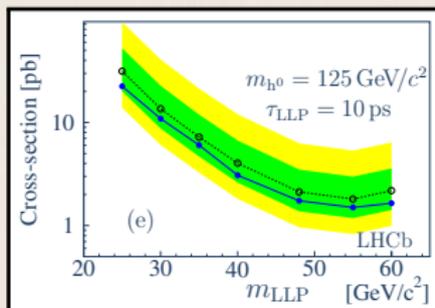
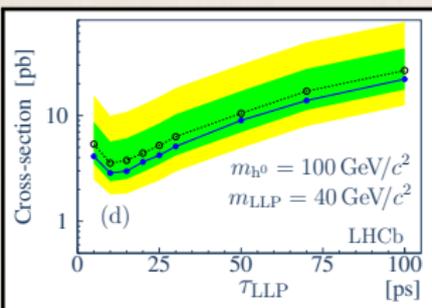
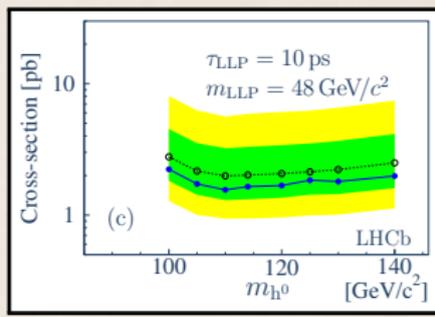
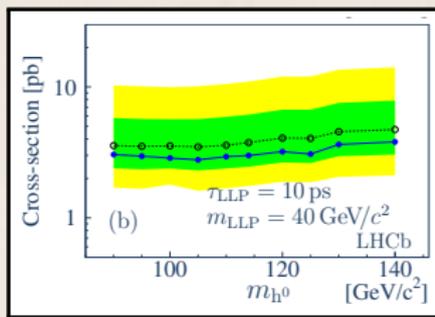
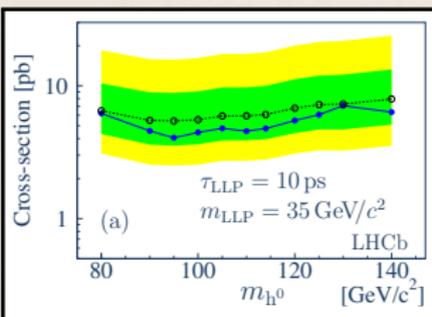
- ▶ search for mSUGRA neutralino pair-produced in Higgs decay $H \rightarrow \chi^0 \chi^0$ where each neutralino decays in three quarks $\chi^0 \rightarrow qqq$ (baryon number violating)
- ▶ look for pairs of high-multiplicity displaced vertices



- ▶ dataset: 0.62 fb^{-1} at 7 TeV

Results, Eur.Phys.J. C (2016) 76:664, arXiv:1609.03124

- no excess found, 95% CL upper limits set on the production cross-sections times branching fraction as function of neutralino mass and lifetime



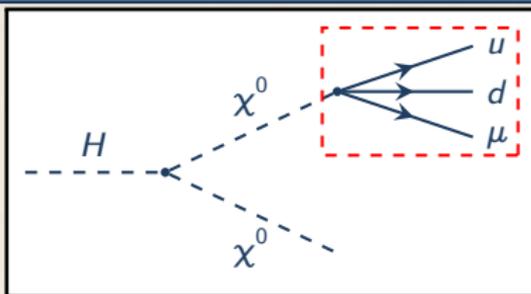
Search for massive long-lived particles decaying semileptonically in the LHCb detector

Eur.Phys.J. C (2017) 77:224, arXiv:1612.00945

Search for massive long-lived particles decaying semileptonically

- ▶ search for **one** long-lived mSUGRA neutralino (LLP) decaying into muon and two quarks
- ▶ several different production mechanisms for single or double neutralinos considered

some production mechanisms have a Higgs decaying into two neutralinos



▶ dataset:

\sqrt{s} [TeV]	integrated luminosity [fb ⁻¹]
7	1
8	2

backgrounds and selection

sources of background

- ▶ $b\bar{b}$ events (most relevant)
- ▶ W and Z decays
- ▶ material interactions

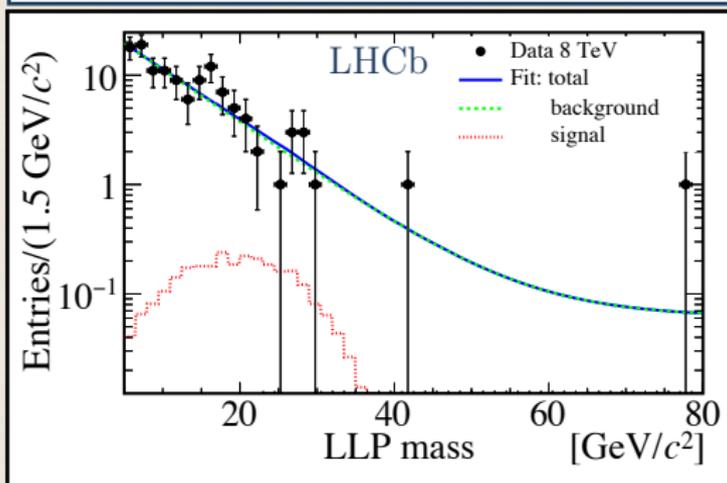
selection

- ▶ relies on trigger requiring a muon with $p_T > 10$ GeV
- ▶ **displaced vertex**: ≥ 4 tracks and significant radial distance R_{xy} from beams line
- ▶ one associated muon with high transverse momentum $p_T > 12$ GeV
- ▶ veto vertices in regions occupied by detector material
- ▶ multi-layer perceptron (MLP)

fit signal + background

- ▶ fit signal + background on LLP candidates mass distribution
- ▶ signal PDF from signal simulation mass distribution histogram
- ▶ signal and background normalizations floated
- ▶ background shape simultaneously fitted on data-driven bkg (see next slide)

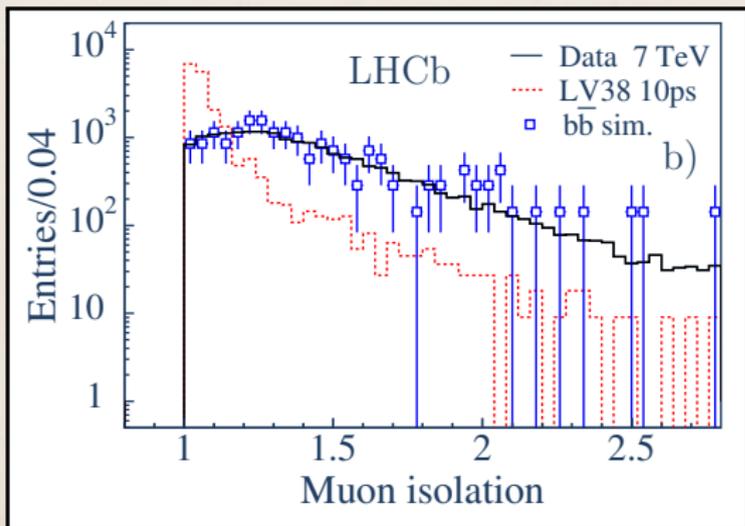
Eur.Phys.J. C (2017) 77:224, arXiv:1612.00945



fit signal + background

background model

- ▶ use selected data candidates with muon isolation variable $I_\mu > 1.4$
- ▶ 90% of signal for all models considered has muon isolation variable $I_\mu < 1.4$
- ▶ empirical PDF, sum of two negative slope exponential functions
- ▶ muon isolation cut checked to be orthogonal to other selection variables



muon isolation variable

$$I_\mu = \frac{\sum E_{\text{tracks}}}{E_\mu}$$

in pseudorapidity-azimuthal cone

$$R_{\eta\phi} < 0.3$$

(tracks include muon)

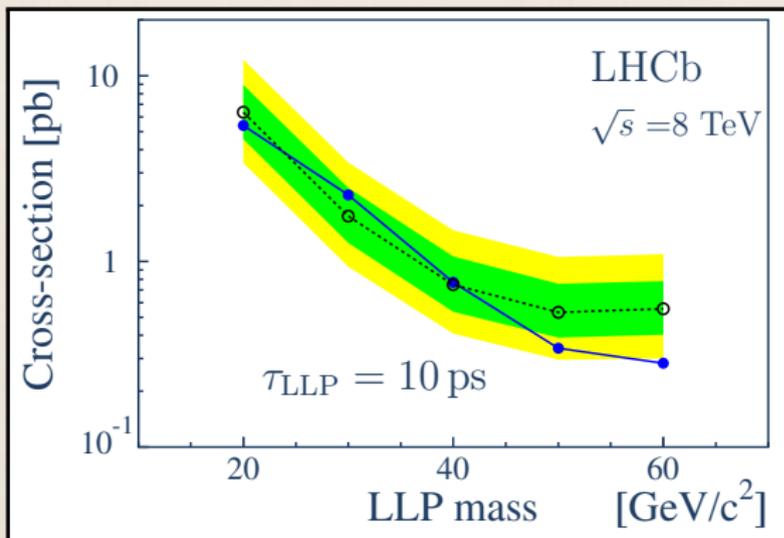
$I_\mu = 1 \Rightarrow \mu$ is isolated,

$I_\mu > 1 \Rightarrow \mu$ is less isolated

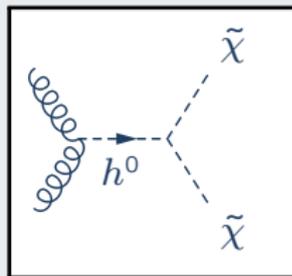
Eur.Phys.J. C (2017) 77:224,
 arXiv:1612.00945

Results, Eur.Phys.J. C (2017) 77:224, arXiv:1612.00945

- no excess found, 95% CL upper limits set on the production cross-sections times branching fraction for each considered model using the CLs method



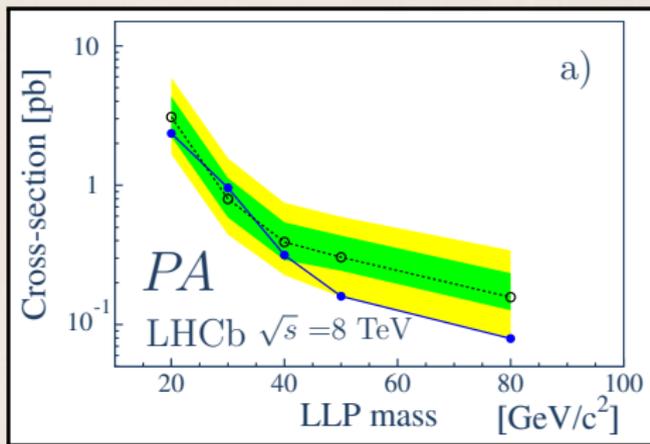
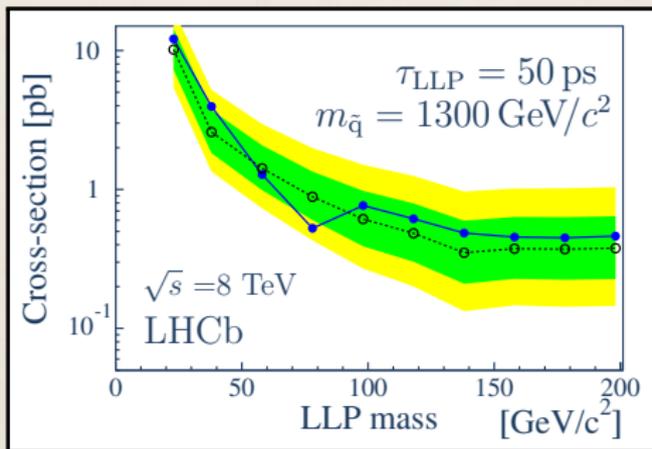
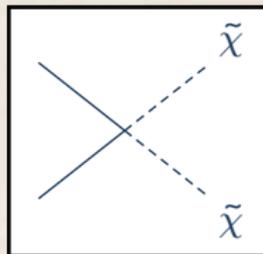
95% CL limits for model with 125 GeV Higgs decaying to two mSUGRA neutralinos



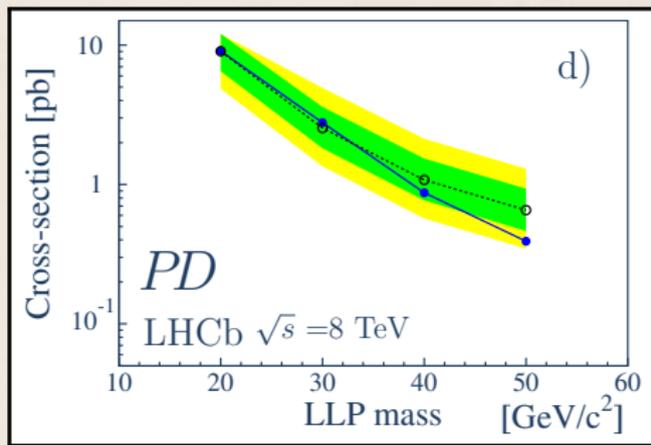
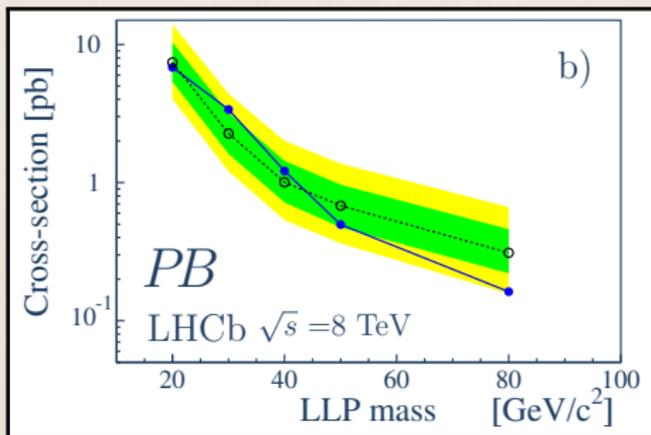
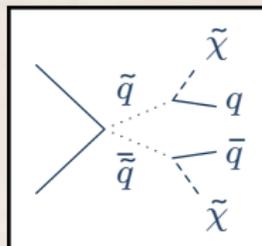
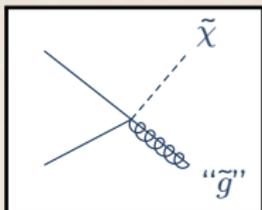
at $m_{\text{LLP}} = 50 \text{ GeV}$
and $\tau_{\text{LLP}} = 10 \text{ ps}$
reject $\mathcal{B}(H \rightarrow \chi\chi) > 1\%$

Results, Eur.Phys.J. C (2017) 77:224, arXiv:1612.00945

SUSY production in Pythia 6 (example)



Results, Eur.Phys.J. C (2017) 77:224, arXiv:1612.00945



Summary

- ▶ LHCb found no statistically significant excess of:
 - ▶ LLPs decaying to jet pairs,
(submitted to Eur.Phys.J. C in May 2017)
 - ▶ LLPs decaying to 3 quarks, pair-produced in Higgs decay
Eur.Phys.J. C (2016) 76:664
 - ▶ LLPs decaying semileptonically in the LHCb detector,
Eur.Phys.J. C (2017) 77:224
- ▶ upper limits have been set to constrain New Physics models



Backup Slides

LLPs to jet pairs, more detail on backgrounds and selection

main background sources

- ▶ displaced vertices from heavy-flavour decays
- ▶ interactions of particles with detector material

selection

- ▶ relies on inclusive trigger on displaced vertex at 2nd level (in addition, one displaced vertex is searched offline in events otherwise triggered)
 - ▶ ≥ 4 tracks, $R_{xy} > 0.4$ mm, $M(\pi_V) > 2$ GeV, $p_T(\pi_V) > 3$ GeV
 - ▶ or more complex requirements in offline vertex search
 - ▶ veto vertices in region around material of VELO vertex detector
- ▶ require two reconstructed jets with tracks associated with the displaced vertex
 - ▶ jets from tracks and calorimeter objects subtracting contribute of (charged) tracks
 - ▶ $p_T > 5$ GeV, at least 10% energy in charged tracks
- ▶ momentum vector of the dijet candidate must be aligned with displacement vector from one reconstructed primary vertex and the displaced vertex
- ▶ kinematic separation of jets in pseudorapidity-azimuth $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 2.2$ (suppresses background from two back-to-back Standard Model background dijets)

LLP to muon and two quarks, more details on backgrounds and preselection

sources of background

- ▶ $b\bar{b}$ events (most relevant)
- ▶ W and Z decays
- ▶ material interactions

preselection

- ▶ relies on trigger requiring a muon with $p_T > 10$ GeV
- ▶ displaced vertex
 - ▶ ≥ 4 forward tracks including muon, no backward track
 - ▶ $R_{xy} > 0.55$ mm
 - ▶ $m(\text{tracks}) > 4.5$ GeV
- ▶ associated muon
 - ▶ $p_T > 12$ GeV
 - ▶ impact parameter $\delta_{IP} > 0.25$ mm
- ▶ veto vertices in regions occupied by detector material

LLP to muon and two quarks, more details on selection

multi-layer perceptron (MLP)

- ▶ muon p_T and impact parameter
- ▶ number of charged particle tracks from displaced vertex
- ▶ vertex radial distance R_{xy} from beam line
- ▶ R_{xy} uncertainties σ_R and σ_z from vertex fit