Searches for Majorana Neutrinos and Direct Searches for Exotics at LHCb

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on behalf of the LHCb collaboration

LISHEP 2015

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Outline

Introduction to LHCb

Searches for Majorana neutrinos

- Majorana neutrinos at LHCb?
- $B^{\pm} \to h^{\mp}\mu^{\pm}\mu^{\pm}$
- $D^{\pm}_{(s)} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$

Searches for exotics

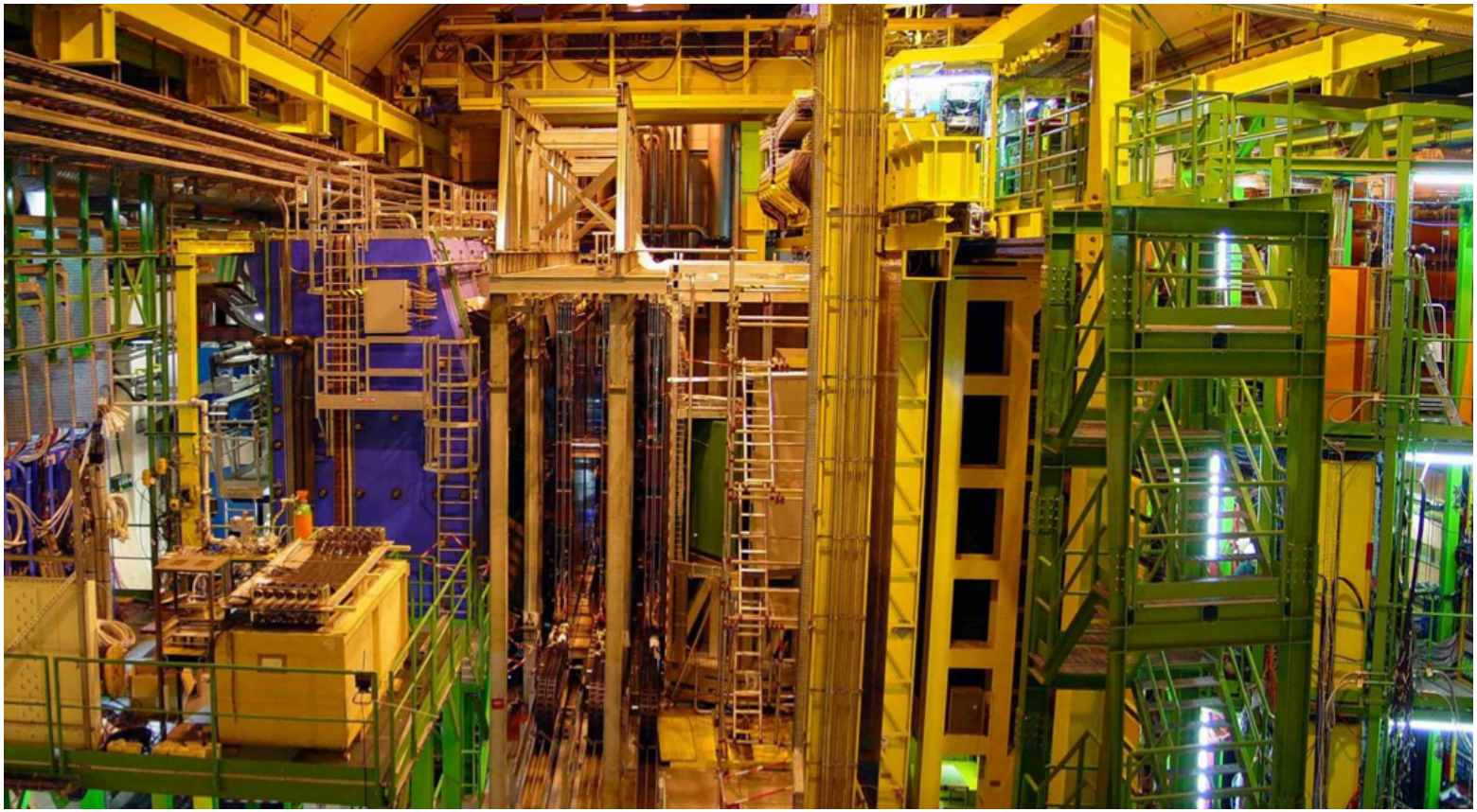
- Limits on $H^0 \to \tau^+\tau^-$ production
- H^0 decays to long-lived particles
- Search long-lived heavy charged particles
- Searches low mass dark bosons
- Towards $H^0 \to b\bar{b}$

Conclusions

Introduction to LHCb

LHCb detector

- LHCb is a single-arm spectrometer with forward angular coverage from 10 mrad to 300 (250) mrad in the bending (non-bending) plane [equivalent to $2 < \eta < 5$]



LHCb detector

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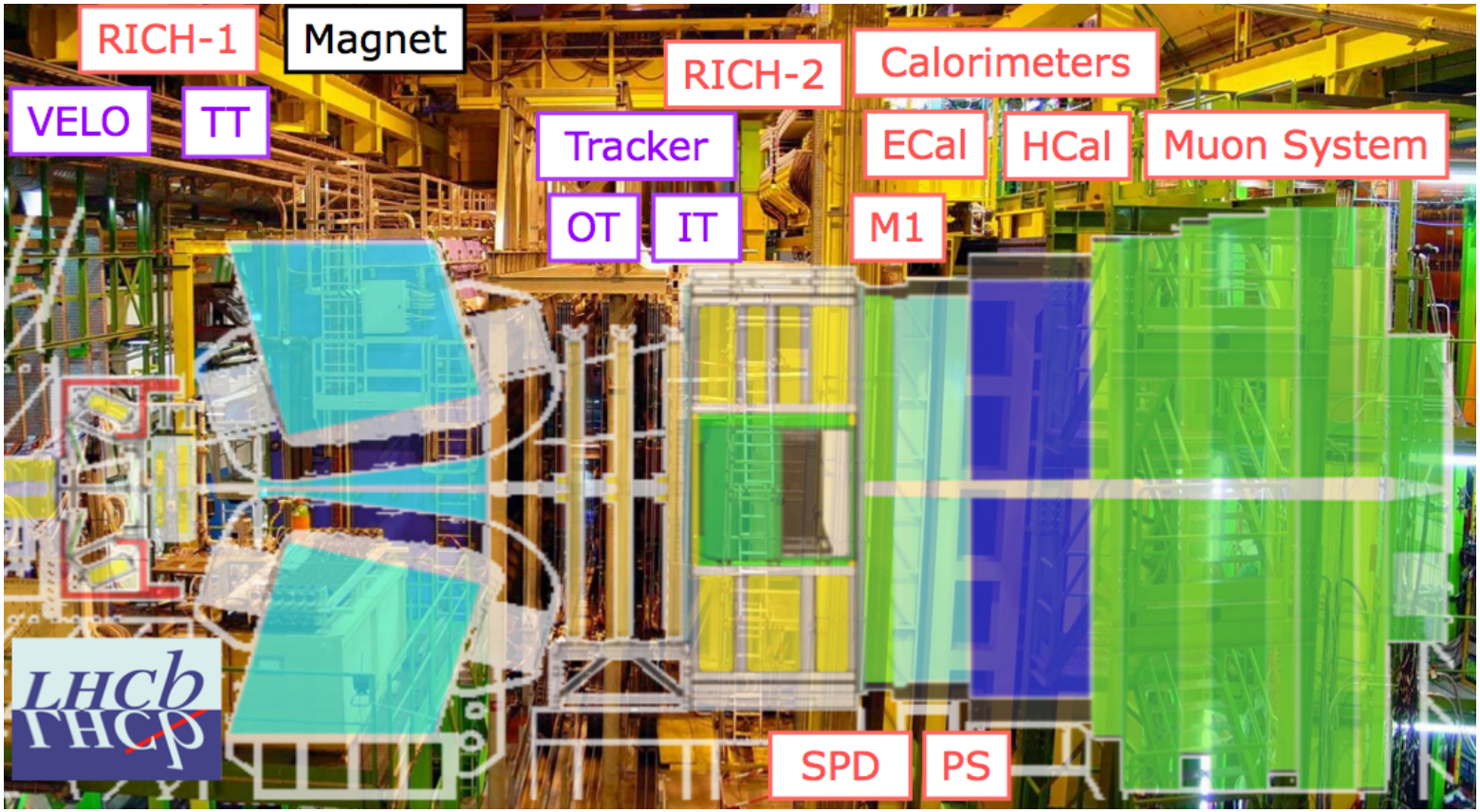


LHCb detector

- LHCb is a single-arm spectrometer with forward angular coverage from 10 mrad to 300 (250) mrad in the bending (non-bending) plane [equivalent to $2 < \eta < 5$]

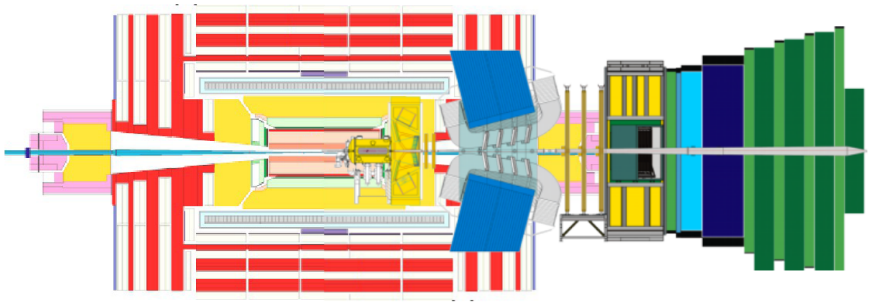
- Initially conceived for *b*-physics, current physics goals have been widely extended

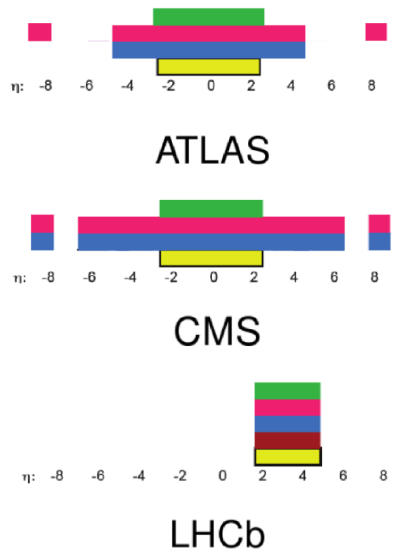
- LHCb strong points:
  - $\to$ Particle identification (including K/π separation)
  - $\to$ Vertexing and IP
  - $\to$ Momentum and mass resolution
  - $\to$ Unique coverage in η!

- More details about LHCb (and its upgrade): see rest of the talks from LHCb speakers!

LHCb complementarity

tracking, ECAL, HCAL,
muon, hadron PID



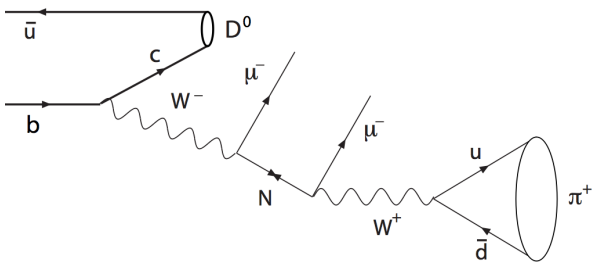


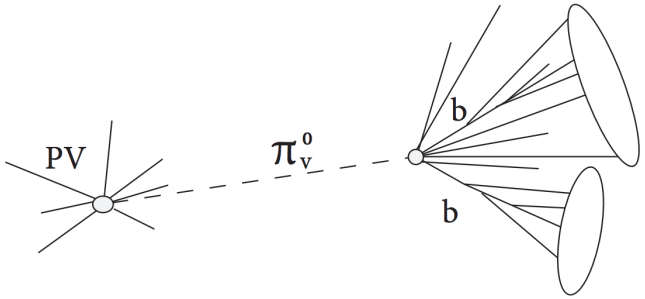
η coverage

- LHCb can offer unique coverage at the LHC
- However b physics imposes dealing with lower luminosities
  - $\to$ 2010: 37 pb^{-1} at $\sqrt{s} = 7$ TeV
  - $\to$ 2011: 1 fb^{-1} at $\sqrt{s} = 7$ TeV
  - $\to$ 2012: 2 fb^{-1} at $\sqrt{s} = 8$ TeV
- As a benefit, very stable conditions in terms of trigger/luminosity (luminosity leveling)

Direct and indirect approach

- For new physics searches, possible to follow indirect or direct approach. LHCb follows both!





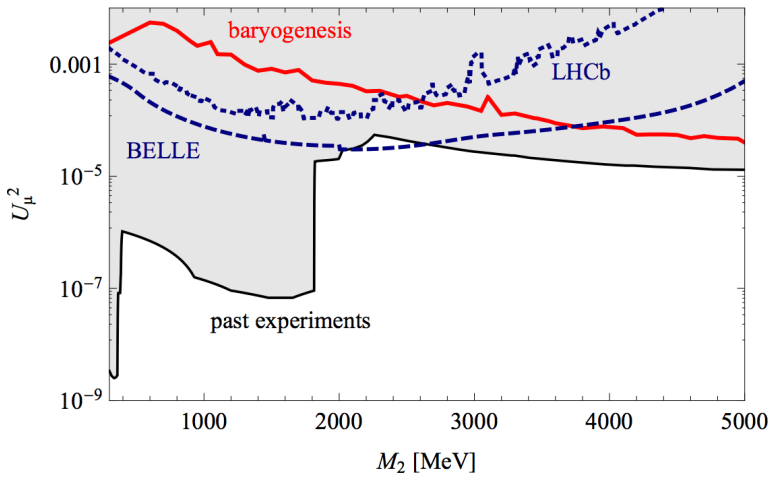
- **Indirect approach**
  - → Sensitive to higher scales than direct, new particles in the loop
  - → Precise measuremen. required
  - → Strategy partly followed for Majorana neutrino searches: decays of heavy mesons to final states with two same sign leptons

- **Direct approach**
  - → Direct search for new particles, à la ATLAS, CMS, or heavy meson decays to new particles
  - → Unique phase space coverage by LHCb
  - → Strategy followed for on-shell Majorana neutrinos and Exotica searches

Searches for Majorana neutrinos

Majorana neutrinos at LHCb?

- LHCb produces $\sim$15 kHz $b\bar{b}$ pairs and $\sim$300 kHz $c\bar{c}$ pairs: possibility of very stringent limits on rare B and D decays (see talk by J. Serrano)
  - $\rightarrow$ Can look both for off and on-shell Majorana neutrinos in B and D decays!
  - $\rightarrow$ For the on-shell case, profit from excellent mass and lifetime resolutions
- Complementary to other searches, such as in neutrino-less double β decay (coupling to muons)
- Example of model constrained by LHCb results: type-I seesaw model with three right-handed neutrinos



L. Canetti, M. Drewes, and B. Garbrecht *Phys. Rev.* **D90** (2014), no. 12 125005, [arXiv:1404.7114]

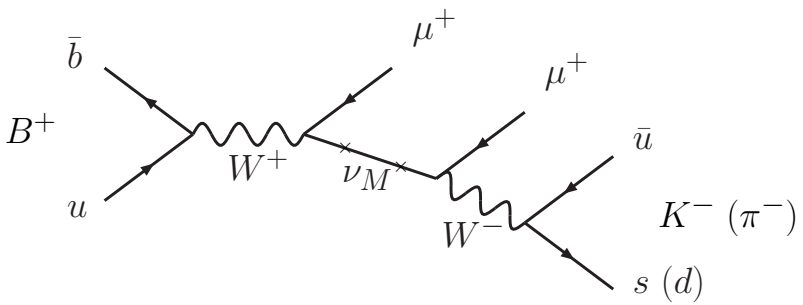
Searches in $B^{\pm} \to h^{\mp}\mu^{\pm}\mu^{\pm}$ decays

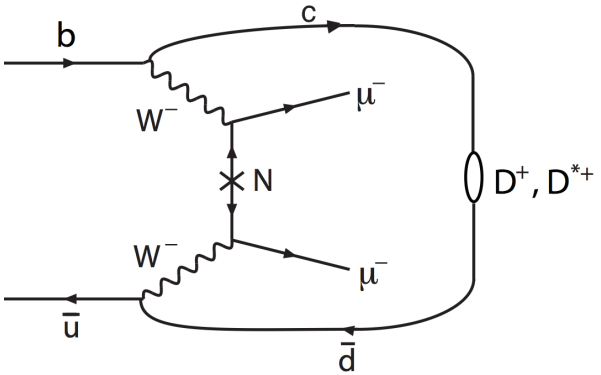
- Probe a wide range of Majorana neutrino masses and lifetimes
- Three different papers at LHCb, with different $h^{\mp}$ and different LHCb datasets
  - $\to$ $h^{\mp} = K^{\mp}$ or $\pi^{\mp}$, with $\sim$36 pb^{-1} (7 TeV)

    Phys. Rev. Lett. **108** (2012) 101601, [arXiv:1110.0730]
  - $\to$ $h^{\mp} = D^{\mp}$, $D^{*\mp}$, $D_s^{\mp}$ and $D^0\pi^{\mp}$, with $\sim$40 pb^{-1} (7 TeV)

    Phys. Rev. **D85** (2012) 112004, [arXiv:1201.5600]
  - $\to$ $h^{\mp} = \pi^{\mp}$, with 3.0 fb^{-1} (7 TeV + 8 TeV)

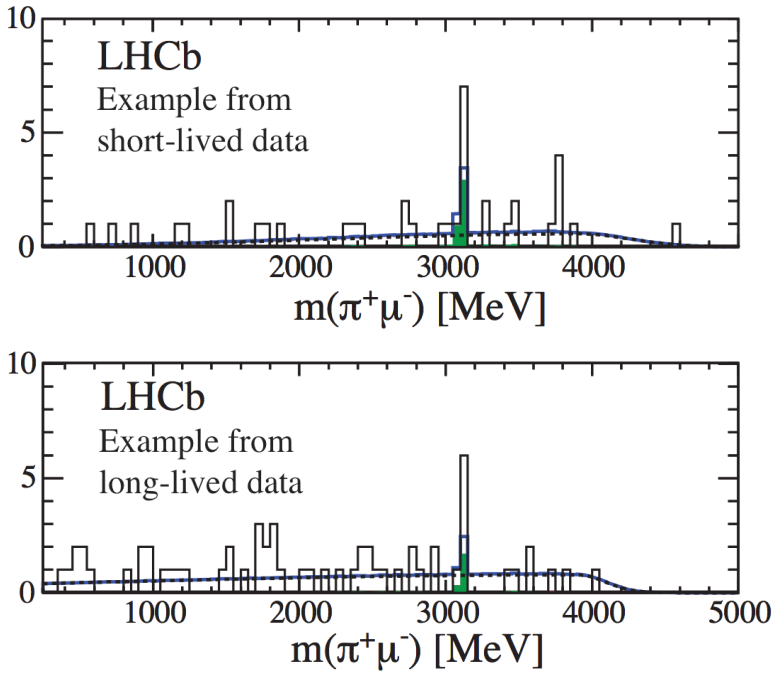
    Phys. Rev. Lett. **112** (2014), no. 13 131802, [arXiv:1401.5361]

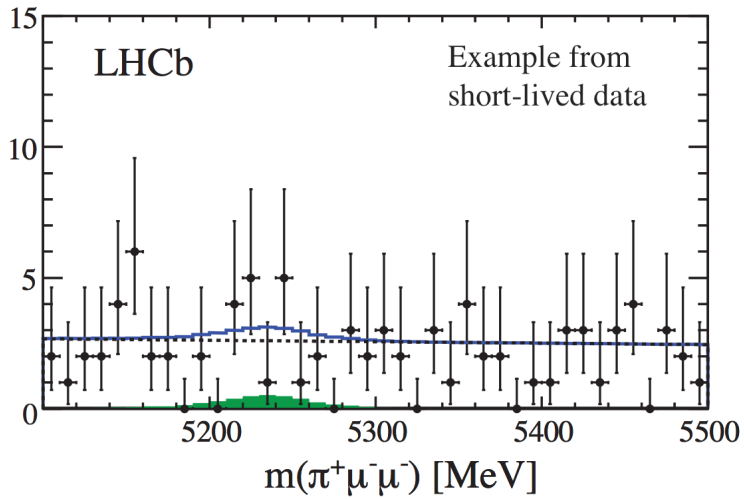




Analyses overview

- Split into short and long neutrino lifetimes (only for $h^{\mp} = \pi^{\mp}$) due to detached vertex
- Normalise to $B^+ \to J/\psi K^+$ (3-body) and $B^+ \to \psi(2S)K^+$ (5-body) with charmonium backgrounds estimated from data
- Search for signal in 2σ around B^+ mass



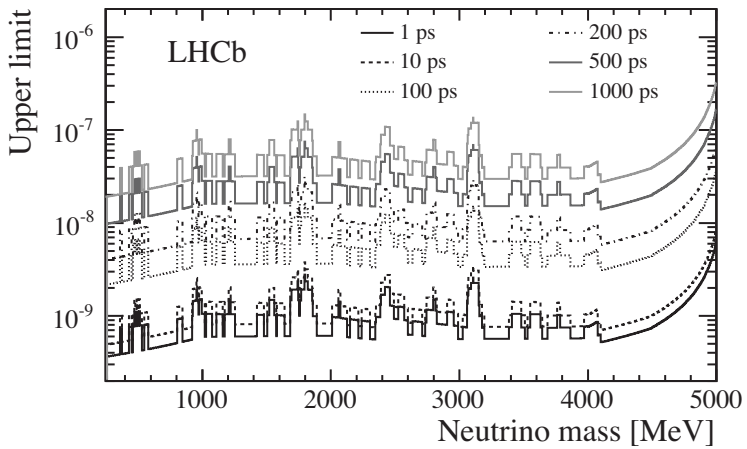


Phys. Rev. Lett. **112** (2014), no. 13 131802, [arXiv:1401.5361]

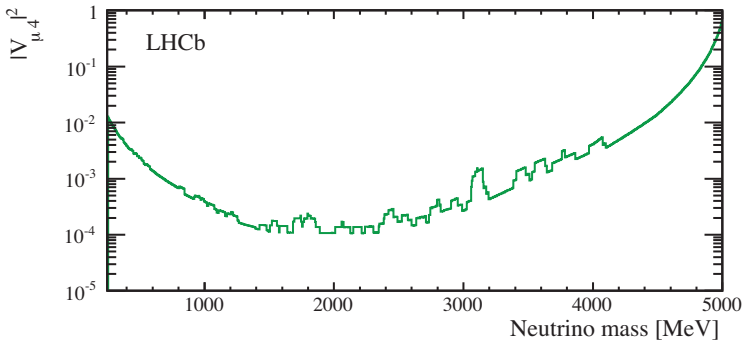
Results for $h^{\mp} = \pi^{\mp}$

- No signal observed, so upper limits on the $\mathcal{B}$ set
- Also scan limit in 5 MeV steps of neutrino mass from 250 - 5000 MeV with varying mass resolution
- For long lived neutrinos, scan in both mass and neutrino lifetime

Upper limit on the $\mathcal{B}$ (95% CL) as a function of mass and lifetime of the neutrino



Limits on fourth generation couplings (95% CL), $|V_{\mu 4}|^2$, as a function of neutrino mass



Phys. Rev. Lett. **112** (2014), no. 13 131802, [arXiv:1401.5361]

Other results

- Limit for short-lived neutrinos from average detection efficiency using CL_s method
- Limit for all the decay modes under scrutiny

Channel	$\mathcal{B}_{\rm UL}$ 95% CL
$B^{\pm} \to K^{\mp}\mu^{\pm}\mu^{\pm}$	5.4×10^{-8}
$B^{\pm} \to D^{\mp}\mu^{\pm}\mu^{\pm}$	6.9×10^{-7}
$B^{\pm} \to D^{*\mp}\mu^{\pm}\mu^{\pm}$	2.4×10^{-6}
$B^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$	4.0×10^{-9}
$B^{\pm} \to D_s^{\mp}\mu^{\pm}\mu^{\pm}$	5.8×10^{-7}
$B^{\pm} \to D^0\pi^{\mp}\mu^{\pm}\mu^{\pm}$	1.5×10^{-6}

Phys. Rev. Lett. **108** (2012) 101601, [arXiv:1110.0730]
Phys. Rev. **D85** (2012) 112004, [arXiv:1201.5600]
Phys. Rev. Lett. **112** (2014), no. 13 131802, [arXiv:1401.5361]

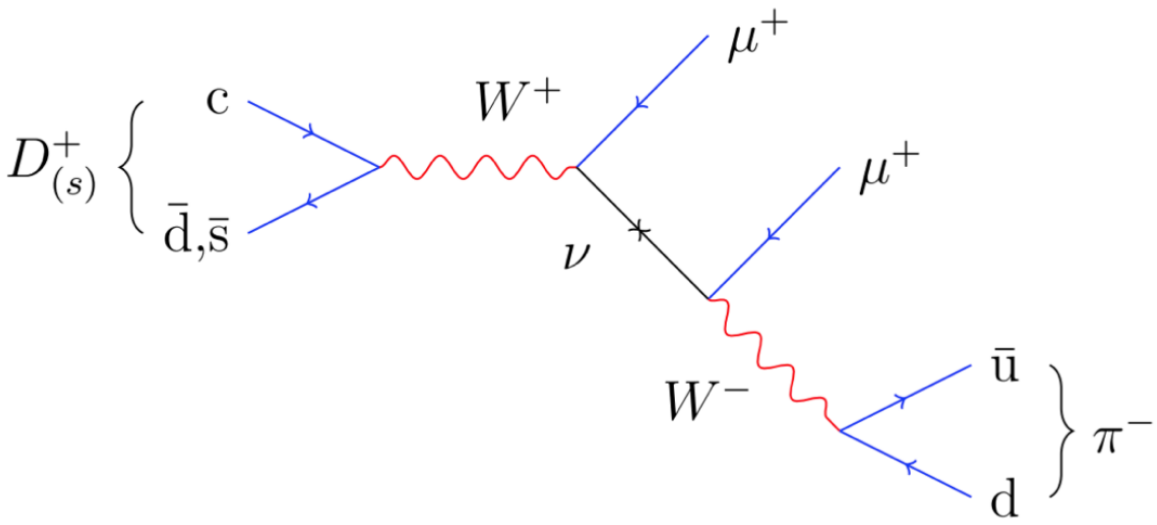
- All limits are world's best, improving by as much as $\sim$100 previous

Searches in $D^{\pm}_{(s)} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$

- Analysis with 2011 data sample (1 fb^{-1} at 7 TeV)

Phys.Lett. **B724** (2013) 203–212, [arXiv:1304.6365]

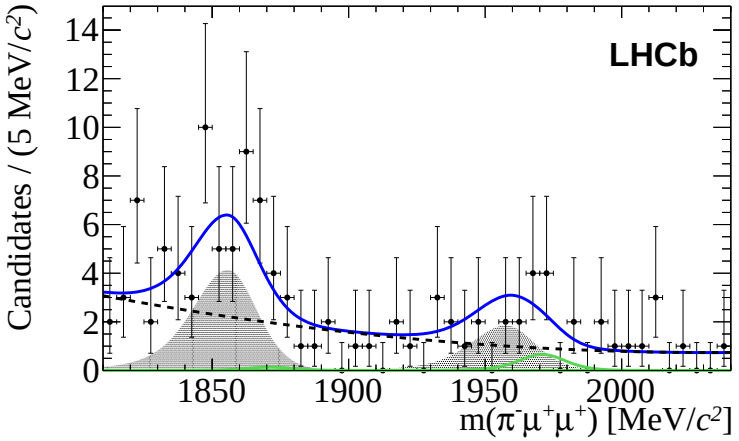
- Similar physics case as in B decays



- Normalisation to $D^+ \to \phi(\mu^+\mu^-)\pi^+$
- Classification of signal and background from PID cuts and a BDT using kinematic and geometrical variables

Results

- Important **peaking background** from $D^+ \to \pi^+\pi^+\pi^-$ decays, measured from data
- Fit in bins of $m(\pi^-\mu^+)$ to improve statistical significance



- Factor of 50 improvement with respect to previous limits!

Channel	$\mathcal{B}_{\mathrm{UL}}$ 95% CL
$D^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$	2.5×10^{-8}
$D_s^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$	1.4×10^{-7}

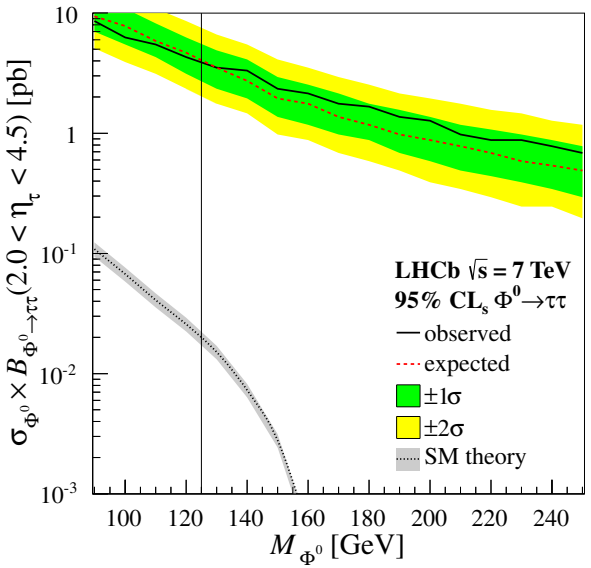
Phys.Lett. **B724** (2013) 203–212, [arXiv:1304.6365]

Direct searches for exotics

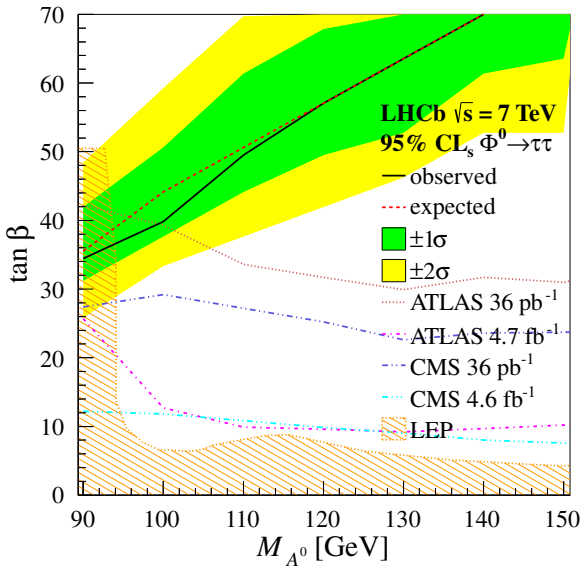
Limits on $H^0 \to \tau^+\tau^-$

- First LHCb paper on search for neutral Higgs in the forward direction *JHEP* **1305** (2013) 132, [arXiv:1304.2591]
- No excess found in 2011 dataset $\to$ limits set for both in a model independent way (as a function of m_H) and in one particular realization of MSSM

  $\to$ Limits set using CL_S method at 95% CL



Model independent limit in terms of $\sigma_H \times BR(H \to \tau^+\tau^-)$[a]



MSSM limit compared to ATLAS, CMS and LEP in the $m(h^0)_{max}$ scenario[a]

[a] Click here for theory references

H^0 decays to long-lived particles: Overview

- Search for Higgs decaying to Long Lived massive Particles, predicted by many BSM theories, using 0.62 fb^{-1} of 2011 LHCb dataset

  Eur. Phys. J. **C75** (2015), no. 4 152, [arXiv:1412.3021]

- Examples of theory models predicting such particles:

$\to$ SUSY models with Baryon number Violation (BV)

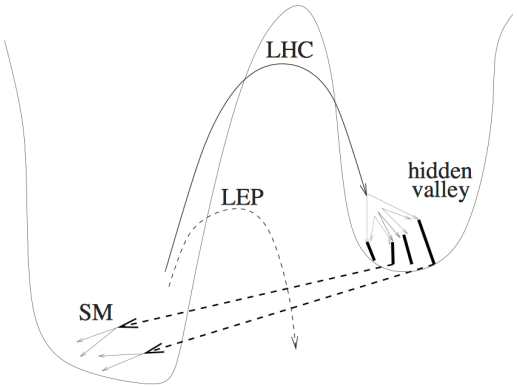
- $h^0 \to \tilde{\chi}^0_1\tilde{\chi}^0_1$, with $\tilde{\chi}^0_1$ neutralino long-lived, $\tilde{\chi}^0_1 \to$ 3 quarks

Phys.Rev.Lett. **99** (2007) 211801, [hep-ph/0607204]

$\to$ Some Hidden Valley (HV) models

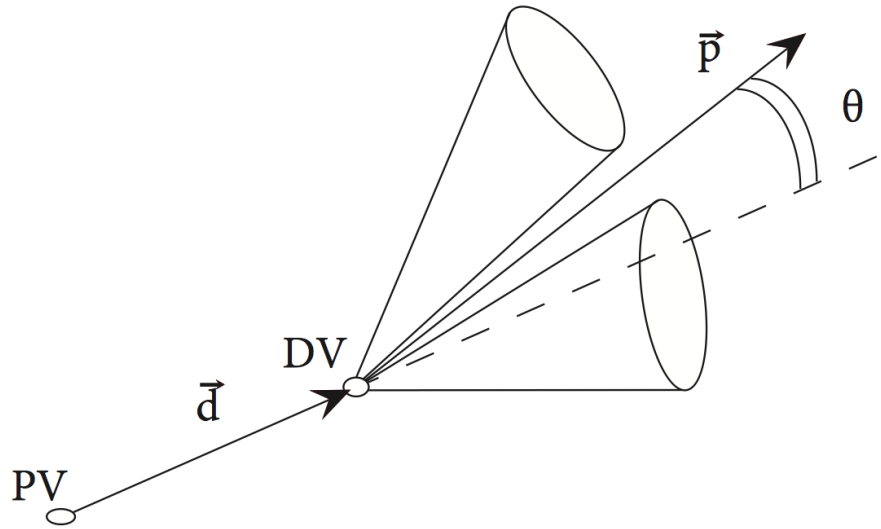
- $h^0 \to \pi^0_V\pi^0_V \to$4 displaced $b-$quarks

Phys.Lett. **B651** (2007) 374–379, [hep-ph/0604261]

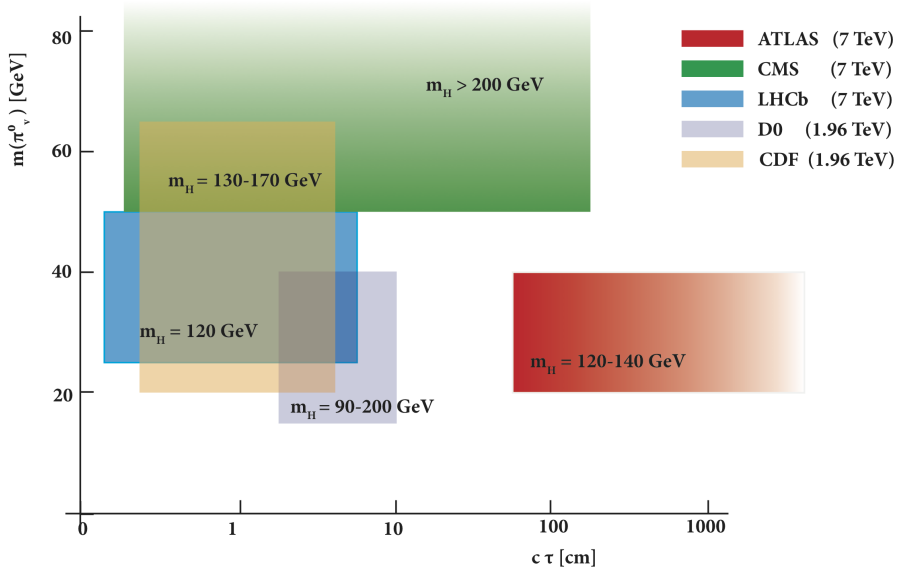


H^0 decays to long-lived particles: LHCb analysis

Experimental signature: displaced vertex with two associated jets. LHCb advantage thanks to Particle Identification, vertexing...

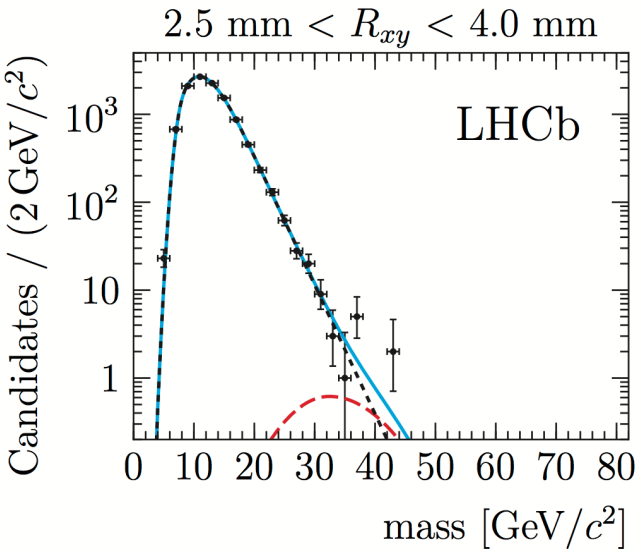


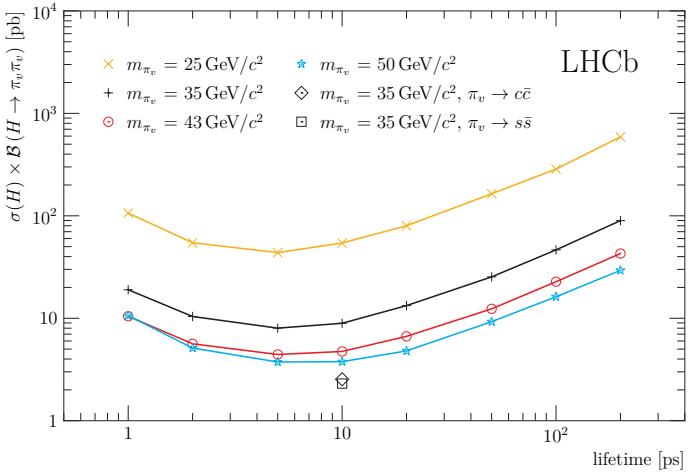
Important LHCb contribution, e.g., for HV models LHCb can look into a complementary phase space region with respect to ATLAS/CMS in terms of π^0_V lifetime and mass.



H^0 decays to long-lived particles: Results

Eur. Phys. J. **C75** (2015), no. 4 152, [arXiv:1412.3021]





No excess above $b\bar{b}$ (main source of background). Example from one of the fits to different radial distances

Limits (95% CL) set in different regions of the BSM models phase space

- Complementary searches by ATLAS and CMS

  ATLAS: *Phys.Rev.Lett.* **108** (2012) 251801, [arXiv:1203.1303]
  CMS: *CMS-PAS-EXO-12-038*

Long-lived heavy charged particles

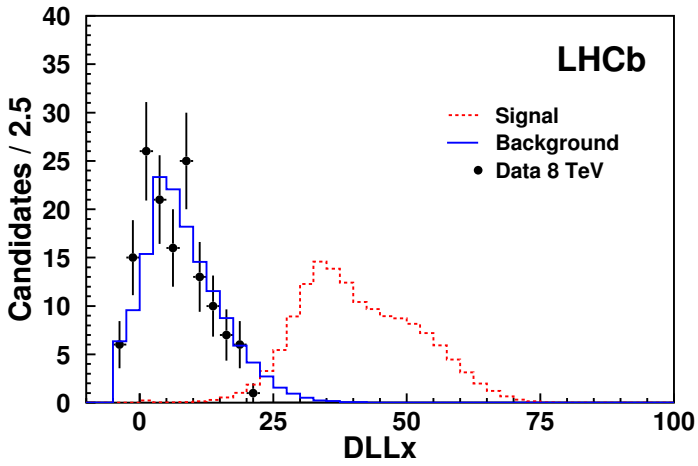
arXiv:1506.9173

- Search for new charged massive stable particles (CMSP) in our detector: Drell-Yan pair production
  - $\to$ Benchmark model: $\tilde{\tau}$ from mGMSB[b]
  - Analysis

    from other experiments typically based on dE/dx and time-of-flight measurements[b]
    - $\to$ Novel technique at LHCb based on ring imaging Cherenkov (RICH) detector
    - $\to$ Build Delta Log Likelihood

      for CMSP (lower β) and other standard particles

    RICH likelihood discrimination between background (Drell-Yan $\mu^+\mu^-$) and signal (124 GeV/c^2 long-lived particle)

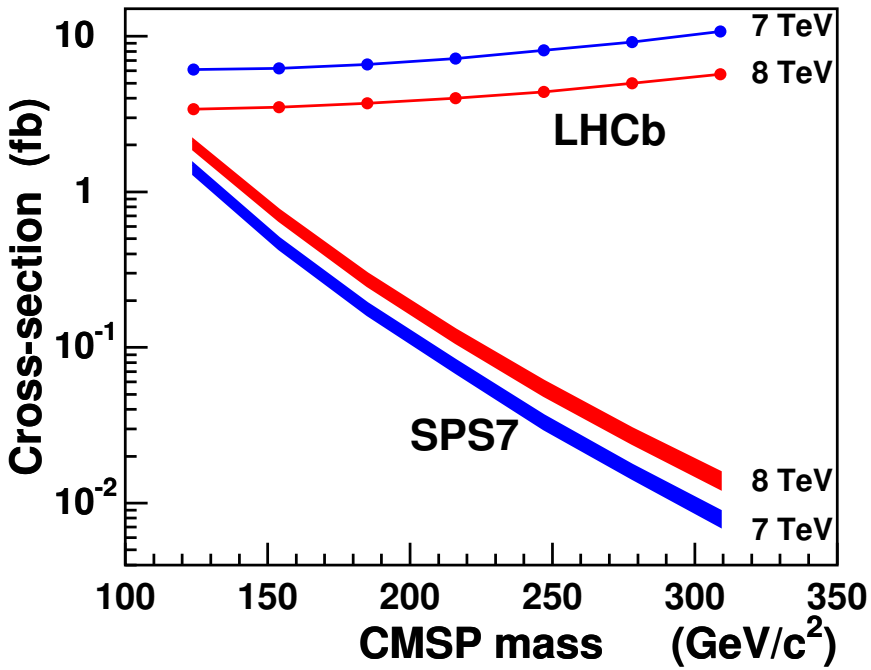
    

  - Main background Drell-Yan $\mu^+\mu^-$

[b] Click here for references

Results

- No signal found, set upper limits using Feldman-Cousins
- 95% CL limits as a function of the heavy particle mass



arXiv:1506.9173

Theoretical cross sections in SPS7, one of the scenarios of mGMSB: B. C. Allanach *et. al. Eur. Phys. J.* **C25** (2002) 113–123, [hep-ph/0202233]

Searches for low mass dark bosons

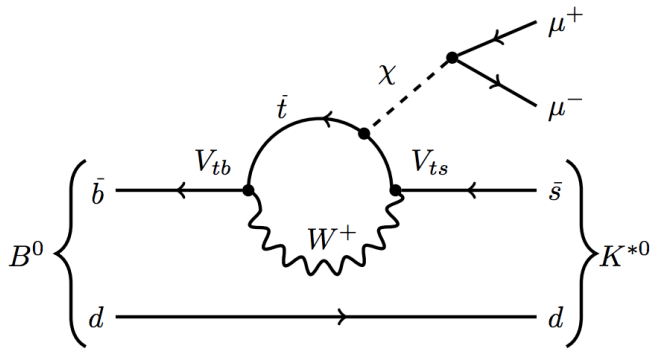
- Several theoretical models predict existence of new particles that couple to SM particles by mixing with the Higgs:
  - → In particular inflaton, axion-like, dark matter mediator models also predict them to be **light**
  - → Depending on the nature of these new particles, they may mix with SM particles
  - → Search for $\chi \to \mu^+\mu^-$ within $B^0 \to K^*\chi(\mu^+\mu^-)$

- Benchmark models
  - → **Inflaton**, detached χ

    F. Bezrukov *et. al. Phys. Lett.* **B736** (2014) 494–498, [arXiv:1403.4638]
  - → **Axion portal**, prompt decay of χ

    M. Freytsis *et. al. Phys. Rev.* **D81** (2010) 034001, [arXiv:0911.5355]

[LHCb-PAPER-2015-036 in preparation]

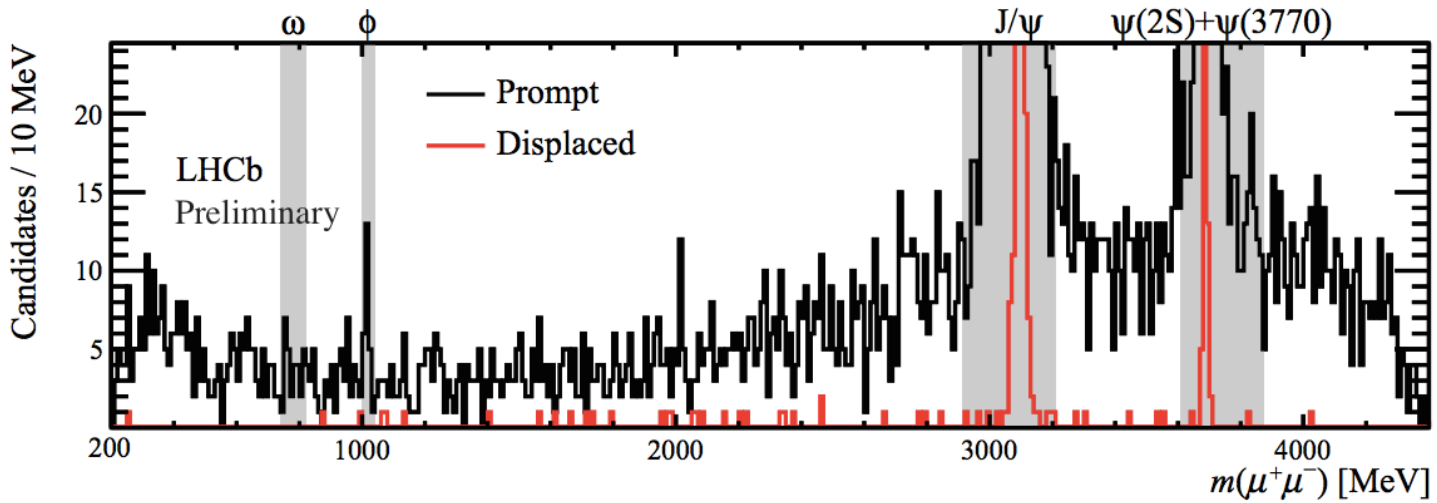


Analysis overview

- Trigger on muons
- Apply multivariate selection not dependent on χ mass or lifetime
- Factorize lifetime into prompt and detached
- Looking for di-muon resonance:
  - $\to$ B^0 mass constrained
  - $\to$ Scan in steps of di-muon mass: perform test statistics

M. Williams *JINST* **10** (2015), no. 06 P06002, [arXiv:1503.0476]

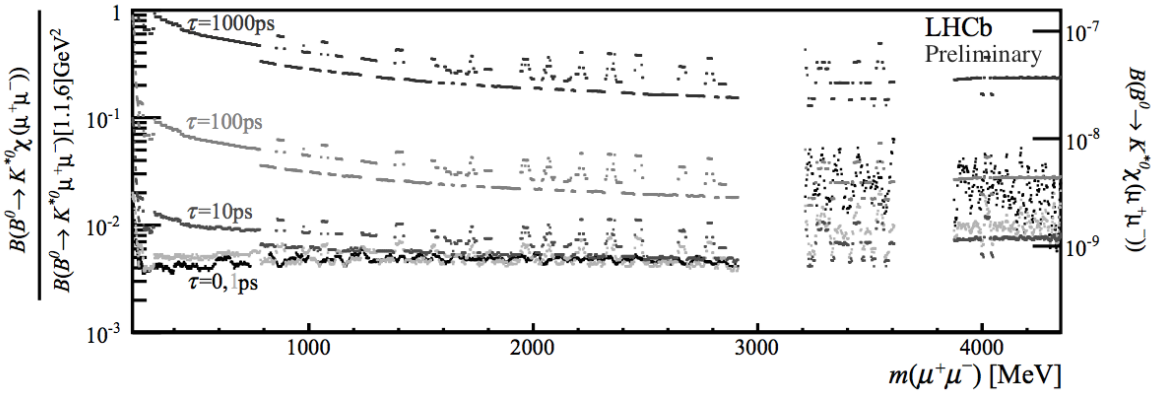
[LHCb-PAPER-2015-036 in preparation]



Results

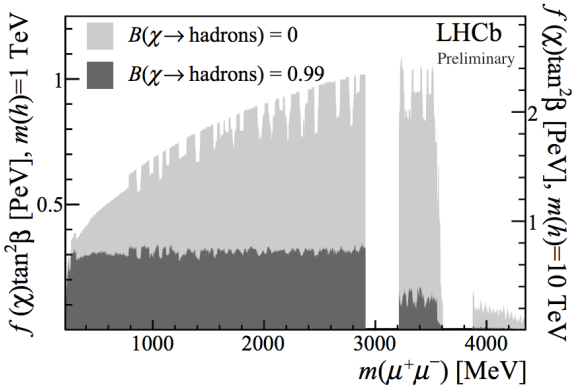
[LHCb-PAPER-2015-036 in preparation]

- 95% CL limit on $\mathcal{B}$ as a function of the χ lifetime and mass



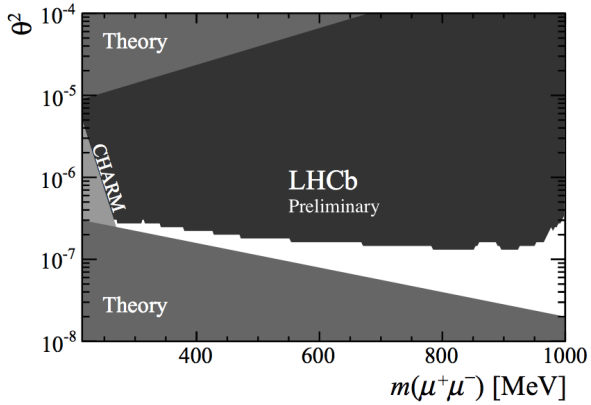
- Exclusion in benchmark models

(Specific) inflaton model



Include 3 sterile neutrinos

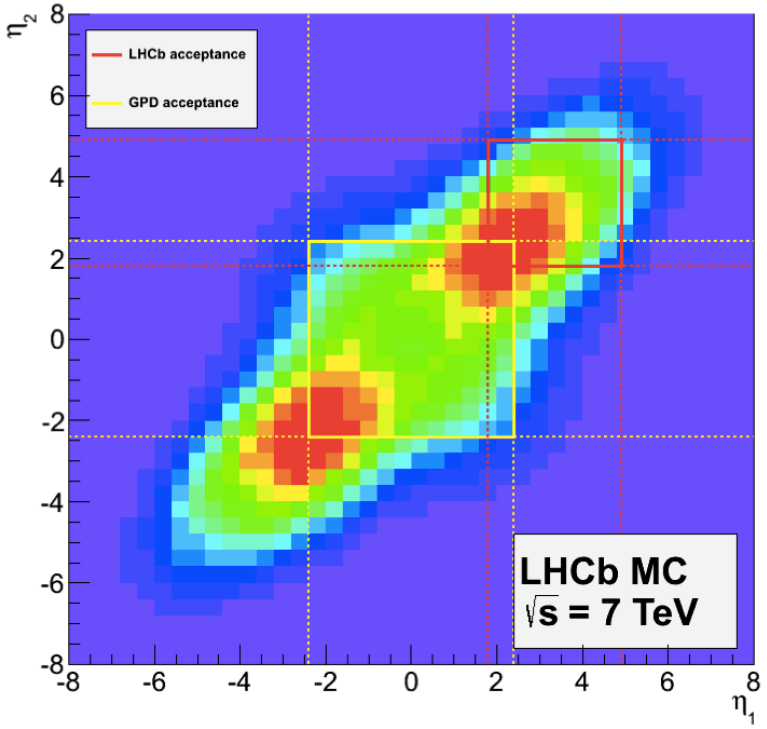
Axion portal



MSSM-like two Higgs doublet model

Towards $H^0 \to b\bar{b}$

- LHCb is also on its way to perform a search for $H^0 \to b\bar{b}$
  - $\to$ Interest: Higgs coupling to quarks
  - $\to$ Probability to have both b quarks in LHCb acceptance: $\sim$5% at 7/8 TeV, better at 13 TeV



Towards $H^0 \to b\bar{b}$

- Our jet reconstruction has been tested to work successfully. Substantial progress in *b*-jet tagging.

  JINST **10** (2015), no. 06 P06013, [arXiv:1504.0767]

- Benchmark analyses done (see talk by M. Rangel):
  - → Top analysis arXiv:1506.0090
  - → Measurements of W and Z + jets or b/c jets
    - W+ b/c jets: arXiv:1505.0405
    - Z+jets: *JHEP* **1401** (2014) 033, [arXiv:1310.8197]
    - Z+b jets: *JHEP* **1501** (2015) 064, [arXiv:1411.1264]
  - → Measurement of the charge $b\bar{b}$ asymmetry

    Phys.Rev.Lett. **113** (2014), no. 8 082003, [arXiv:1406.4789]

Conclusions

Conclusions

- LHCb has been shown to be competitive for NP searches following both direct and indirect approaches
- We offer unique phase-space coverage
  - $\to$ Majorana neutrino searches
    - No Majorana neutrino found, but important constraints using both B and D decays to same sign muons
    - Complementary to other kind of searches!
  - $\to$ Also, relevant exotica results
    - First LHCb paper on Higgs searches: $H^0 \to \tau^+\tau^-$
    - Long lived particles decaying to jets and search for heavy long lived particles
    - Brand new paper on search for low mass dark bosons
    - In our path to $H^0 \to b\bar{b}$
  - $\to$ And an exciting future ahead of us...

Thanks!

Backup

$H^0 \longrightarrow \tau^+\tau^-$ references

- SM prediction
  - → hep-ph/9510347
  - → *Comput.Phys.Commun.* **124** (2000) 76–89, [hep-ph/9812320]
- $m(h^0)_{max}$ scenario: *Eur.Phys.J.* **C26** (2003) 601–607, [hep-ph/0202167]
- ATLAS on $H \longrightarrow \tau^+\tau^-$:
  - → *Phys.Lett.* **B705** (2011) 174–192, [arXiv:1107.5003]
  - → *JHEP* **1302** (2013) 095, [arXiv:1211.6956]
- CMS on $H \longrightarrow \tau^+\tau^-$:
  - → *Phys.Rev.Lett.* **106** (2011) 231801, [arXiv:1104.1619]
  - → *Phys.Lett.* **B713** (2012) 68–90, [arXiv:1202.4083]
- LEP on $H \longrightarrow \tau^+\tau^-$: *Eur.Phys.J.* **C47** (2006) 547–587, [hep-ex/0602042]

Heavy long-lived particles references

- mGMSM model
  - → S. Dimopoulos, S. D. Thomas, and J. D. Wells *Nucl. Phys.* **B488** (1997) 39–91, [hep-ph/9609434]
  - → G. F. Giudice and R. Rattazzi *Phys. Rept.* **322** (1999) 419–499, [hep-ph/9801271]
  - → S. P. Martin hep-ph/9709356. [Adv. Ser. Direct. High Energy Phys.18,1(1998)]
- Other results
  - → ATLAS: *Phys. Lett.* **B720** (2013) 277–308, [arXiv:1211.1597]
  - → CMS: *JHEP* **1307** (2013) 122, [arXiv:1305.0491]

ATLAS, CMS and LHCb on $H^0 \rightarrow$LLP

- ATLAS and CMS: Two triggering approach
  - $\rightarrow$ Displaced vertex object dedicated trigger ATLAS $\rightarrow$ sensitivity to low masses not to low proper time ($c\tau_{min} \sim 1$ m) *Phys.Rev.Lett.* **108** (2012) 251801, [arXiv:1203.1303]
  - $\rightarrow$ Inclusive jet trigger in CMS $\rightarrow$ sensitivity to low proper time not to low masses *CMS-PAS-EXO-12-038*
- Displaced vertex object dedicated trigger at LHCb
  - $\rightarrow$ Region of sensitivity $\rightarrow$ complementary to GPDs: low mass ($20 < \pi^0_V < 50$ GeV/c^2) and low proper time ($c\tau \sim$ O cm)
  - $\rightarrow$ Trigger strategy for semi-leptonic and fully leptonic decay of LLP in place too.

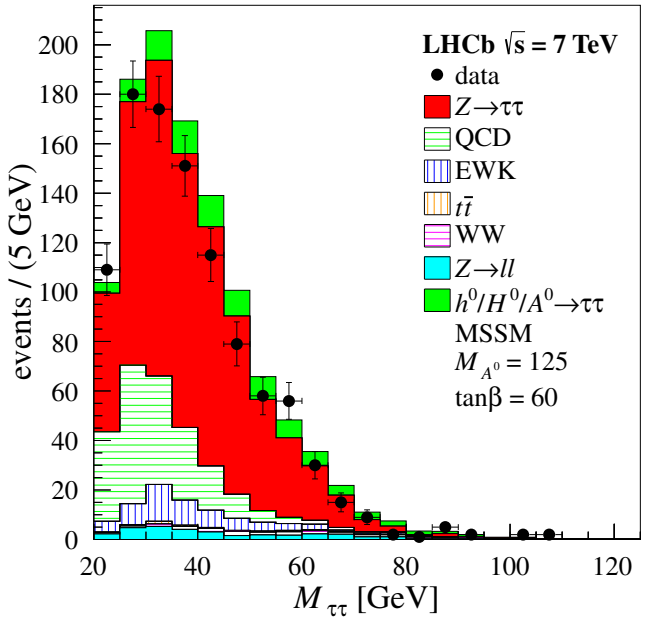
Limits on $H^0 \rightarrow \tau^+\tau^-$: Analysis overview

- First LHCb paper on search for neutral Higgs in the forward direction

  JHEP **1305** (2013) 132, [arXiv:1304.2591]

- Using 2011 dataset Search using different τ decay modes: $\tau_\mu\tau_\mu$, $\tau_\mu\tau_e$, $\tau_e\tau_\mu$, $\tau_\mu\tau_h$, $\tau_e\tau_h$
- Discrimination based on having isolated leptons, lifetime of the τ and back-to-back objects

Yields using all samples combined



A_C in $b\bar{b}$: Overview

- Measurement of $b\bar{b}$ charge asymmetry (A_C) using 2011 LHCb dataset

Phys.Rev.Lett. **113** (2014), no. 8 082003, [arXiv:1406.4789]

$$A_C^{b\bar{b}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \quad \Delta y = |y_b| - |y_{\bar{b}}|$$

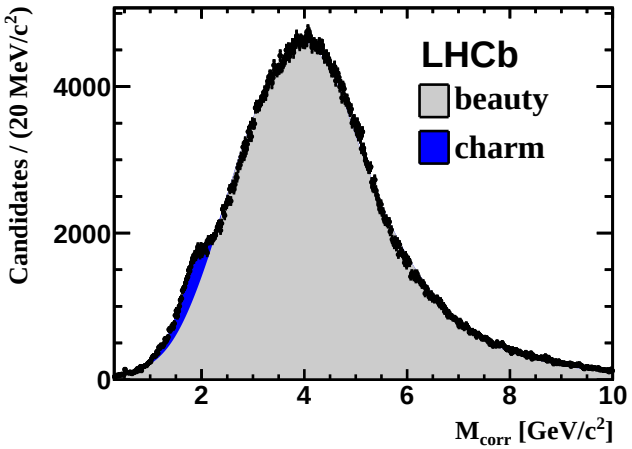
- Related to $t\bar{t}$ asymmetry from Tevatron, so that models to explain it predict also large A_C in $b\bar{b}$

JHEP **1201** (2012) 069, [arXiv:1108.3301]
Phys.Rev.Lett. **111** (2013) 062003, [arXiv:1302.6995]

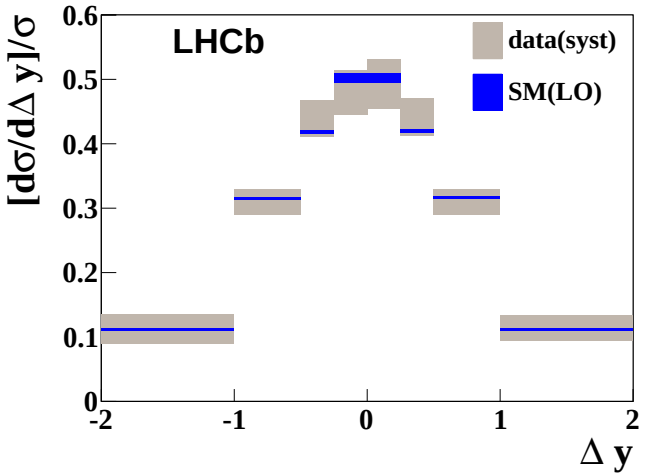
- Strategy:
  - $\rightarrow$ Reconstruct the $b\bar{b}$ as a pair of jets
  - $\rightarrow$ Use b-tagging to select jets and muon from semi-leptonic decays to determine their charge
  - $\rightarrow$ Measure asymmetry in bins of $M_{b\bar{b}}$

A_C in $b\bar{b}$: Results

Phys.Rev.Lett. **113** (2014), no. 8 082003, [arXiv:1406.4789]



Corrected mass distribution



Corrected Δy distribution, L0 SM

from PYTHIA

JHEP **0605** (2006) 026, [hep-ph/0603175]

- Results in different mass regions (in GeV/c^2)

$$A_C^{b\bar{b}}(40, 75) = 0.4 \pm 0.4(\mathrm{stat}) \pm 0.3(\mathrm{syst})\%$$
$$A_C^{b\bar{b}}(75, 105) = 2.0 \pm 0.9(\mathrm{stat}) \pm 0.6(\mathrm{syst})\%$$
$$A_C^{b\bar{b}}(> 105) = 1.6 \pm 1.7(\mathrm{stat}) \pm 0.6(\mathrm{syst})\%$$

$\rightarrow$ Asymmetry is not significant and the results found are consistent with SM (expected to be $O(1\%)$ from QCD with an extra $O(1\%)$ in the Z mass region)

R. Gauld, U. Haisch, B. D. Pecjak, and E. Re arXiv:1505.0242

Higgs search in LHCb future

- possibility of $H^0 \rightarrow c\bar{c}$ via VBF or associated vector?
- golden four-lepton modes still largely out of reach
- some numbers for the HL-LHC...
  - $\rightarrow$ expected $H^0[b, b, j]$ (VBF) cross-section 70 fb $\rightarrow$ 3800 events
  - $\rightarrow$ expected $H^0[\tau, \tau, j]$ (VBF) cross-section 7.9 fb $\rightarrow$ 150 events
  - $\rightarrow$ expected $H^0[c, c, j]$ (VBF) cross-section 3.6 fb $\rightarrow$ 27 events
  - $\rightarrow$ expected $H^0 + W[b, b, l]$ cross-section 12 fb $\rightarrow$ 680 events
  - $\rightarrow$ expected $H^0 + W[\tau, \tau, l]$ cross-section 1.4 fb $\rightarrow$ 30 events

Summary of systematics and backgrounds

Channel	**Dominant background**	**Main systematics**
Majorana searches in $B^{\pm} \to h^{\mp}\mu^{\pm}\mu^{\pm}$	Comb. and peaking	$\mathcal{B}(B^+ \to J/\psi K^+)$
Majorana searches in $D^{\pm}_{(s)} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$	Comb. and peaking	$\mathcal{B}(D^+ \to \phi(\mu^+\mu^-)\pi^+)$
$H^0 \to \tau^+\tau^-$	$Z \to \tau^+\tau^-$	Exp. bkg.
$H^0 \to$ LLP	$b\bar{b}$	$\epsilon^{TRIGGER}$ SV reconstruction
Long-lived heavy charged particles	Drell-Yan $\mu^+\mu^-$	Background estimation
Low mass dark bosons	$B \to K^* X$ decays	MC stats
$A_C^{b\bar{b}}$	–	Flav. tagging