Searches for Long-Lived Particles with LHCb

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on behalf of the LHCb collaboration

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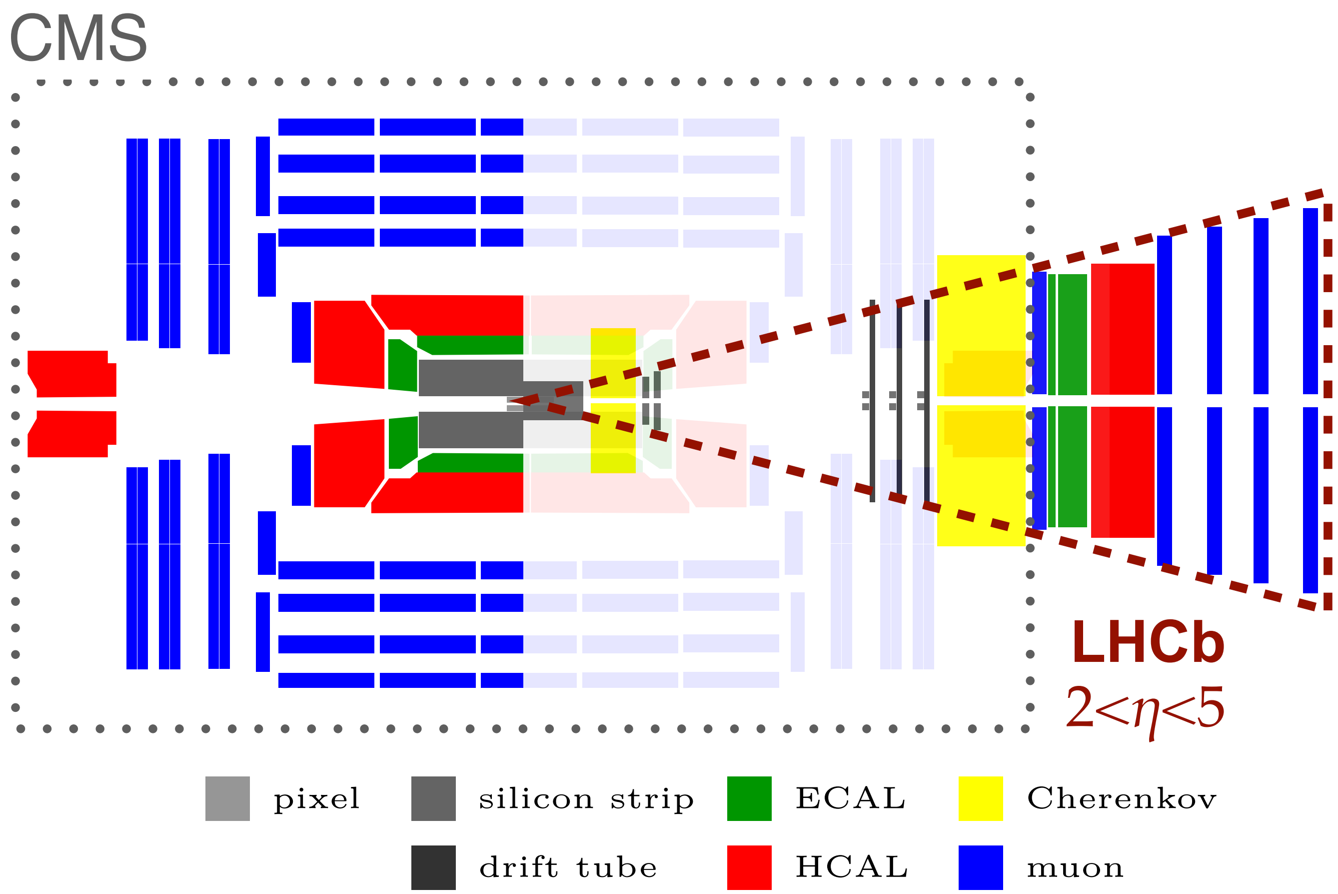
LHCb Detector

Int.J.Mod.Phys. A 30,1530022 (2015)
JINST 10 (2015) P06013



unique acceptance

$2 < \eta < 5$

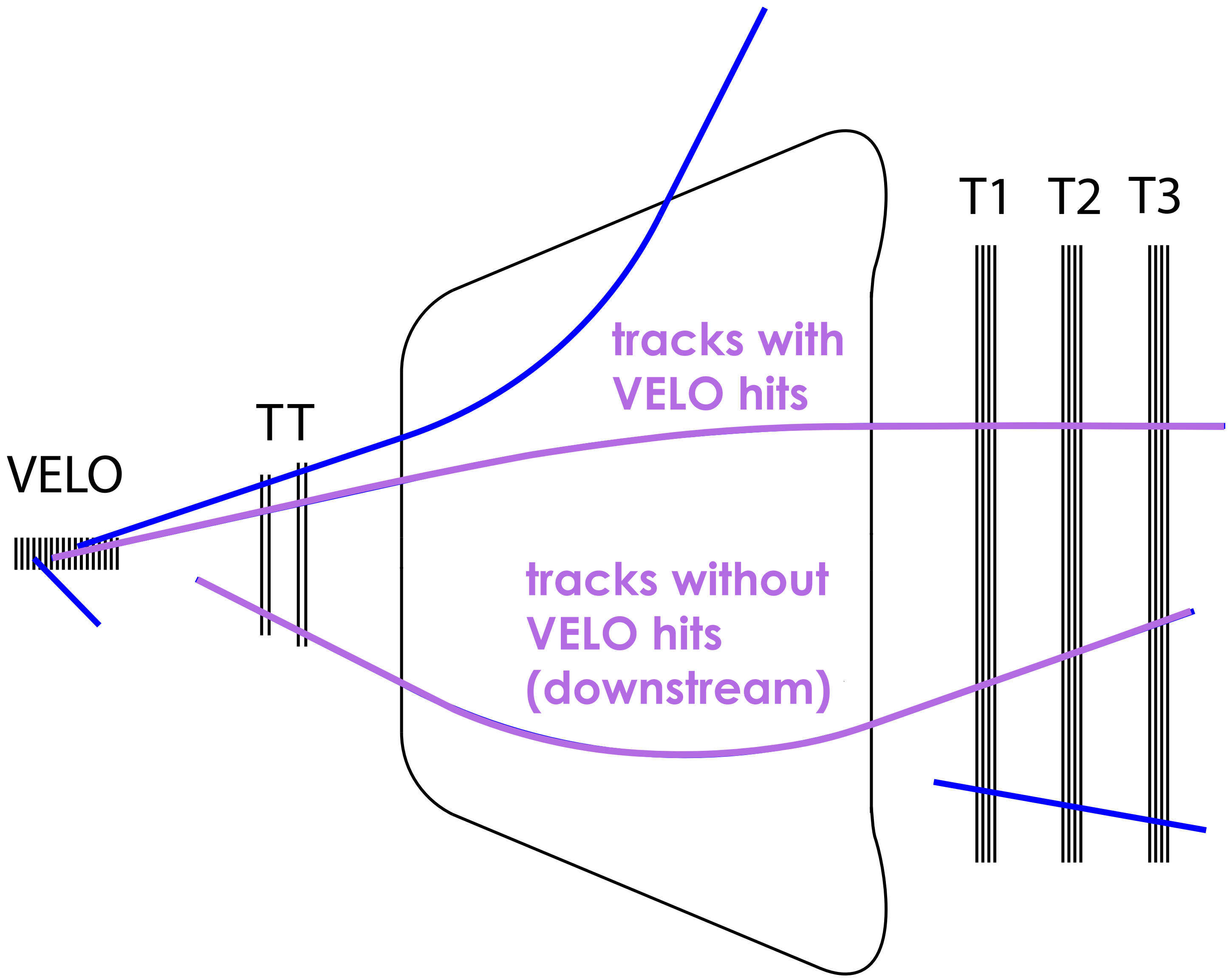
low pile-up

~1-2 visible interaction

- excellent vertex resolution (σ_T~45 fs for B_s^0)
- excellent mass resolution (0.5% in μμ)
- muon ID efficiency ~97% for 1-3% π→μ misid
- IP resolution ~20 μm for tracks with high p_T
- jet reconstruction:
  - efficiency > 80% (jets with p_T>15 GeV)
  - energy resolution ~10% (jets with p_T>10 GeV)
  - b(c) tagging efficiency ~65%(25%) for 0.3% light-parton contamination

Tracking system and trigger crucial for LLP searches!

LLP Tracks



tracks with VELO hits

- accessible decay lengths at LHCb ~20 cm
  (decay within the VELO)

tracks without VELO hits

- worse momentum and vertex resolution
- not available in HLT1
  (studies on going)
- decay length accessible would be extended up to ~200 cm

Trigger

J. Phys. Conf. Ser. 664, 082004 (2015)

very soft triggers!

at **hardware** level (L0):

- muons with $p_T > 1.5$ GeV
- calo deposits with $E_T > 3$ GeV

at **software** level (HLT):

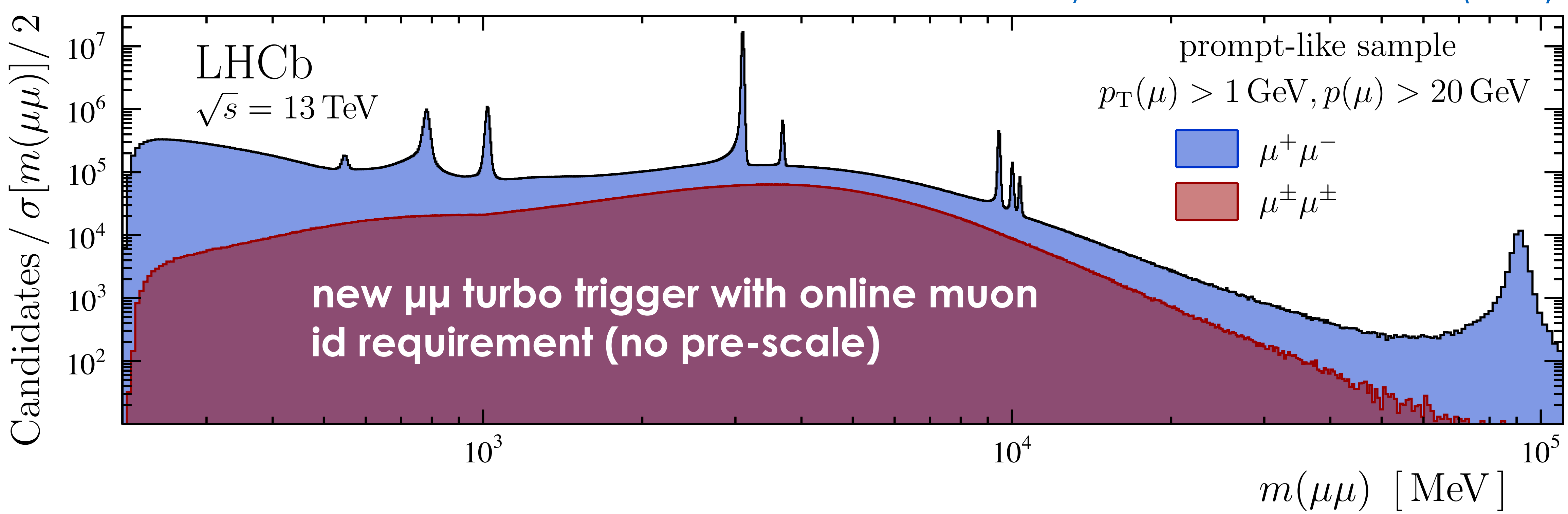
- topological triggers on detached vertices
- PID and jets in trigger

new **turbo** lines since 2015:

- store online reconstructed particles
- reduce event size by discarding lower level info
- output can be directly used for analysis

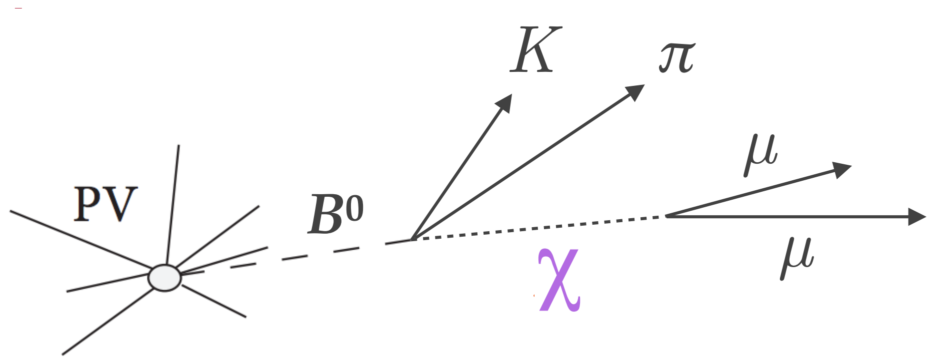
→ **excellent for light dimuons (prompt and detached)**

Phys. Rev. Lett. 120, 061801 (2018)



LLPs in LHCb

produced in B/D decays



SIGNATURE

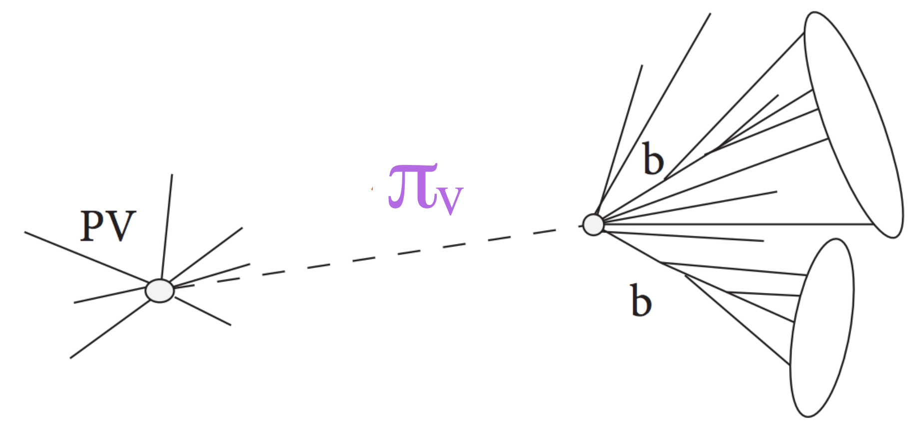
displaced dileptons

- light boson from b → s
- Majorana neutrino

BACKGROUND

- background reduced by constraining m(decay particles)=m(B)
- background further reduced with additional constraints on vertices

produced in pp collision



displaced jets

- LLP → jet jet
- LLP → μ + jets

displaced dileptons (inclusive)

- dark photon ➡ talk by Federico Redi

VELO RF box at ~5 mm from the beam:

- < 5 mm: background dominated by heavy flavour
- > 5 mm: background mainly from material interaction

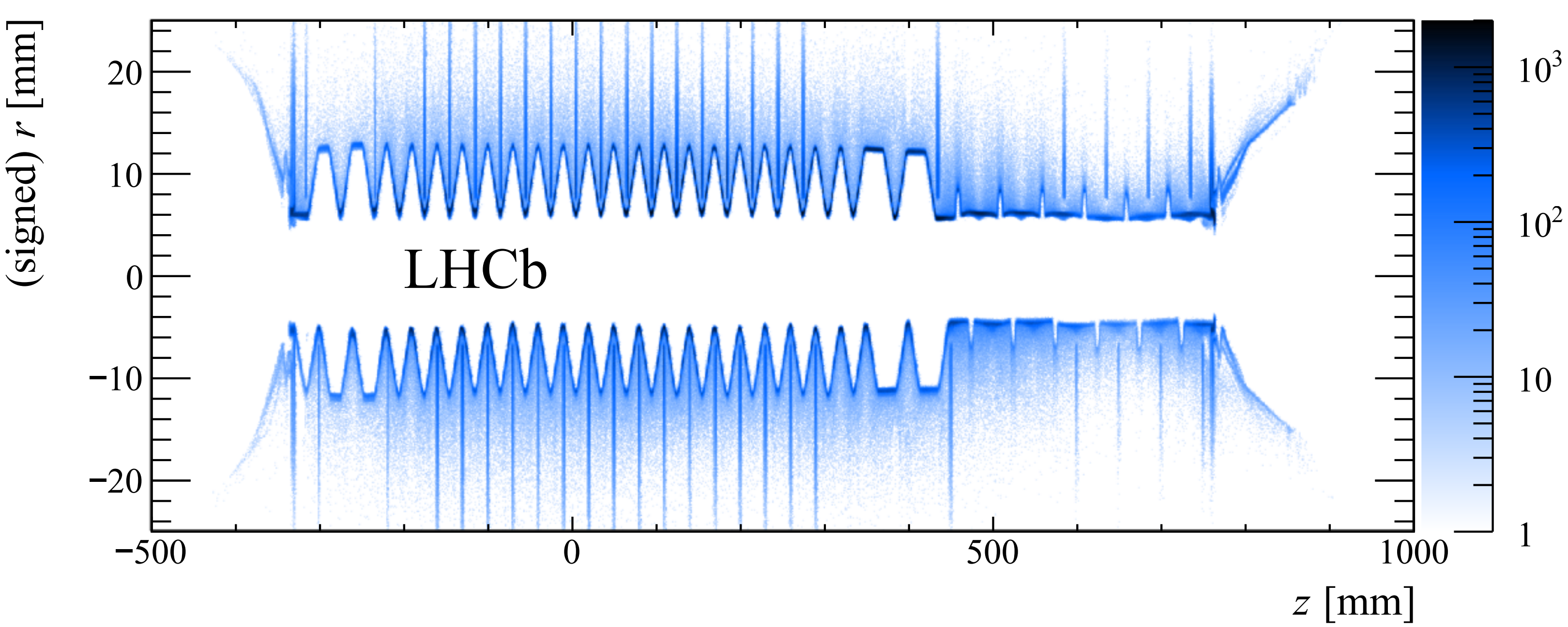
VELO Material

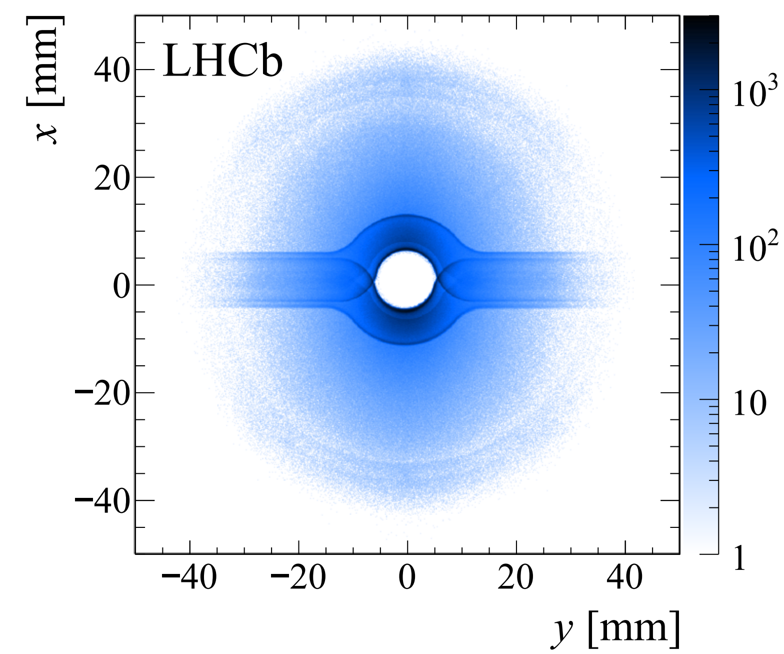
CERN-LHCb-DP-2018-002

material map of the VELO is essential to reduce the background in LLP searches!

- beam-gas (helium) collisions
- material interaction along the full length of the VELO
- secondary interactions of hadrons used to map the material

- the map can be used in analyses with displaced vertices:
  a p-value can be assigned to the hypothesis that a SV originates from material interaction

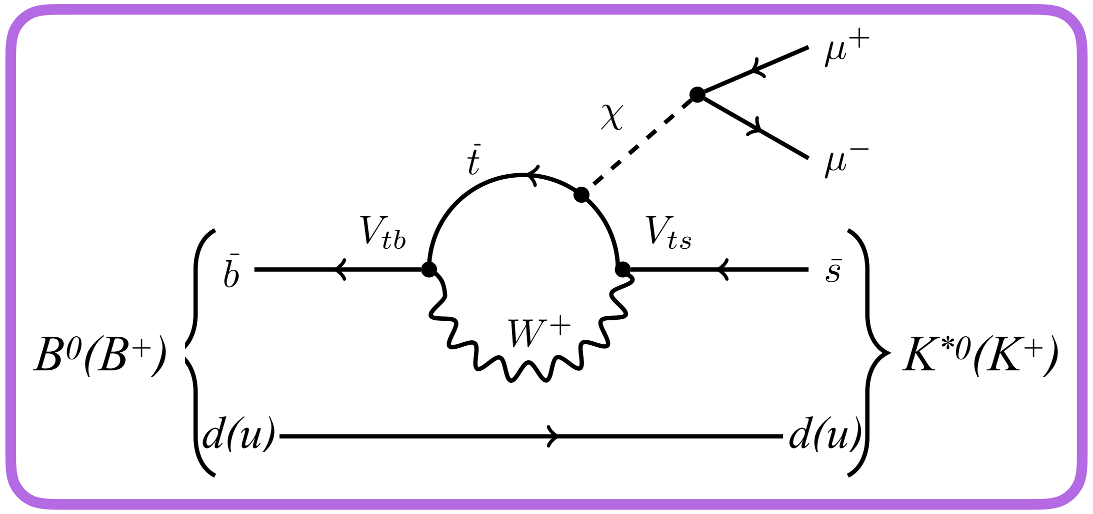




analysis already performed for Run1 and Run2!

Light Boson from $b \to s$

Phys. Rev. Lett. 115, 161802 (2015)
Phys. Rev. D. 95, 071101 (2017)



- search for a hidden sector boson χ in a decay mediated by $b \to s$ transition
- interaction via Higgs portal
- **dataset:** run I (3 fb^{-1})

$B^0 \to K^{*0} \chi$ with $K^{*0} \to K^+ \pi^-$ and $\chi \to \mu^+ \mu^-$

- $2\,m(\mu) < m(\chi) < m(B^0) - m(K^{*0})$
- $K^+ \pi^-$ vertex requirement: better decay time resolution and reduced background
- 2 region of dimuon lifetime per mass point (displaced for τ>0.6-3 ps depending on the mass)

$B^+ \to K^+ \chi$ with $\chi \to \mu^+ \mu^-$

- $250 < m(\chi) < 4700$ MeV
- more background (SM $B \to K\mu\mu$ for prompt)
- higher BR
- 3 region of dimuon lifetimes (τ<1 ps, 1<τ<10 ps, τ>10 ps)

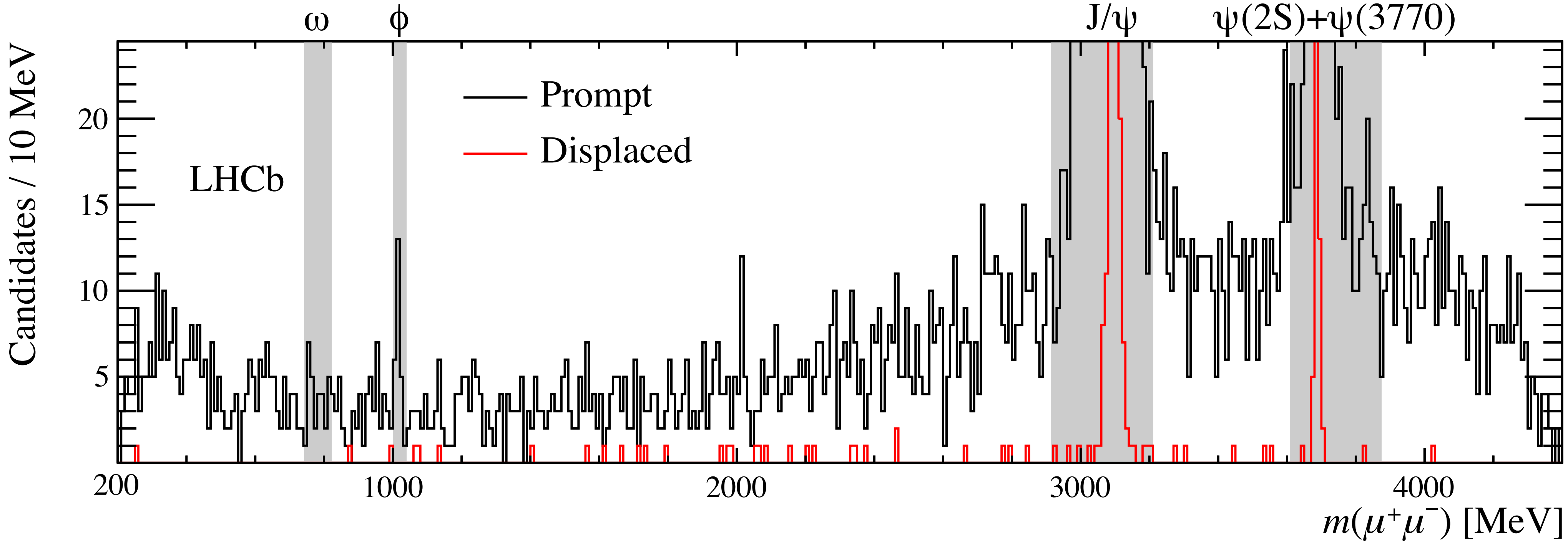
Similar strategy for both analyses

- $\chi \to \mu^+ \mu^-$ vertex allowed (but not required) to be displaced
- BDT classifier trained to reduce combinatorial (uniform in m and τ for K^{*0} search)
- narrow resonances vetoed

Light Boson from b → s

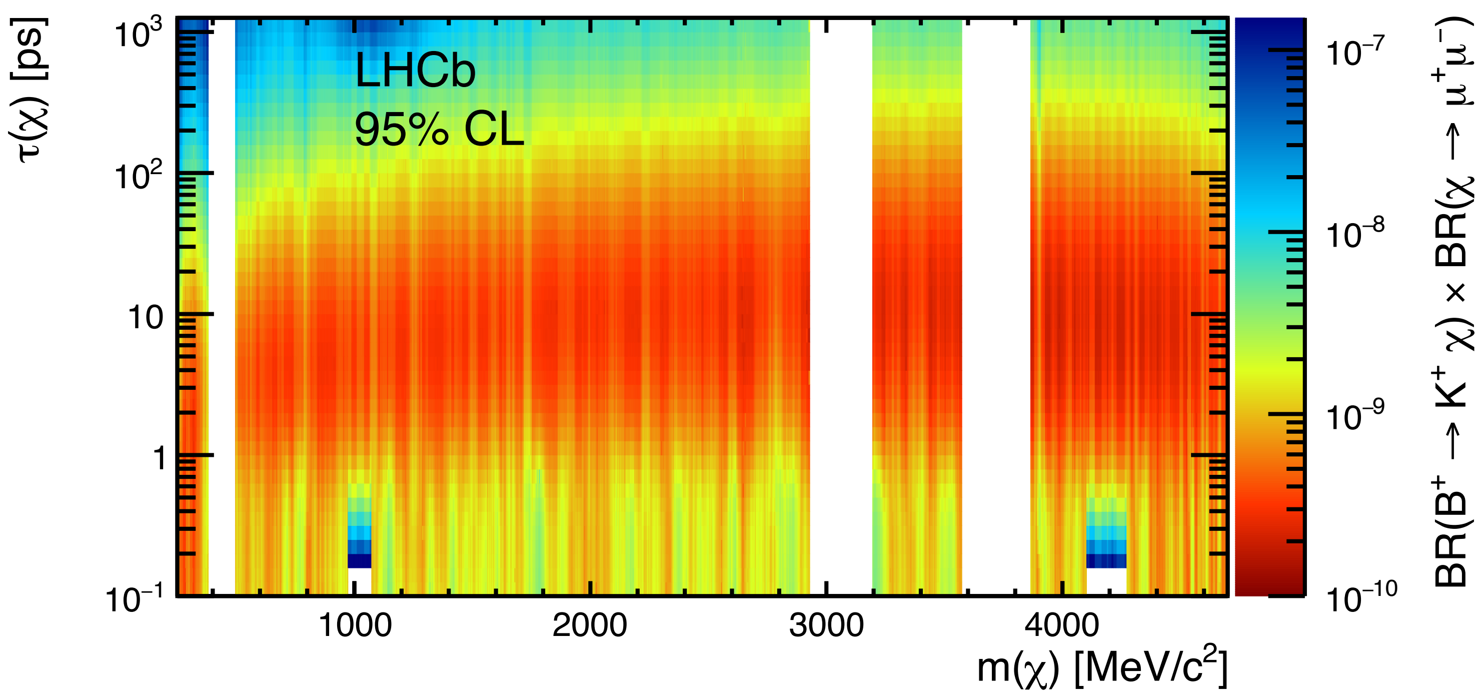
Phys. Rev. Lett. 115, 161802 (2015)
Phys. Rev. D. 95, 071101 (2017)

scan of the dimuon mass distribution



model independent limit

- upper limits as a function of mass for lifetimes [0.1,1000] ps
- precision on the upper limits dominated by statistical uncertainties
- efficiency drops at ~100 ps due to VELO acceptance



Light Boson from b → s

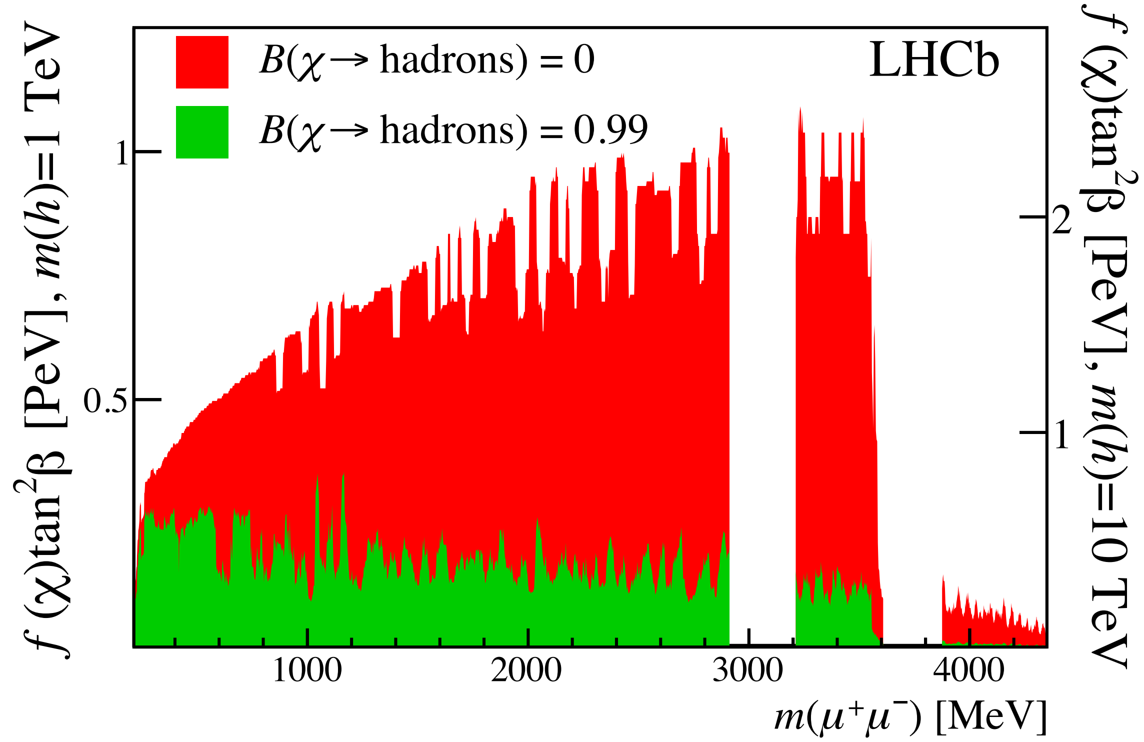
Phys. Rev. Lett. 115, 161802 (2015)
Phys. Rev. D. 95, 071101 (2017)

model dependent limits

axion model (axial vector portal)

Phys. Rev. D 81, 034001 (2010)

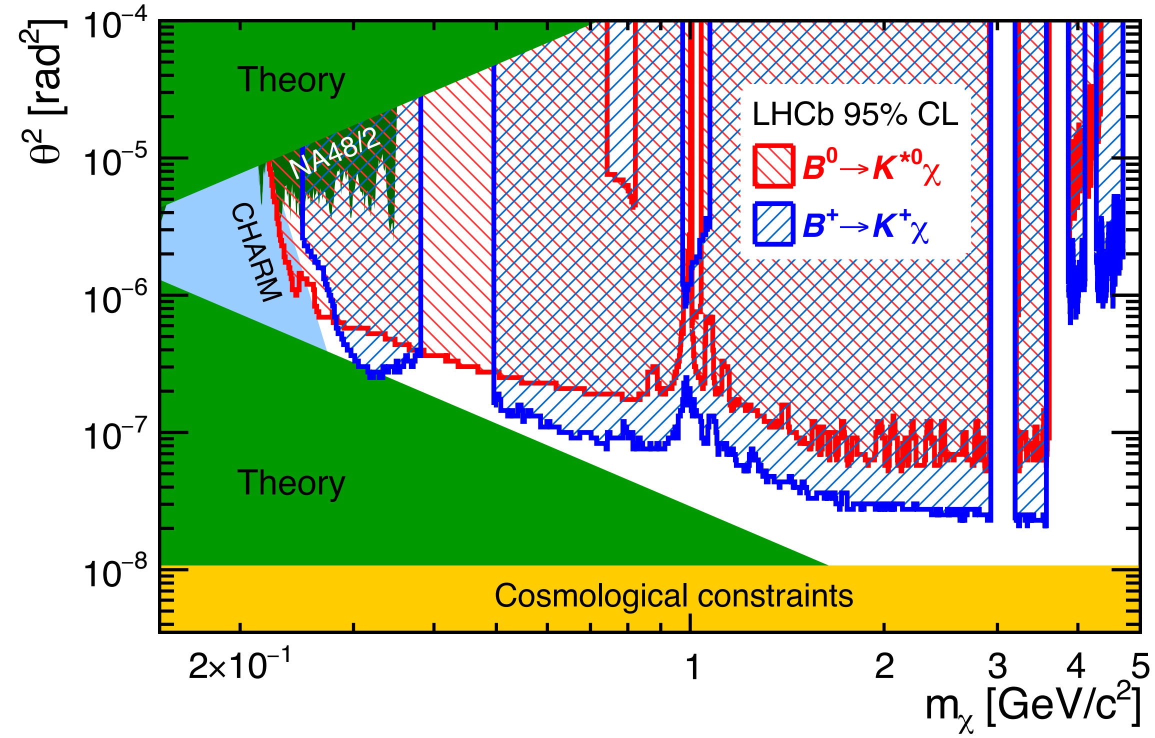
- limit on the ratio of Higgs-doublet vacuum expectation values
- BR(χ → hadrons) changes a lot in different models: two extreme cases considered



inflaton model (scalar portal)

Phys. Lett. B 736, 494 (2014)

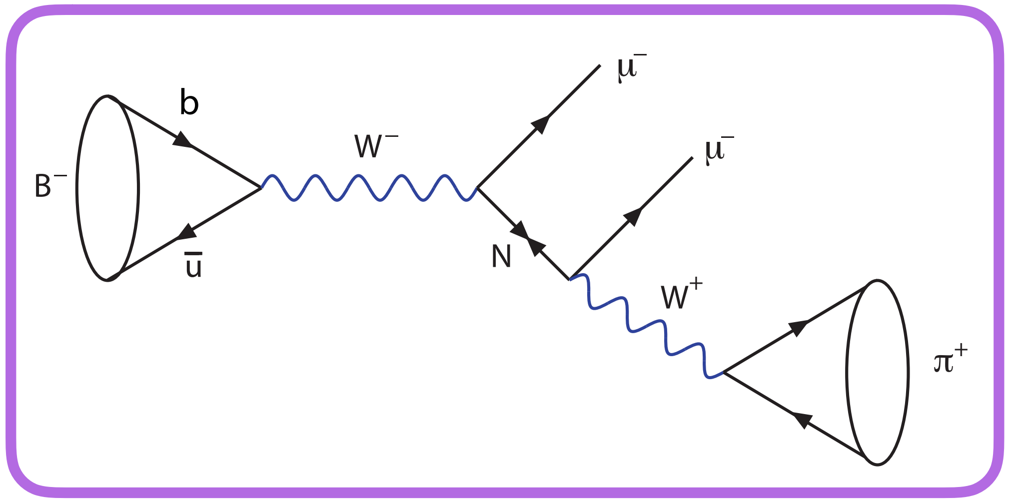
- constraint on mixing angle θ with SM Higgs
- excluded large fraction of theoretically allowed parameter space



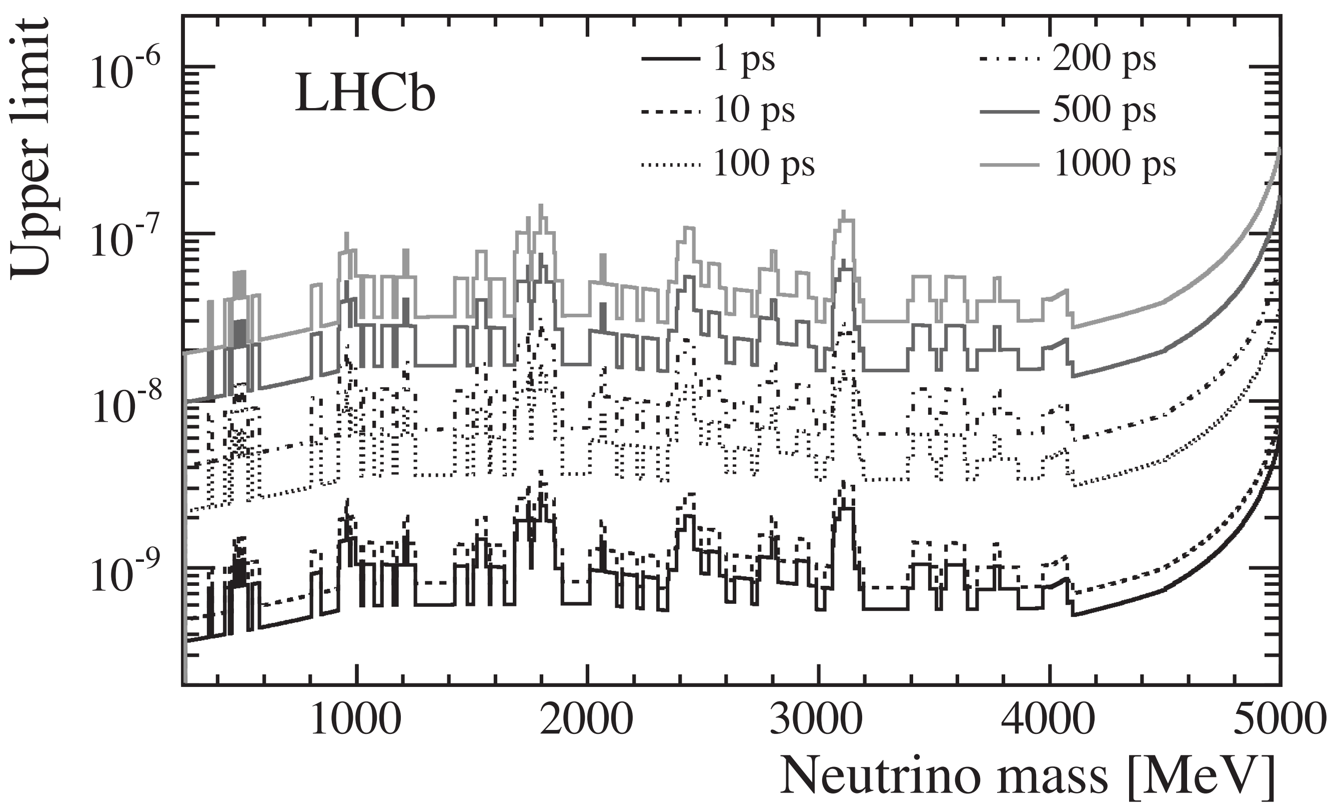
Majorana Neutrinos

Phys. Rev. Lett. 112, 131802 (2014)

- search for lepton number violating decay $B^- \to \pi^+ \mu^- \mu^-$
- **mass range:** 250 MeV - 5 GeV
- **lifetime range:** 0-1000 ps (extending sensitivity wrt previous LHCb analyses)
- **dataset:** run I (3 fb^{-1})



model independent upper limits

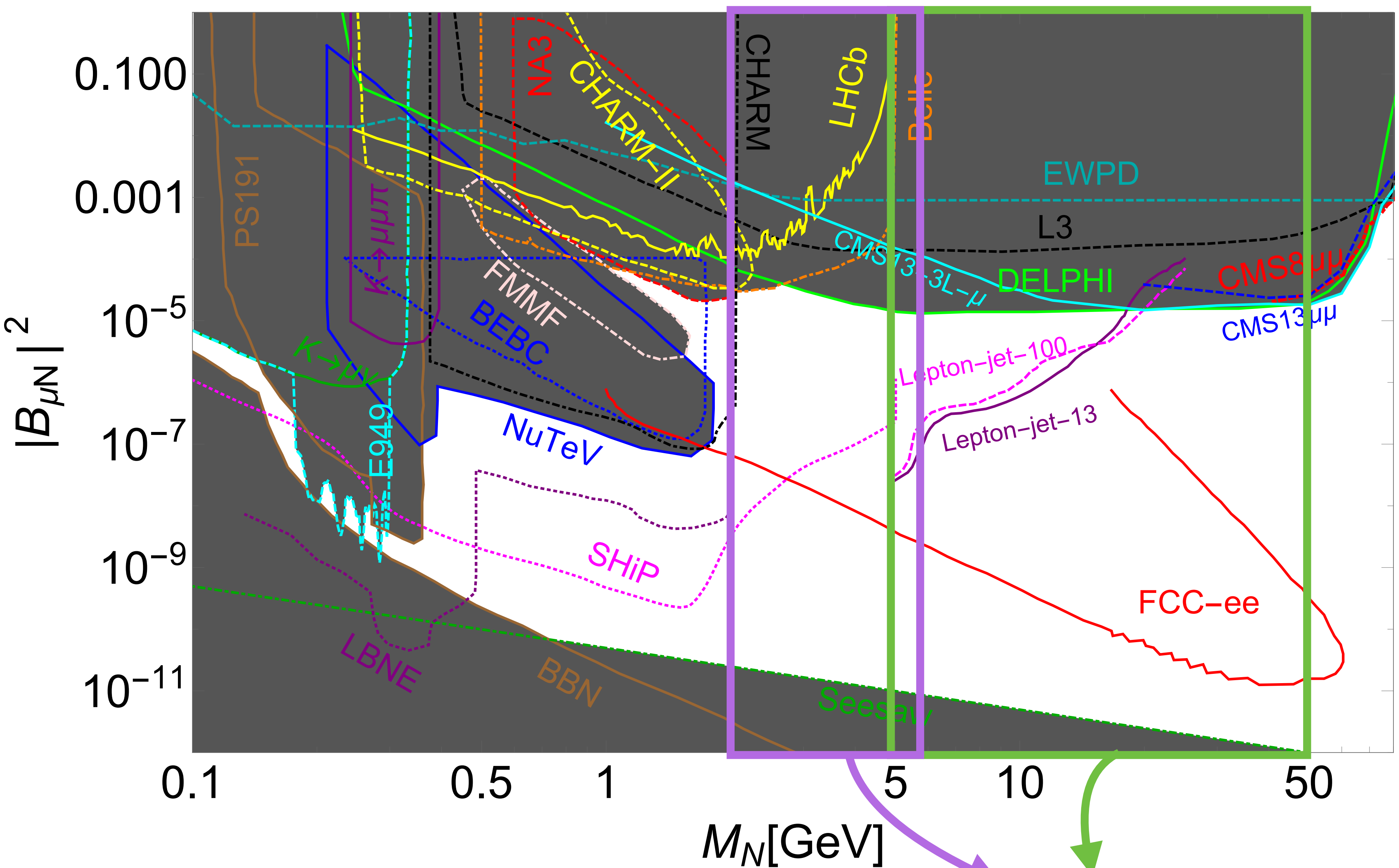


- normalisation wrt $B^- \to J/\Psi K^-$
- 2 selections: for short and long lived N (τ > 1 ps)
- fitted backgrounds:
  - B decays to charmonium
  - combinatorics
- upper limits set scanning the neutrino mass
- lifetime dependence in long lived sample taken into account by detection efficiency

Majorana Neutrinos

constraints on the BR reinterpreted as limits on N mixing angle

arXiv:1805.00070v1



we are now looking here…

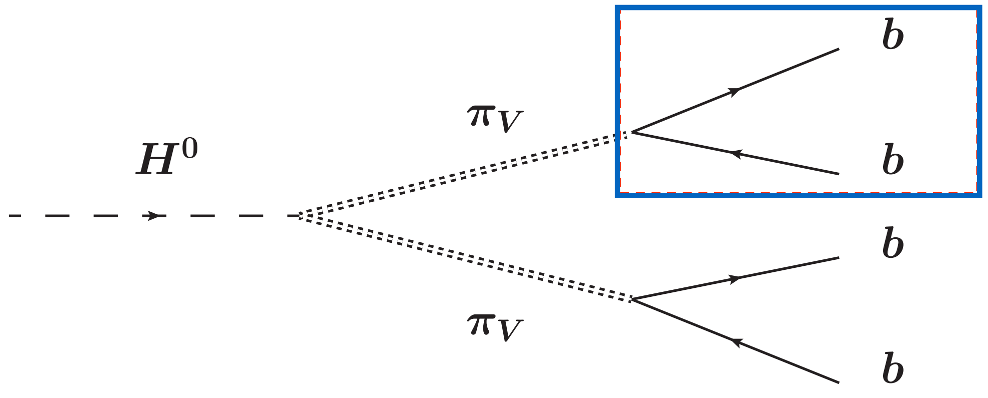
LHCb and Belle limits revised in:
Phys. Rev. D94, no.11, 113007 (2016)
Phys. Rev. D95, no.9, 099903 (2017)

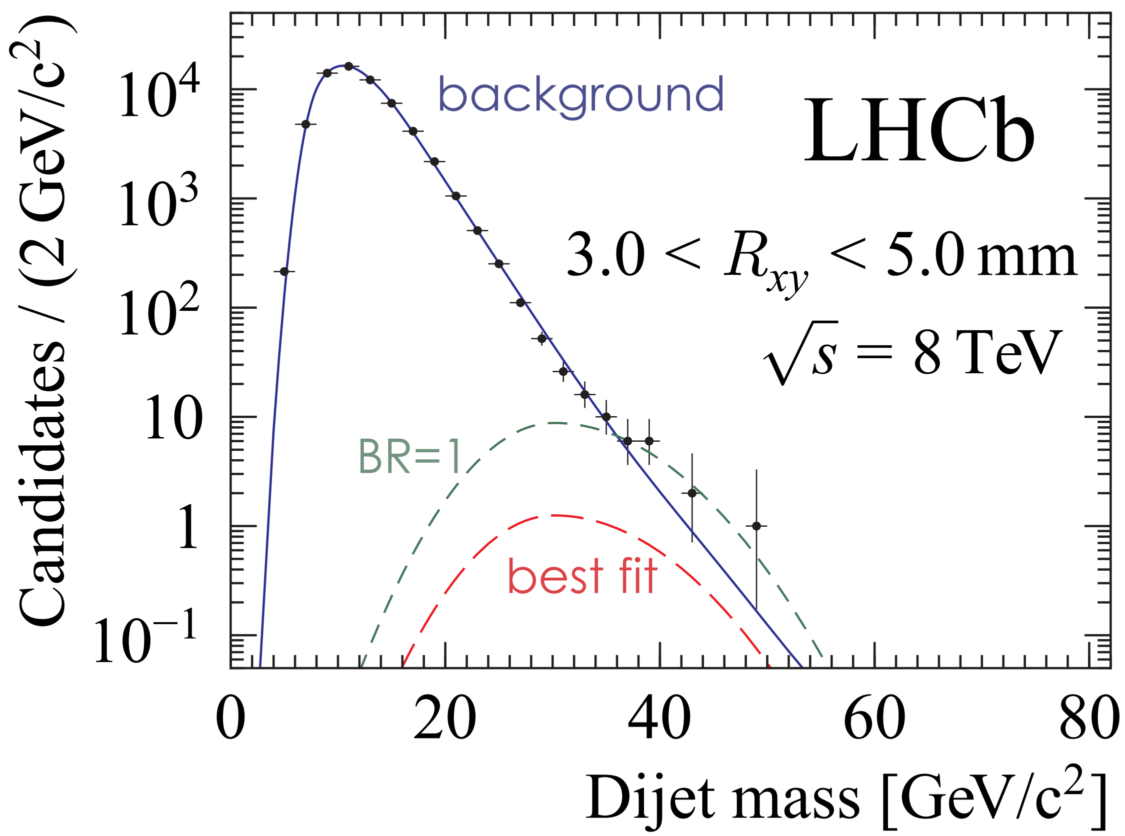
LLPs Decaying to Jet Pairs

Eur. Phys. J. C77 (2017) 812

- search for hidden sector LLP produced via SM Higgs portal
- **mass range:** 25-50 GeV
- **lifetime range:** 2-500 ps
- **dataset:** run I (2 fb^{-1})
- **signature:** single displaced vertex with 2 associated jets

in most cases only 1 π_v within LHCb acceptance



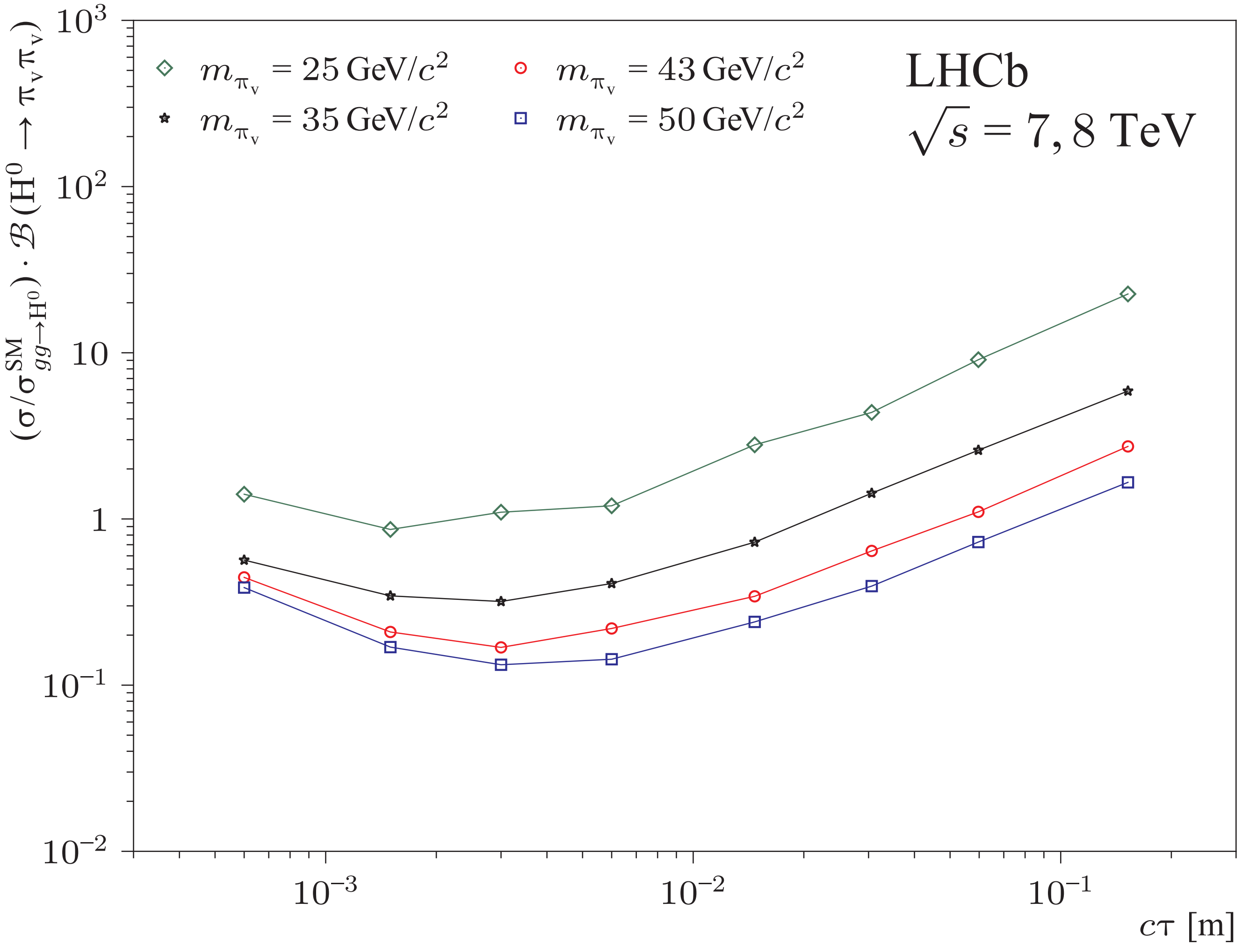


- trigger on displaced vertex
- requirements on jet pointing and material interaction veto to reduce main backgrounds:
  - vertex from heavy flavour decay or material interaction
  - SM dijet events
- fit of the di-jet mass in bins of transverse displacement R_{xy}

LLPs Decaying to Jet Pairs

Eur. Phys. J. C77 (2017) 812

upper limits set on SM-Higgs BR to dark pions



LLPs Decaying to Jet Pairs

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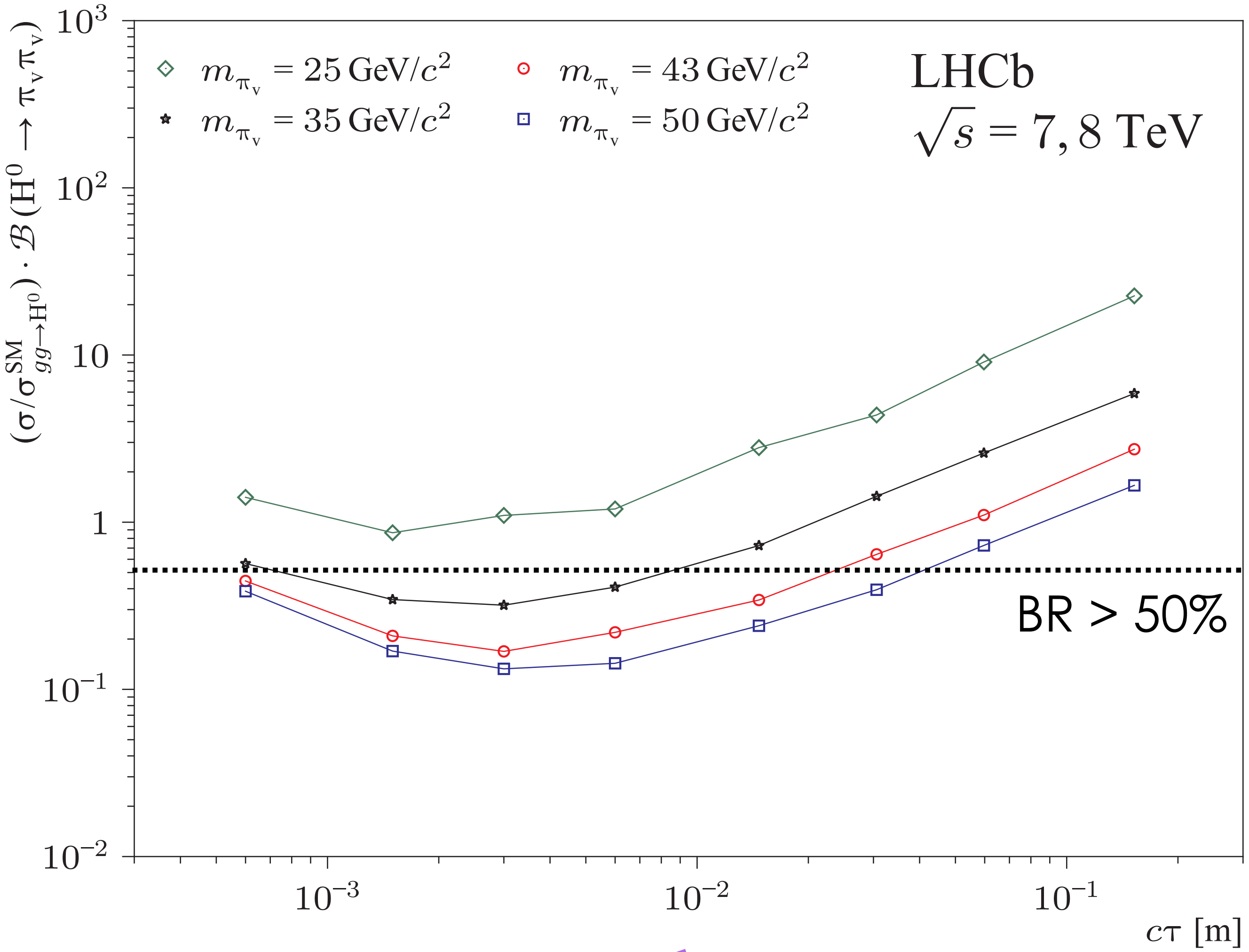
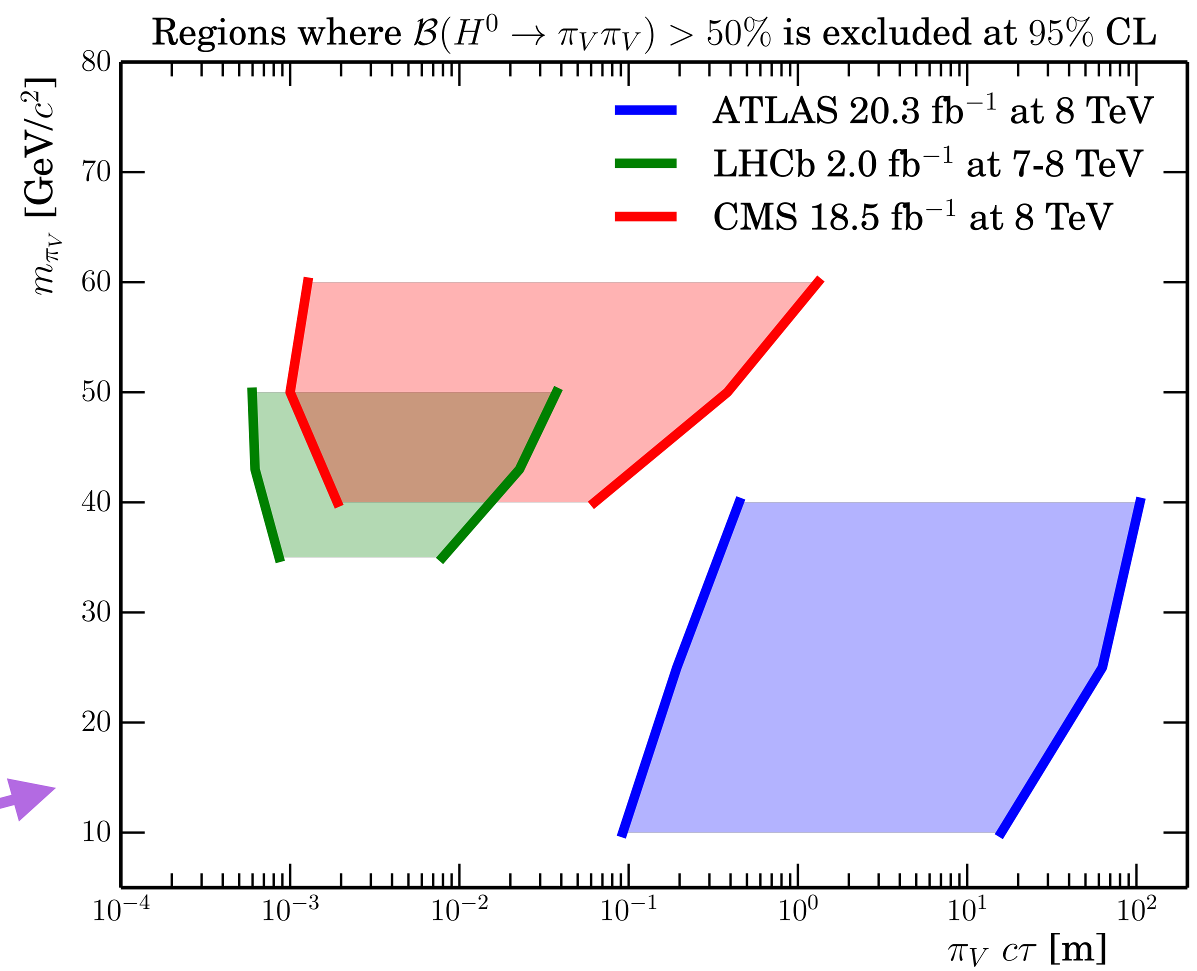


competitive and complementary to ATLAS and CMS!



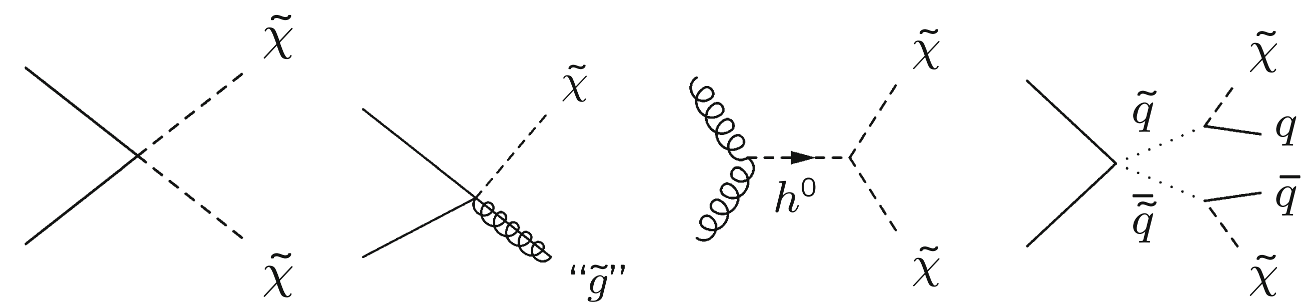
Supplementary material of LHCB-PAPER-2016-065

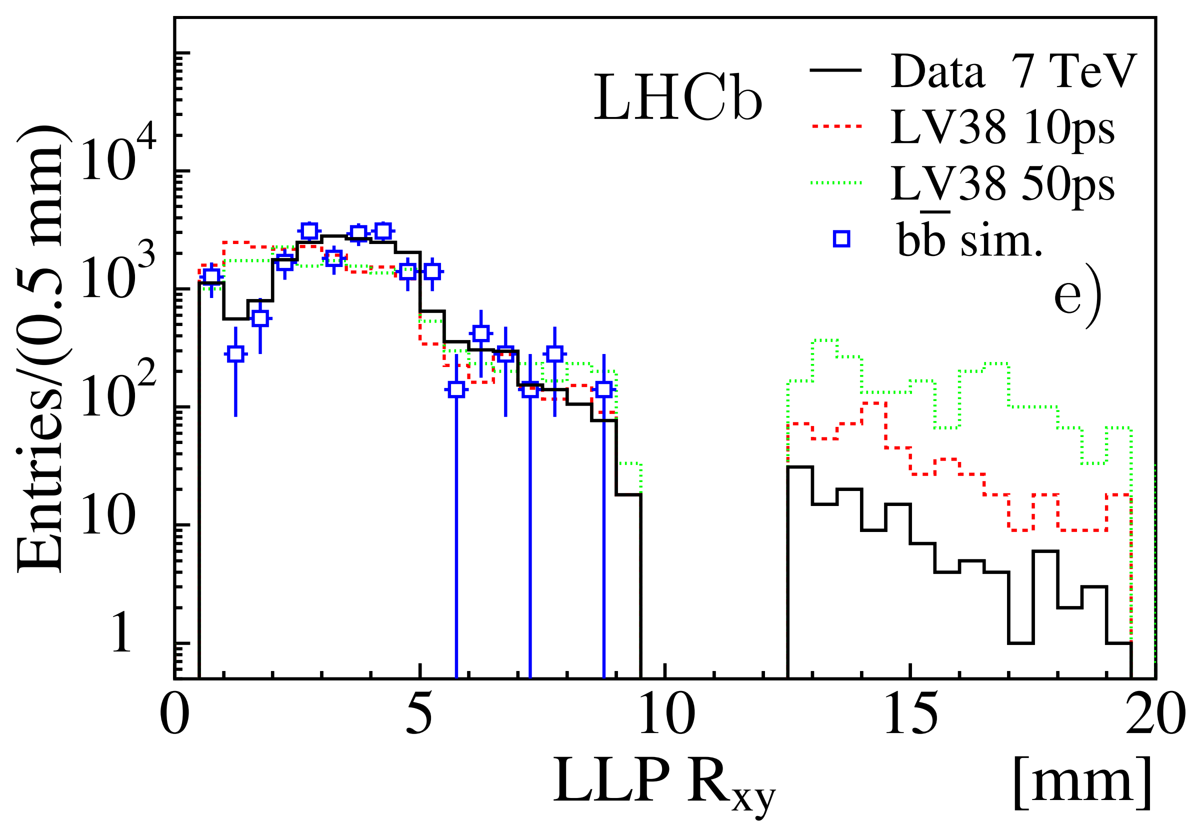
LLP Decaying Semileptonically

Eur. Phys. J. C (2017) 77:224

- search for massive LLP decaying semileptonically into SM particles
- 2 approaches:
  - RPV mSUGRA neutralino as benchmark
    mass range: 23-198 GeV
  - simplified topologies, less model dependent
    mass range: 25-50 GeV
- recasted in terms of heavy neutral lepton
  arXiv:1706.05990

4 production mechanisms considered



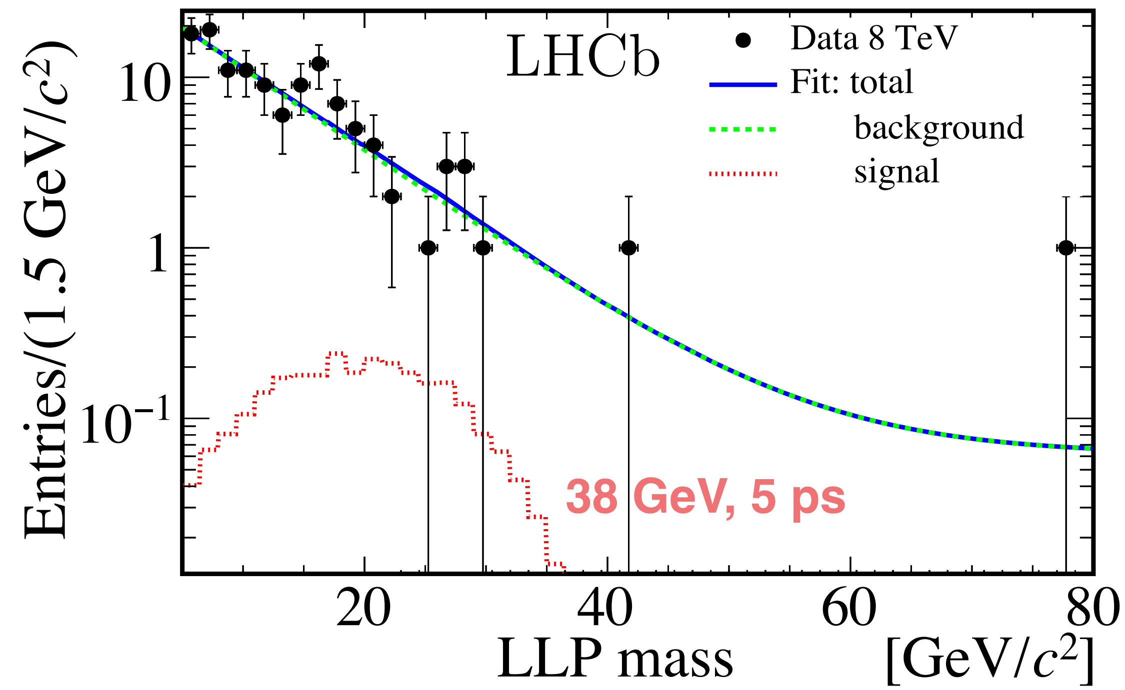


- **lifetime range:** 5-100 ps
- **dataset:** run I (1+2 fb^{-1})
- **signature:** single displaced vertex with several tracks and a high p_T μ
- background dominated by $b\bar{b}$

LLP Decaying Semileptonically

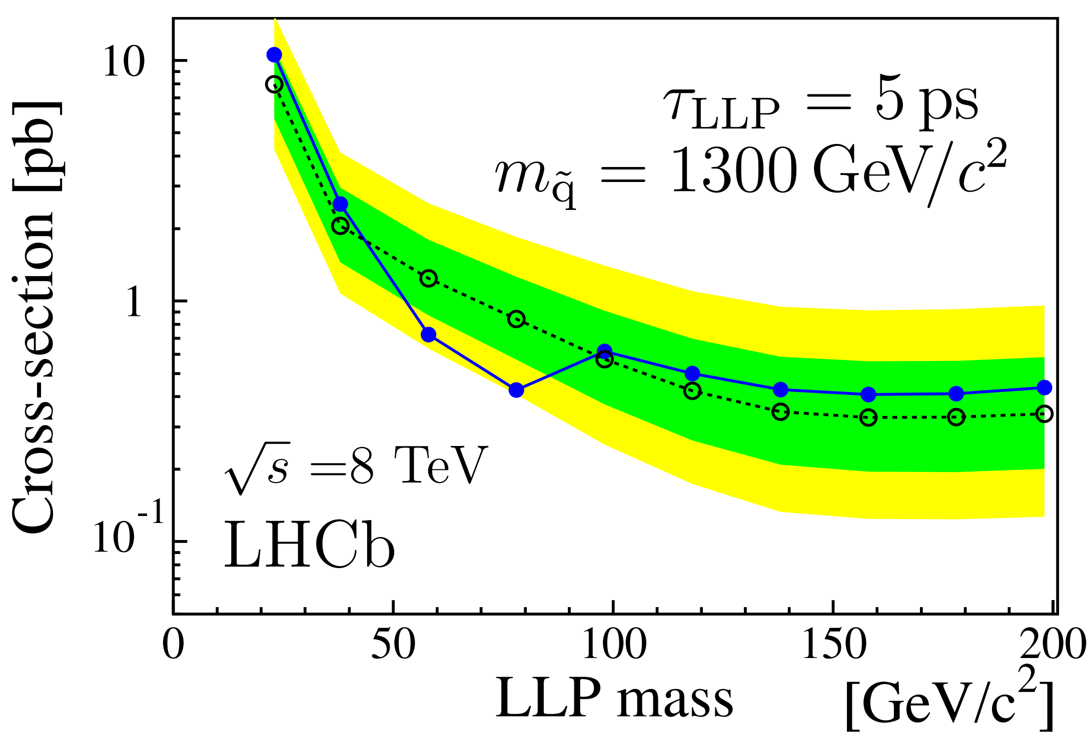
Eur. Phys. J. C (2017) 77:224

- trigger on μ + displaced vertex
- exploit μ isolation to define a signal and a control region enhanced in background
- simultaneous fit of the LLP mass in the 2 regions to extract number of candidates

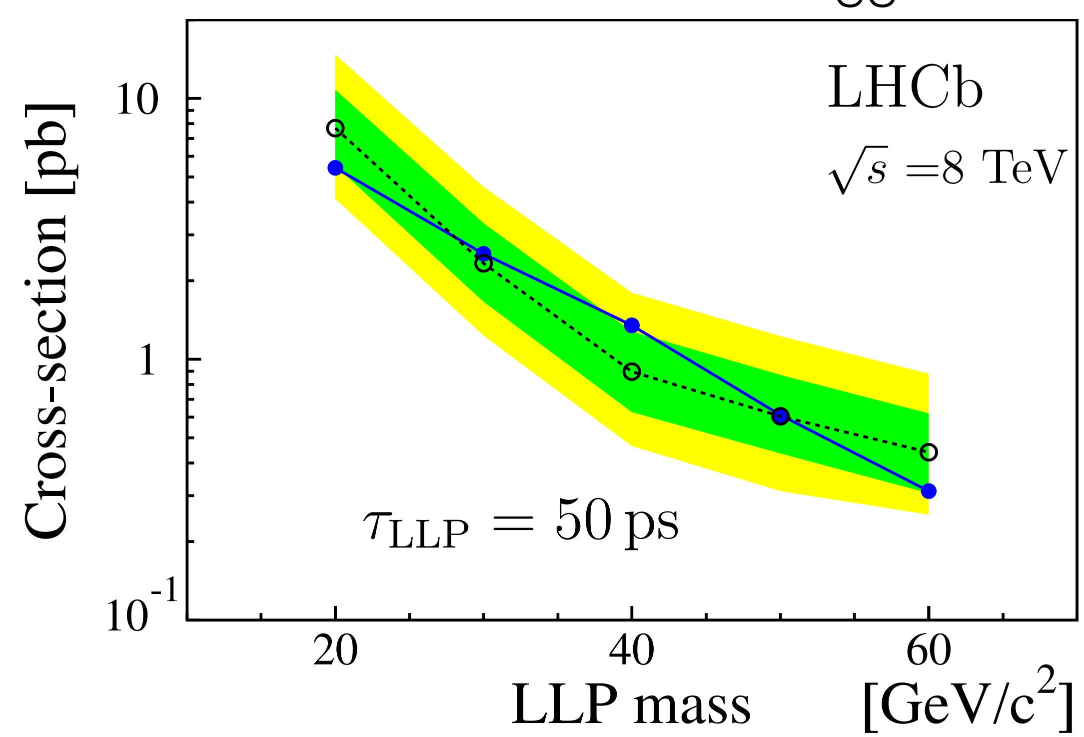


no significant excess observed

RPV mSUGRA



double LLP from 125 GeV Higgs



LLP Decaying Semileptonically

Eur. Phys. J. C (2017) 77:224

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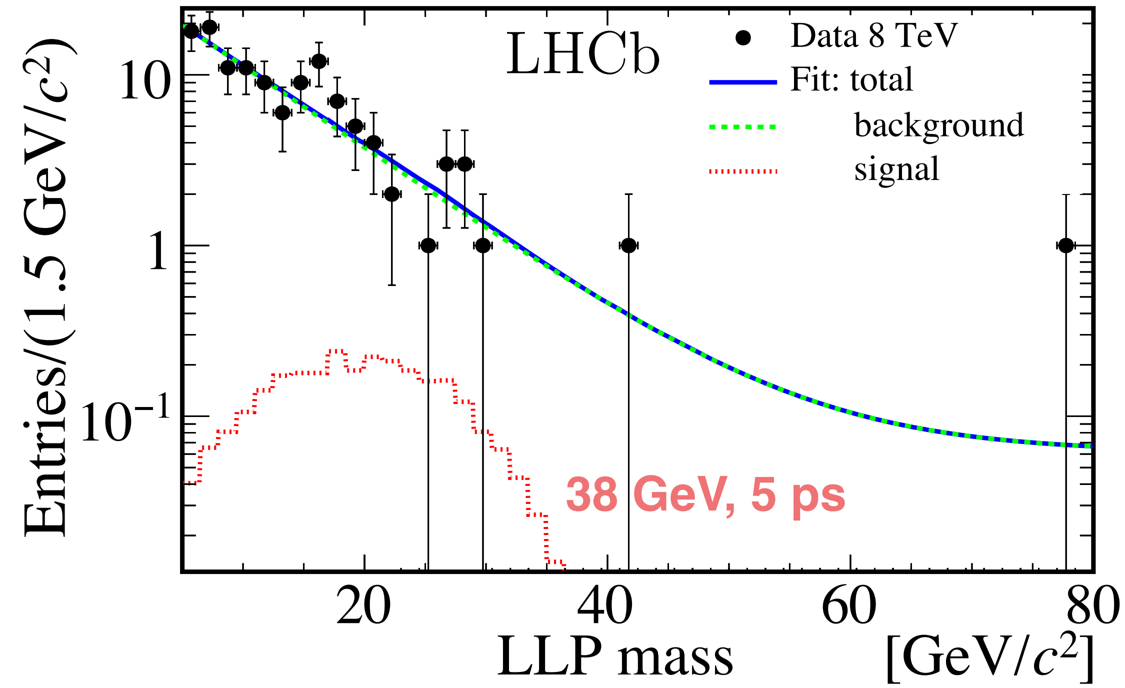
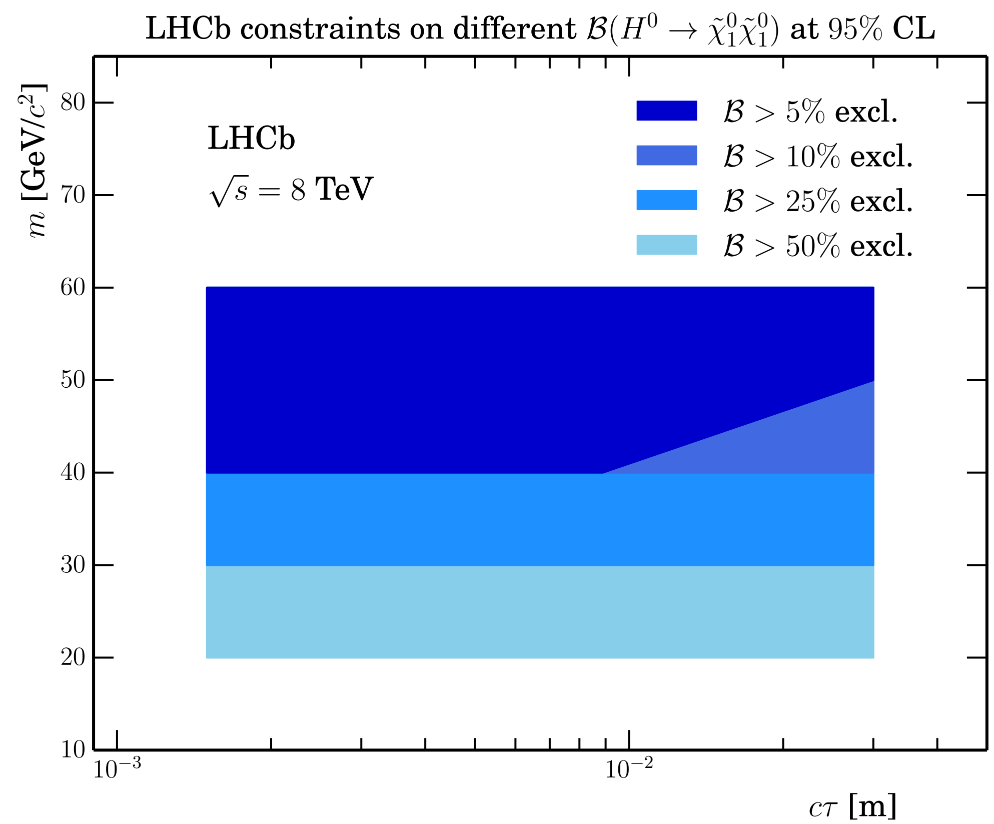
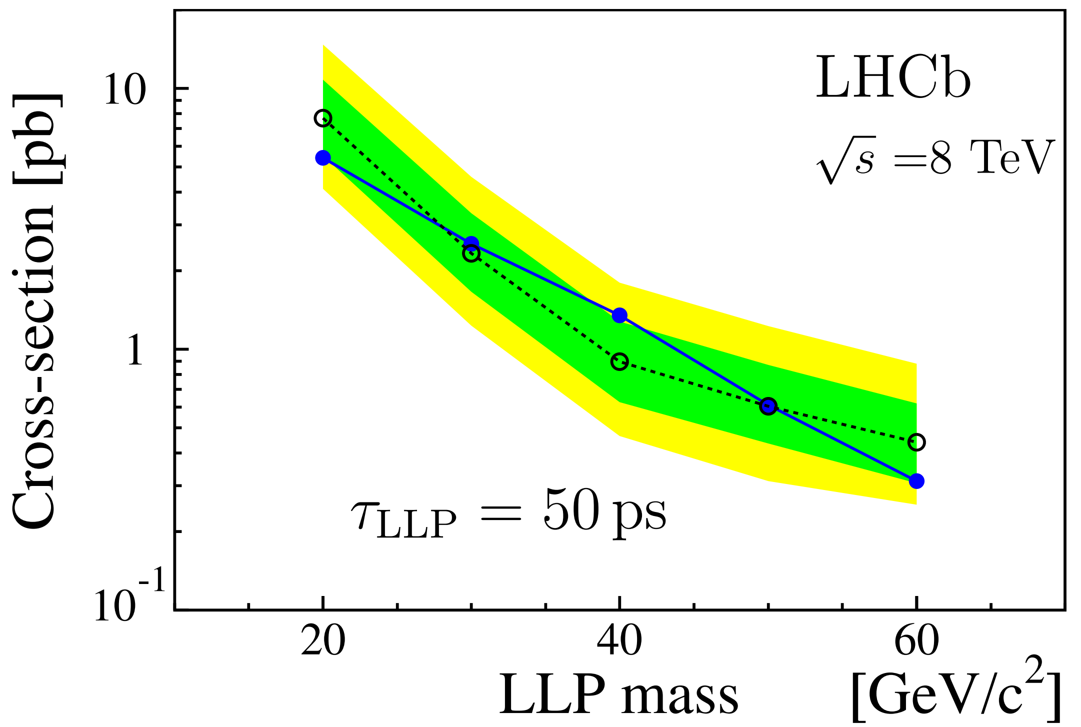




Supplementary material of LHCB-PAPER-2016-047

double LLP from 125 GeV Higgs



Summary

Increasing interest in direct searches

- LHCb proved to be competitive in many signatures
  - low masses
  - low lifetimes
  - LLP from B decays
- unique coverage complementary to ATLAS and CMS
- 3 fb^{-1} in Run 1, expected +6 fb^{-1} in Run 2

Lot of potential with the upgrade in LS2

- more data (5x instantaneous luminosity)
- triggerless readout
- potential improved efficiency for longer decay lengths

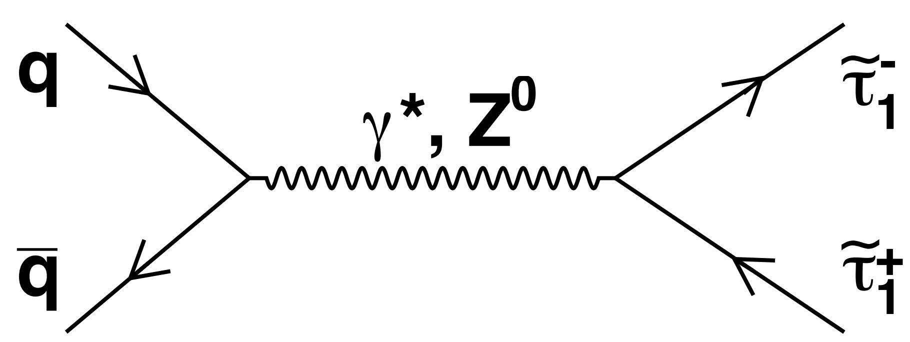
Back Up

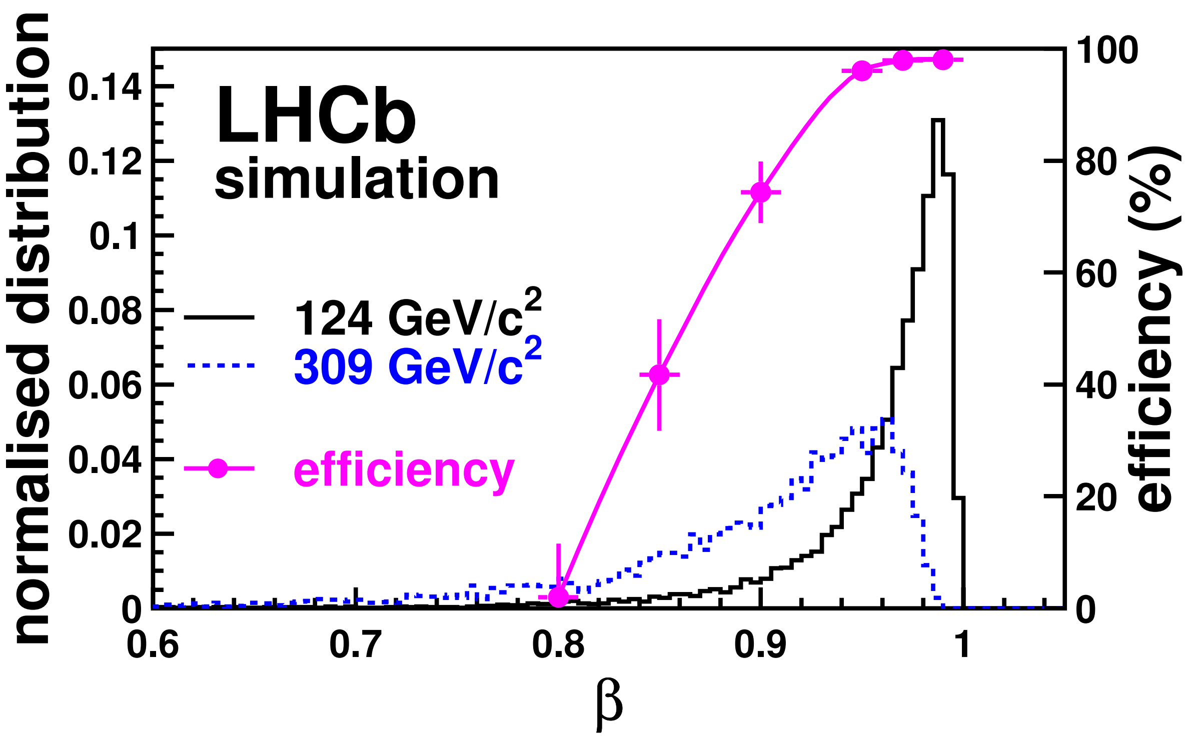
Charged Massive Stable Particle

EPJC 75 (2015) 595

- search for charge massive stable particles (CMSP)
- benchmark: stau pairs predicted by mGMSB model
- **mass range:** 124-309 GeV
- **dataset:** run I (3 fb^{-1})
- **signature:** absence of a signal in the RICH

Drell-Yan production of stau pairs



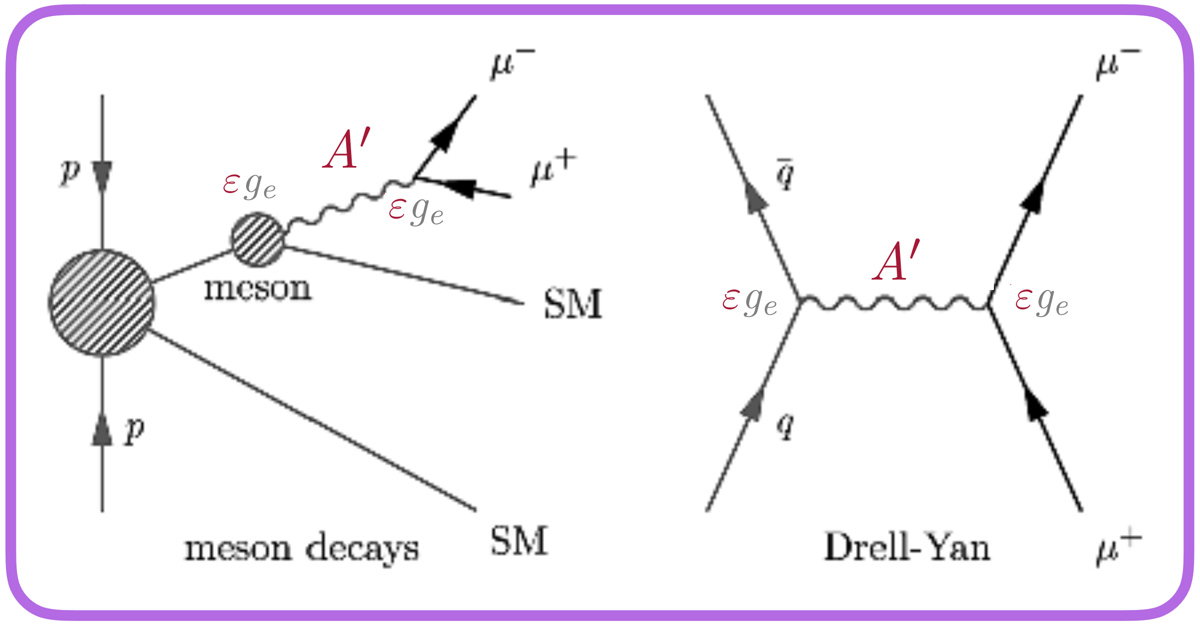


- staus assumed to interact only via weak interactions
  ➡ behave like heavy muons
- detection time window for muons limits sensitivity to $\beta>0.8$
- main background: Drell-Yan production of muon pairs

upper limits set on Drell-Yan CMSP pair production cross section ➡ **proof of concept for future searches!**

Dark Photon

Phys. Rev. Lett. 120, 061801 (2018)



- dark matter might interact via a new dark force
- a massive dark photon A' could kinetically mix with the ordinary photon
  - same production and decay kinematics of an off-shell photon with same mass
  - normalising to γ^* allows to get rid of most of the systematics

- fully data driven search
- **dataset:** run II (1.6 fb^{-1})
- **inclusive:** $pp \rightarrow X\ A' \rightarrow X\ \mu^+\mu^-$
- if m x ε^2 small dark photon is long-lived
- trigger turbo lines:
  - prompt: no requirement on dimuon mass
  - displaced: looser cuts on muon p and p_T

prompt search

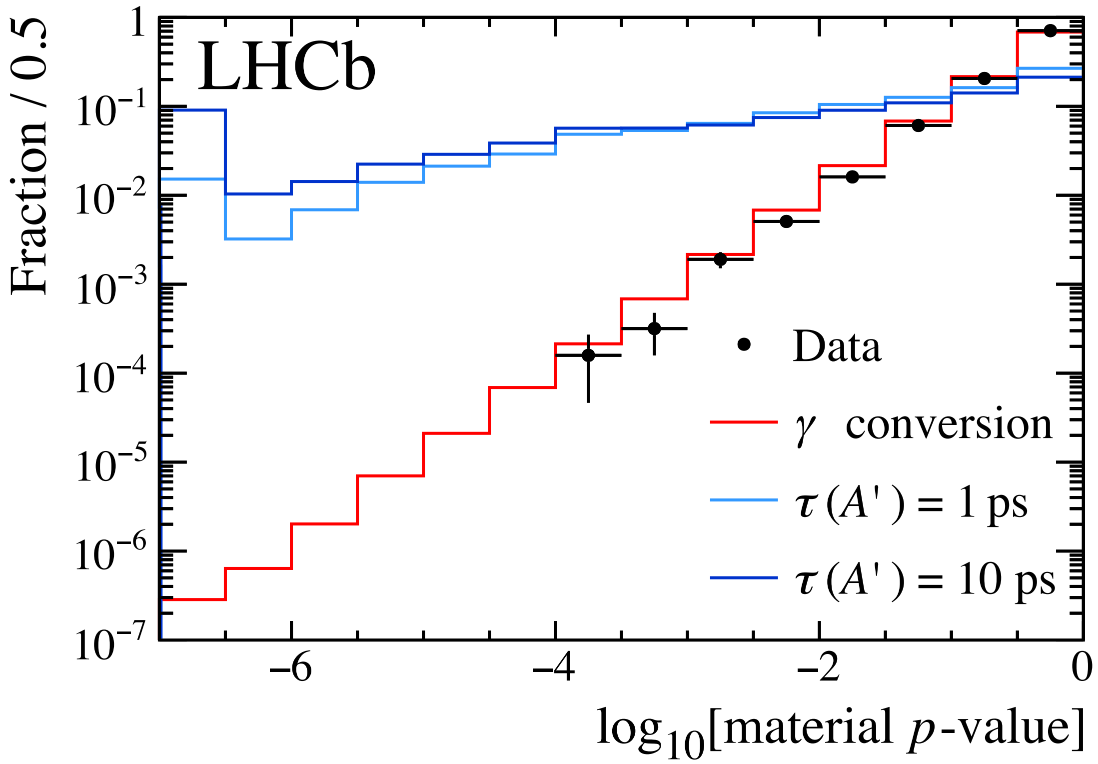
$2m_\mu < m_{A'} < 70$ GeV

displaced search

$214 < m_{A'} < 350$ MeV

Dark Photon: Long Lived

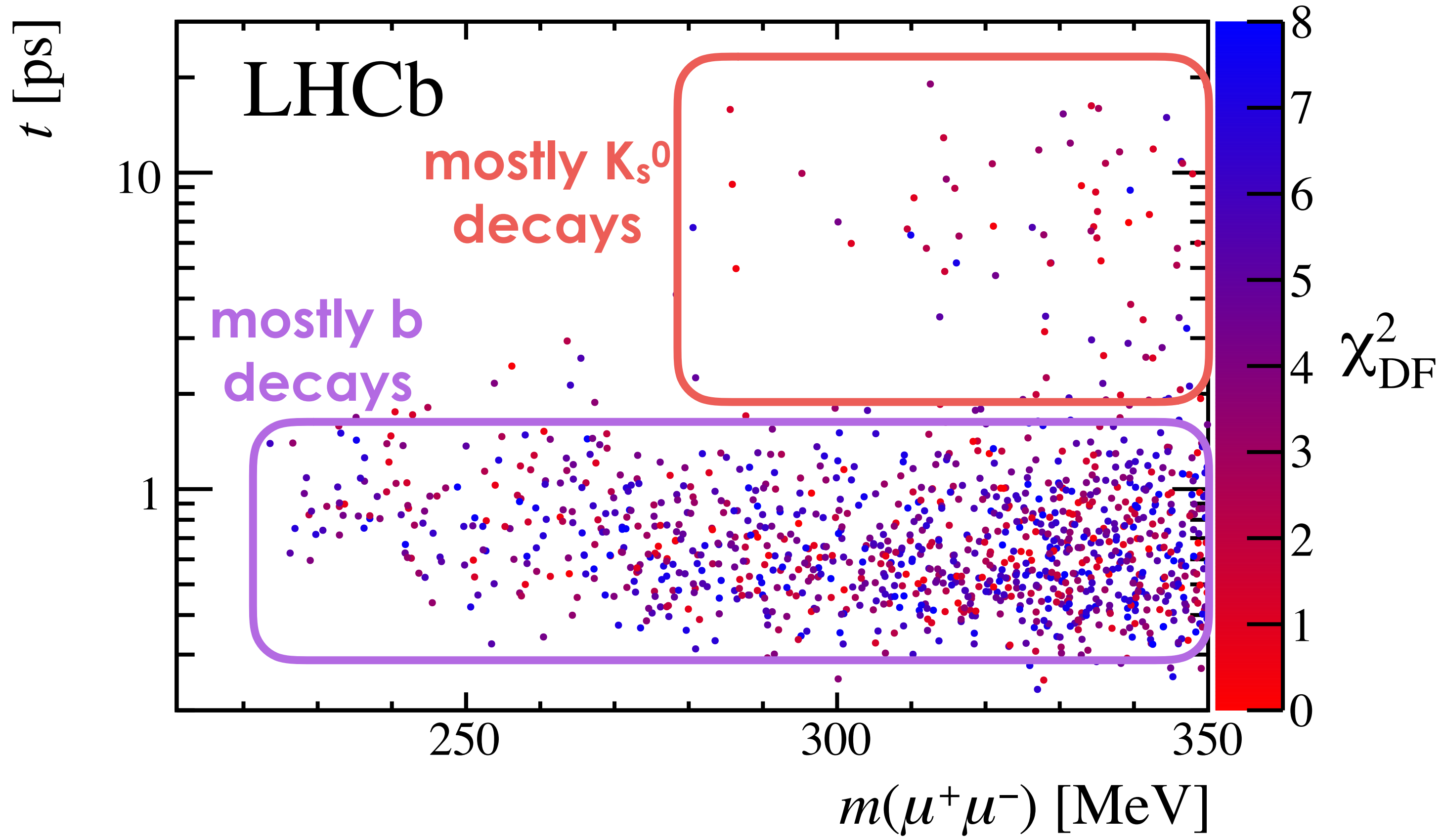
Phys. Rev. Lett. 120, 061801 (2018)
CERN-LHCb-DP-2018-002



main backgrounds:

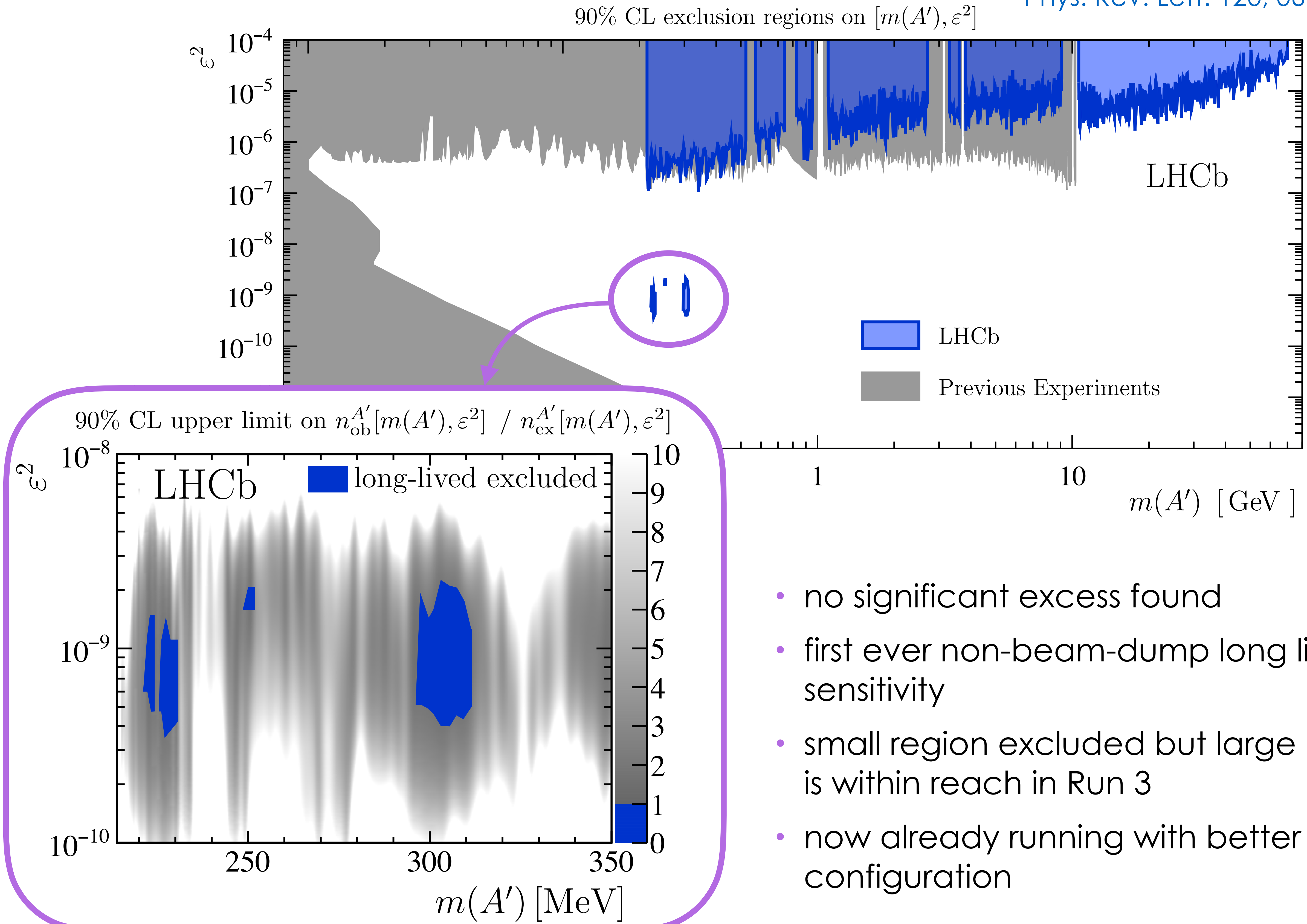
- photon conversions in VELO material
  - ➡ material map
- 2 semileptonic b hadrons decays
  - ➡ isolation BDTs (from $B_s \to \mu\mu$)
- double misID $K_s \to \pi\pi$ decays
  - ➡ modelled from PID sideband

- scan of m(μμ)
- bins of τ(A') and decay fit χ^2
- fit to the mass distribution to get long-lived A' signal yield



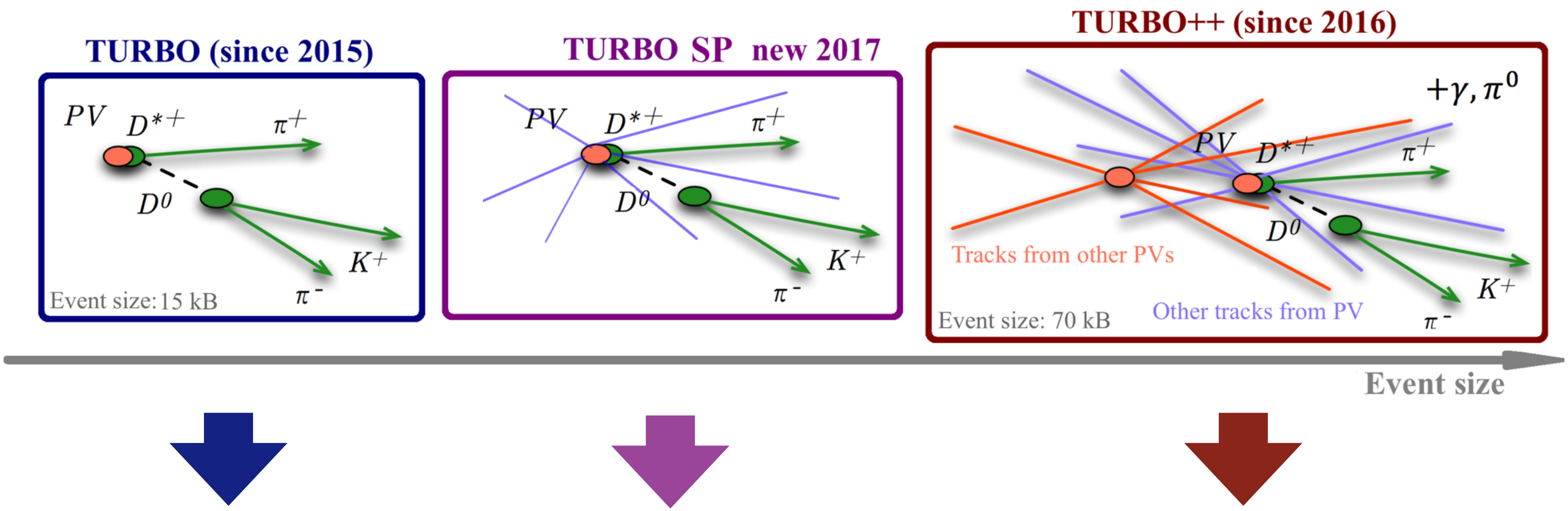
Dark Photon: Results

Phys. Rev. Lett. 120, 061801 (2018)



- no significant excess found
- first ever non-beam-dump long lived A' sensitivity
- small region excluded but large region is within reach in Run 3
- now already running with better trigger configuration

Turbo



only exclusive decays (nothing else saved)

- new intermediate solution
- trigger candidate + subset of reconstruction saved

- full event reconstruction can be persisted
- variables such as isolation, objects for jet reconstruction can be saved

Majorana Neutrinos

Phys.Rev. D94 (2016) no.11, 113007

constraints on the BR reinterpreted as limits on N mixing angle