FLAVOUR & DARK MATTER

WORKSHOP DEDICATED TO THE POTENTIAL OF MODERN FLAVOUR PHYSICS EXPERIMENTS TO EXPLORE THE DARK SECTOR

SEPTEMBER 25 – 28, 2017 | UNIVERSITÄT HEIDELBERG

# Direct dark sector searches at LHCb

Martino Borsato

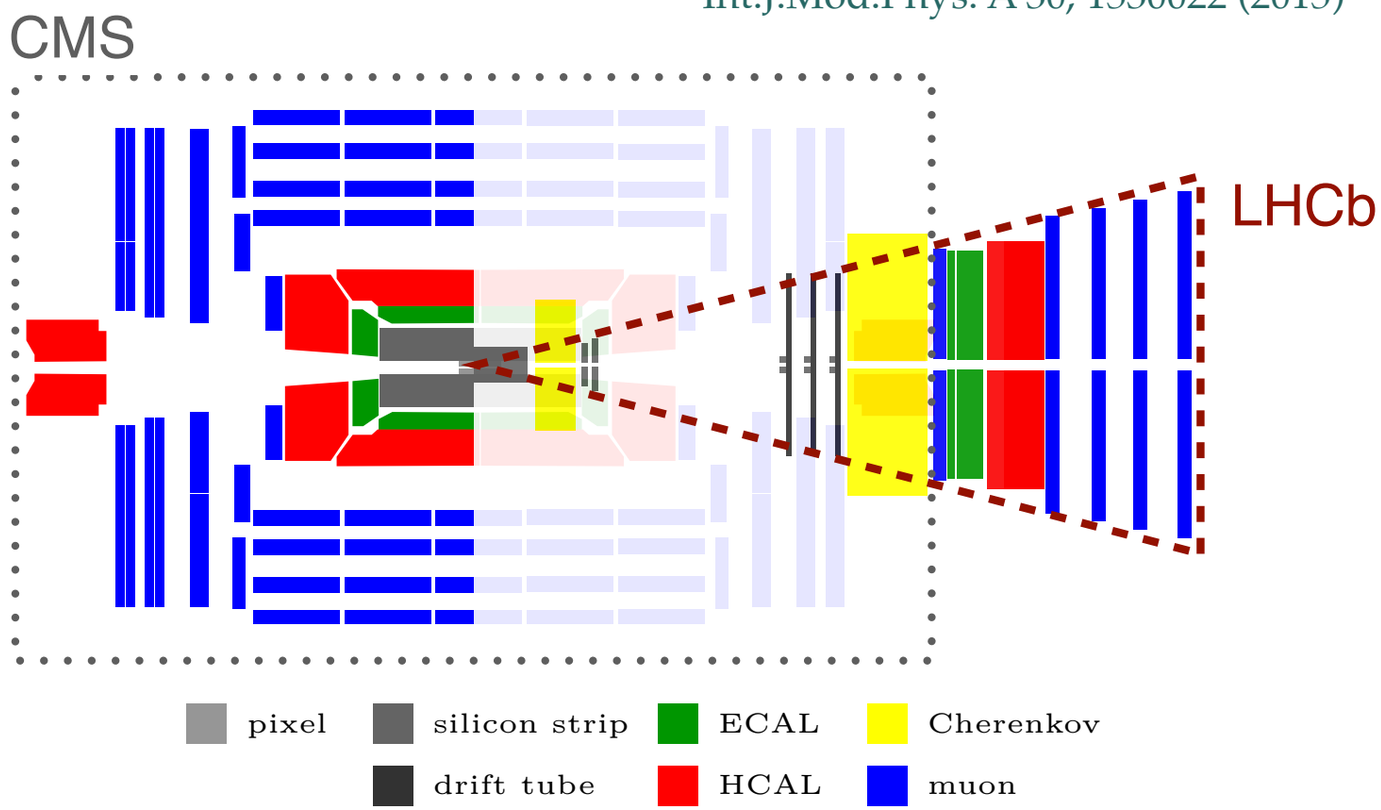
Universidade de Santiago de Compostela

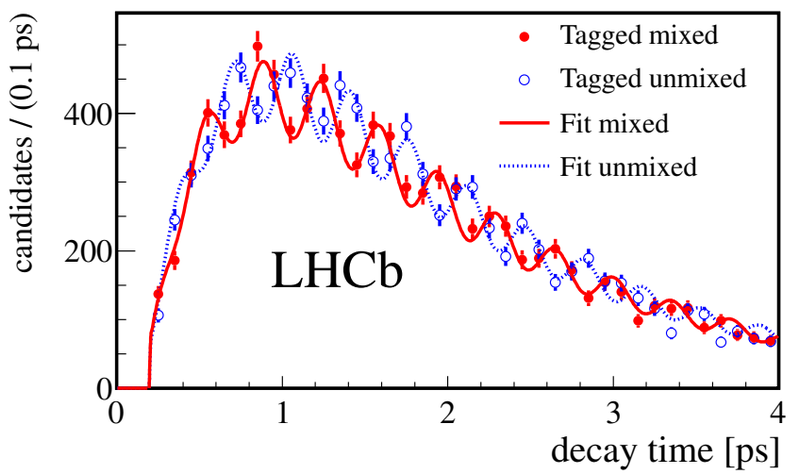
*on behalf of the LHCb collaboration*

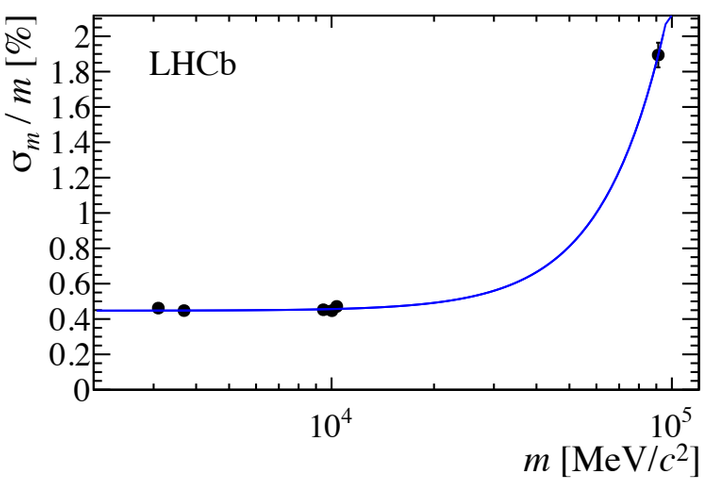
# The LHCb detector

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

- At LHC $pp$ collisions (7-13 TeV)
- Fully instrumented in **forward** region $2<\eta<5$ for $B$ physics
  - also **light states** in general
- Excellent vertex resolution
  - $B_s$ oscillation at 40 fs (average boost $\beta\gamma \sim 3$)
- Excellent mass resolution
  - ~0.5% on $m(\mu\mu)$ up to 20 GeV
- Unique PID capabilities
  - dedicated Cherenkov detectors
- Good jet reconstruction
  - 10-20% energy resolution for jets with $p_T > 10$ GeV
  - $b(c)$ tagging eff 65%(25%) for 0.3% contamination

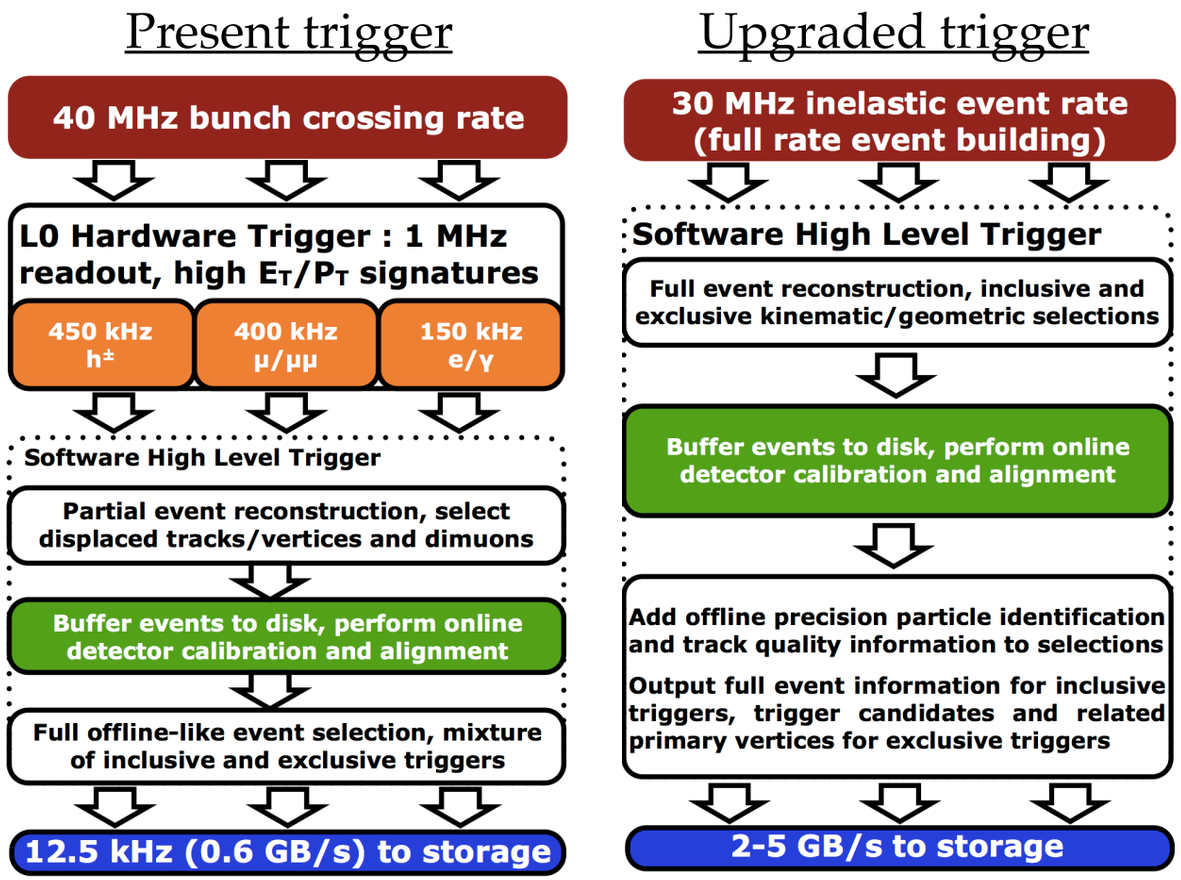


# The LHCb detector

- Lower luminosity (and low pile-up)
  - 1/8 of ATLAS/CMS in Run 1
- **Capable of very soft triggers!**
  - At hardware level (L0):
    - $\varepsilon = 95\%$ for detached $\mu\mu$ with $p_T > 1\text{GeV}/c$
    - Calo trigger at ~3.5 (~2.5) GeV for hadrons (electrons)
  - At Software level (HLT):
    - Topological triggers on detached vertices
    - Lately PID and jets in trigger!
- **Trigger-less upgrade (2021)**
  - Read-out detector in *real time*
  - **Can trigger on detached vertices and particle ID at first level!**

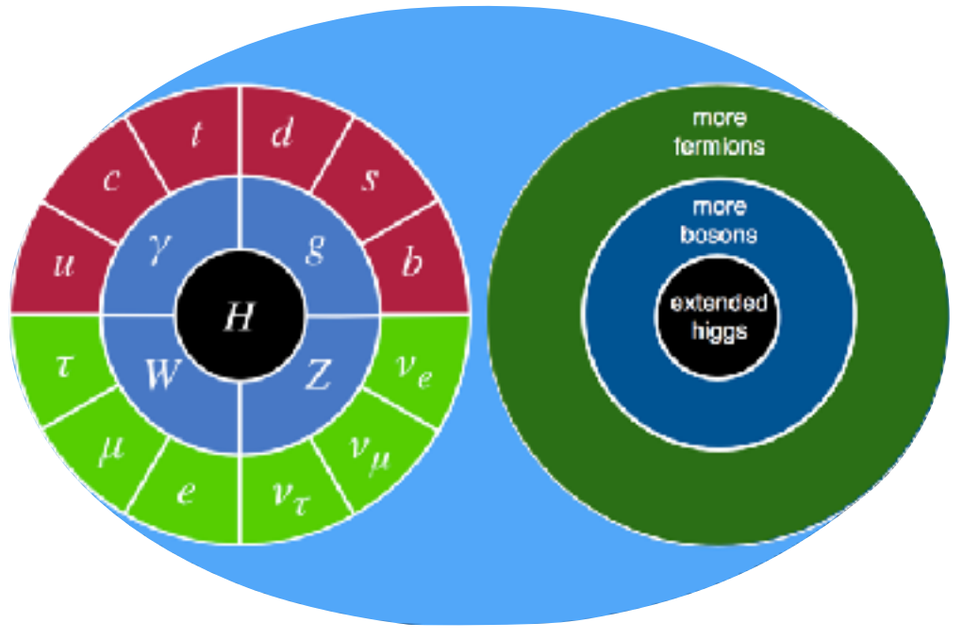



[LHCB-TDR-016]

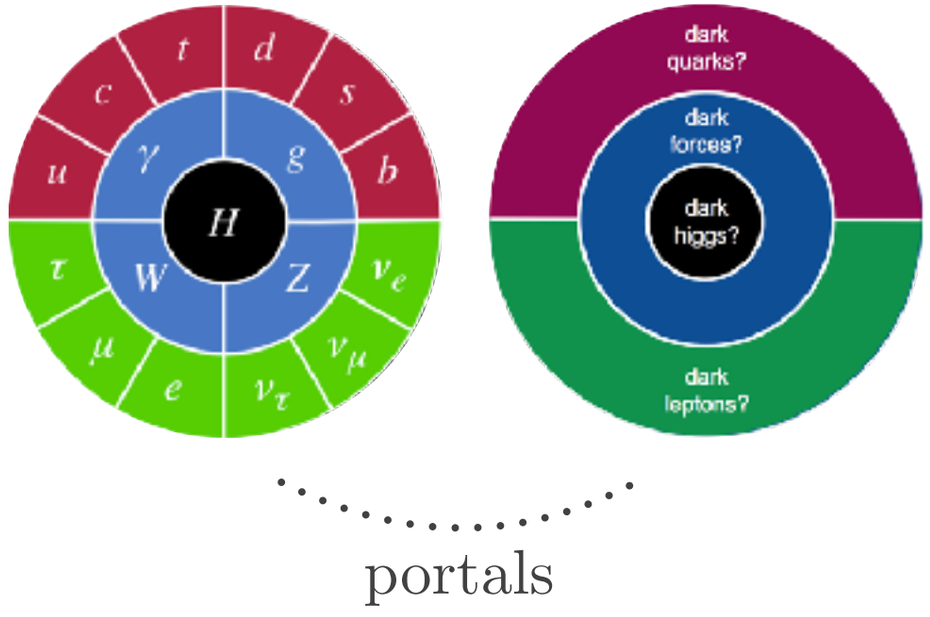
# Dark Sector searches

diagrams are a courtesy of M.Williams

1. **Unified theory of DM and SM**
   at TeV scale (e.g. SuperSymmetry)
   - Missing energy + SM jet
   - DM decay to SM (R-parity violating)
   - Indirect searches via quantum effects in SM decays (flavour physics)




2. **Separated DM sector with portals to SM**
   - Scalar portal (e.g. inflaton)
   - Axial vector portal
   - Vector portal (dark photons, $Z'$)
   - Dark pions (Hidden valley)



# Dark Sector searches

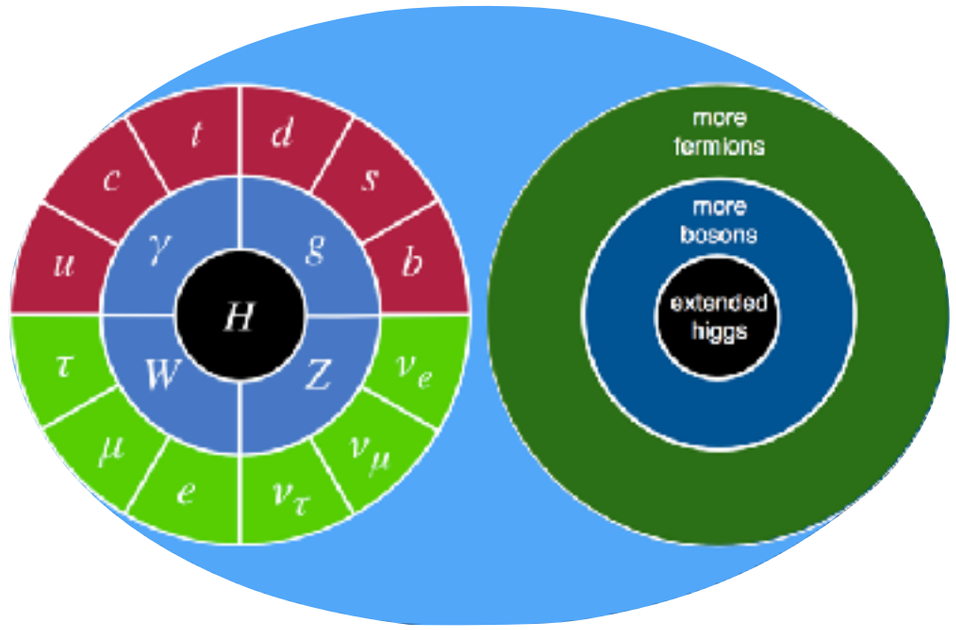
diagrams are a courtesy of M.Williams

1. **Unified theory of DM and SM**
   at TeV scale (e.g. SuperSymmetry)

- Missing energy + SM jet

- DM decay to SM (R-parity violating)

- Indirect searches via quantum effects in SM decays (flavour physics)



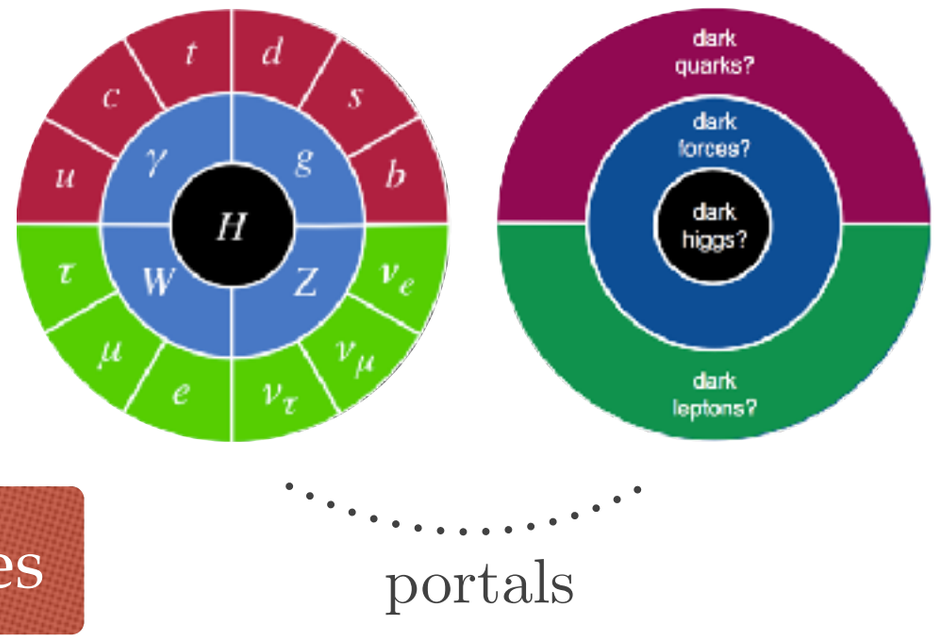

2. **Separated DM sector with portals to SM**

- Scalar portal (e.g. inflaton)

- Axial vector portal

- Vector portal (dark photons, $Z'$)

- Dark pions (Hidden valley)




LHCb can search for many signatures

# Dark Sector searches

diagrams are a courtesy of M.Williams

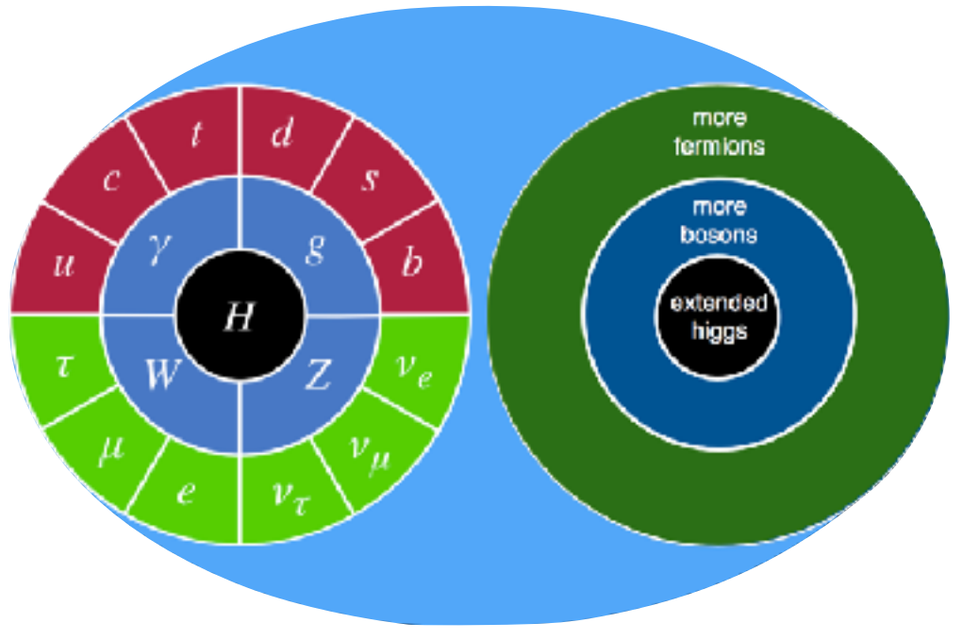
1. **Unified theory of DM and SM**
   at TeV scale (e.g. SuperSymmetry)

- Missing energy + SM jet

- DM decay to SM (R-parity violating)

- Indirect searches via quantum effects in SM decays (flavour physics)

today only direct searches



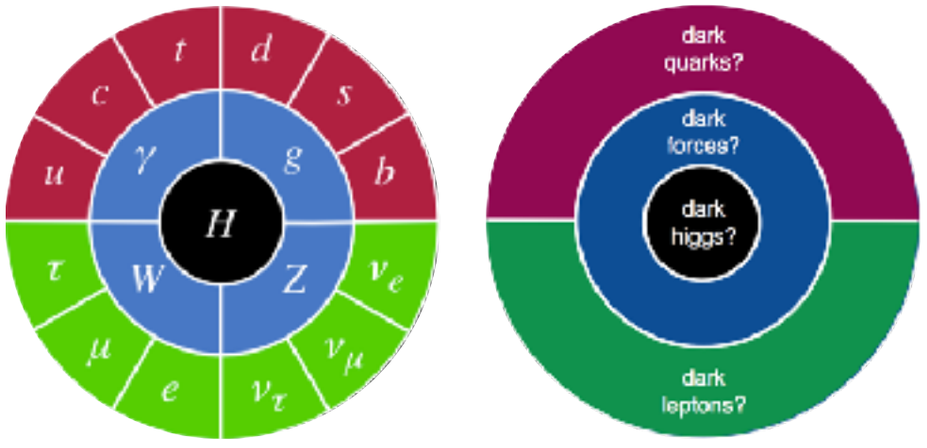

2. **Separated DM sector with portals to SM**

- Scalar portal (e.g. inflaton)

- Axial vector portal

- Vector portal (dark photons, $Z'$)

- Dark pions (Hidden valley)




portals

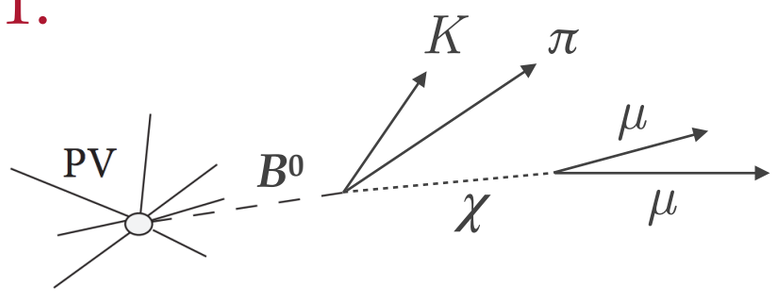
LHCb can search for many signatures

# Direct searches at LHCb

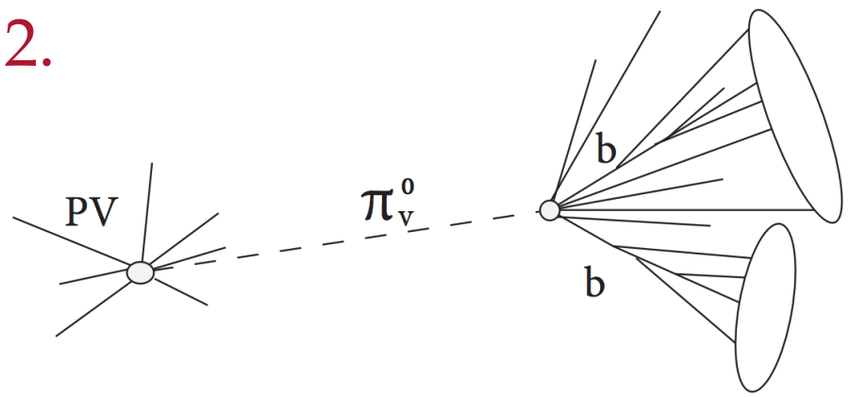
- LHCb has world-leading sensitivity at:
  - **Lighter masses** w.r.t. ATLAS/CMS
    - soft trigger and forward acceptance
  - **Low lifetimes** down to 1 ps
    - excellent vertexing and boost

- Increasing interest in direct searches!
  1. **Produced in *B*/*D* decays** (prompt / long-lived)
  2. **Produced in *pp* collision** (prompt / long-lived)

1.



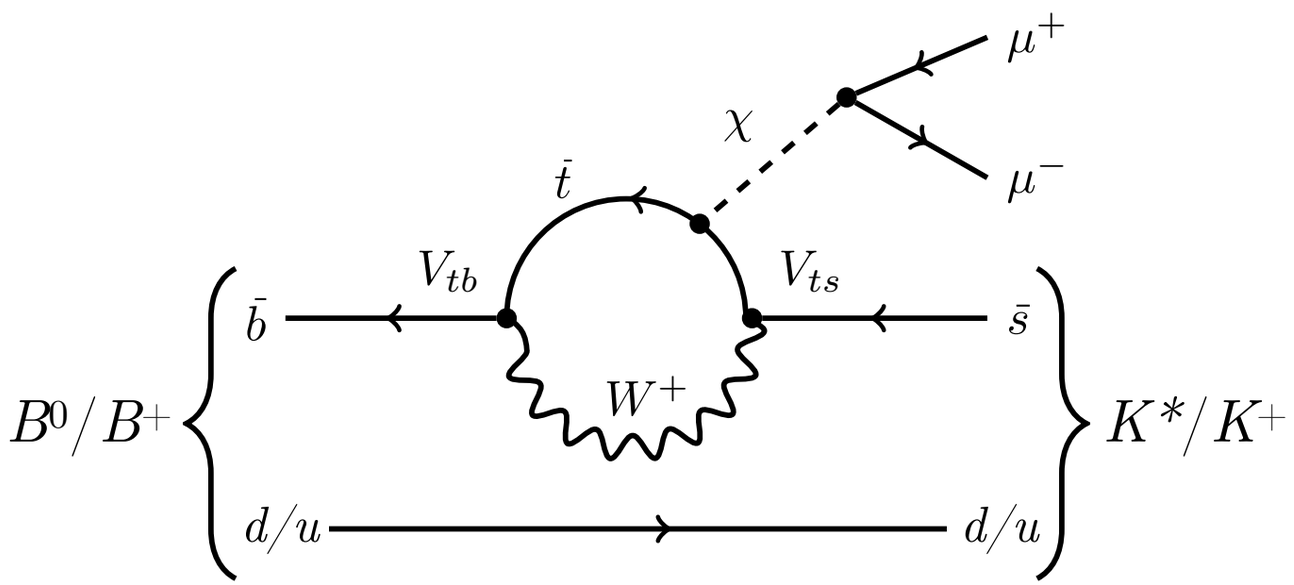

2.



# Hidden Sector in $B \to K^{(*)} \chi(\mu\mu)$

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

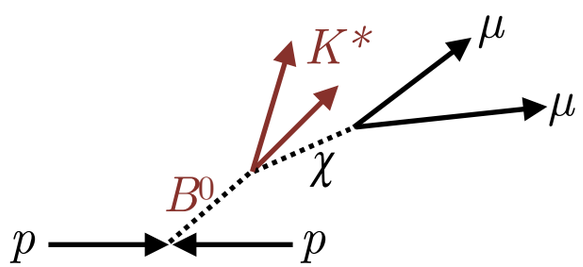
- Look for new hidden-sector bosons in $b \to s$ penguin transitions
  - Can be **scalar portal** (inflaton) or **axial vector portal** (only in vector $K^*$)

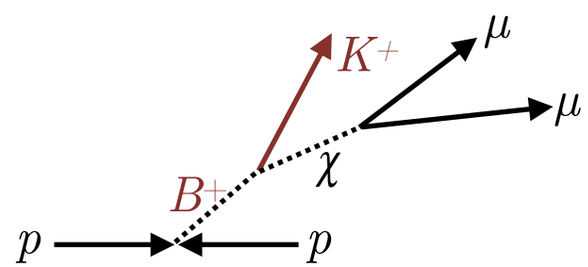



- LHCb collected world record samples of rare decay $B \to K^{(*)}\mu\mu$

- Allow detached $\mu\mu$ (within VELO)
  - small SM mixing can give lifetime

- MVA selection independent of $m(\mu\mu)$ and $\tau$ (boosting to uniformity)

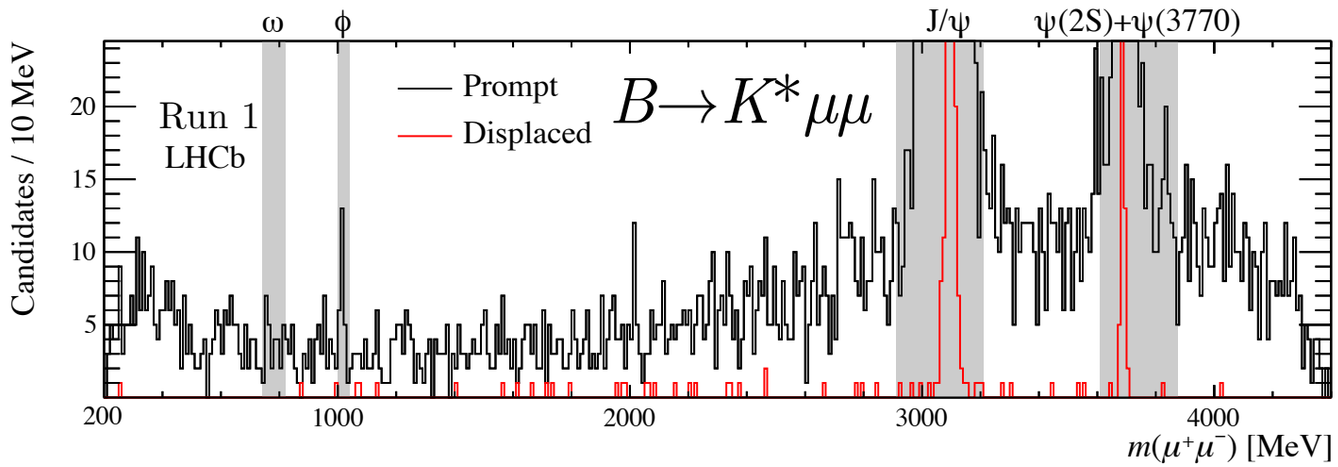


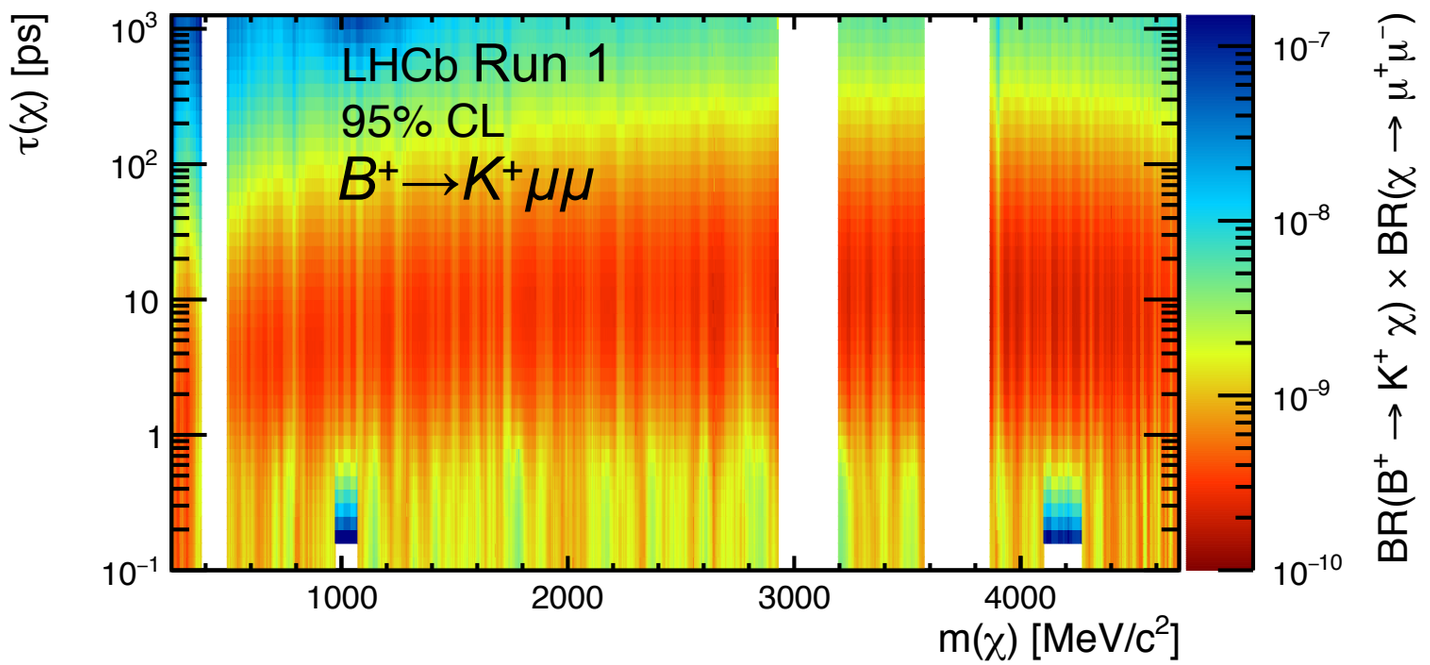
# Hidden Sector in $B \to K^{(*)} \chi(\mu\mu)$

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

- Search for narrow peak in m($\mu\mu$)
  - $B$ mass constrained
    - m($\mu\mu$) resolution 3-9 MeV
  - Excluding QCD resonances




- **Model independent limit**
  - BR limit normalised to *rare* SM decay (in $q^2$ range 1-6 GeV$^2$)
  - Constraint set on lifetimes [0.1-1000] ps (~ 30$\mu$m to 30cm)



# Hidden Sector in $B \to K^{(*)} \chi(\mu\mu)$

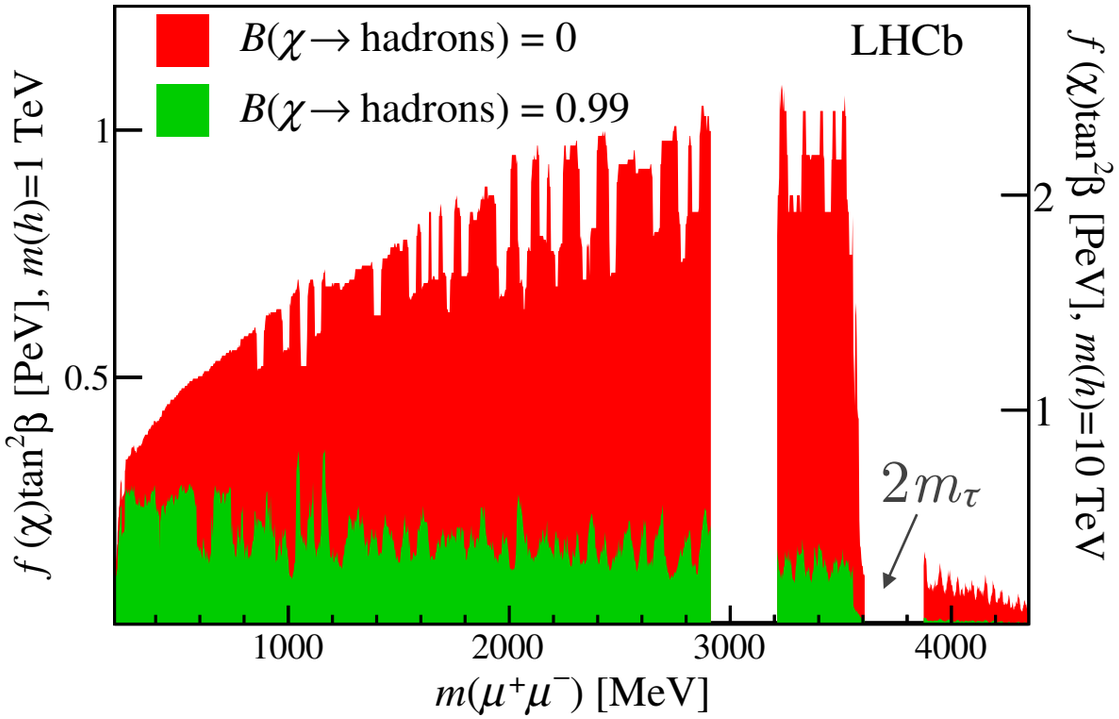
Phys Rev Lett 115 161802 (2015)
**Phys Rev D 95, 071101(R) (2017)**

## Model dependent limits

- On **axial vector portal** model

  M.Dine, W.Fischler, M.Srednicki PL 104B 199-202 (1981)
  A.R.Zhitnitsky Sov.J.Nucl.Phys. 31, 260 (1980)

  - Only from $B \to K^* \mu\mu$
  - $B(\chi \to \text{hadrons})=0$ gives larger $B(\chi \to \mu\mu)$ and larger $\chi$ lifetime
  - Reaching PeV scale on axion decay constant

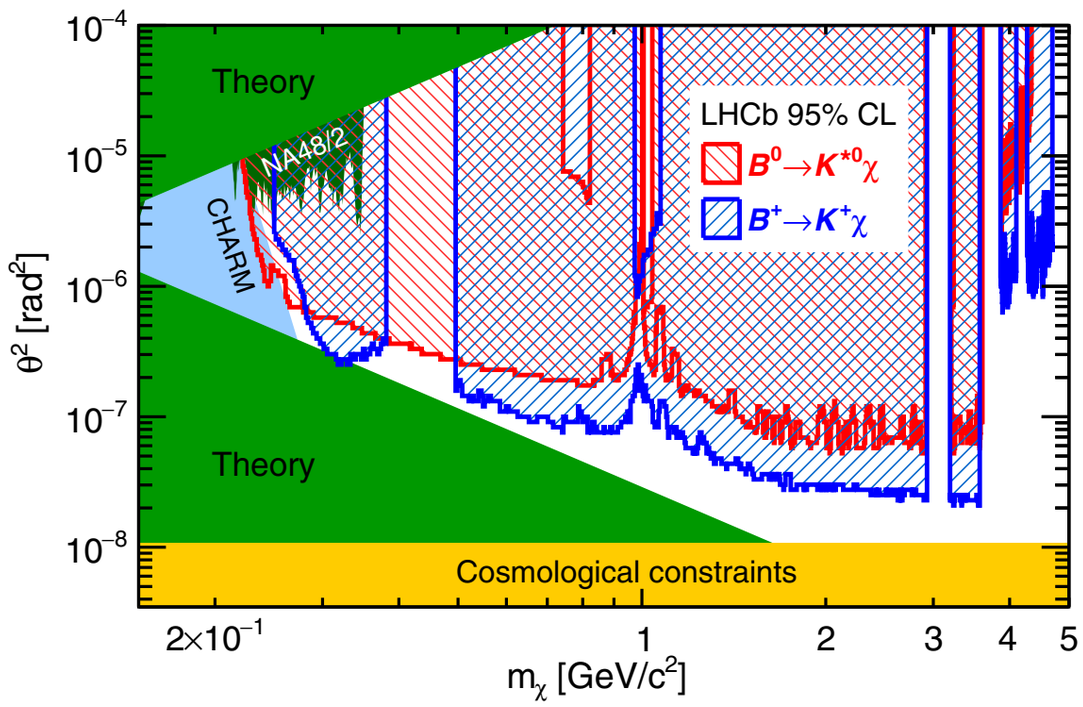



- Constrain on **scalar portal** mixing with the SM Higgs

  B.Batell, M.Pospelov, A.Ritz, PRD 83, 054005 (2011)
  F.Bezrukov, D.Gorbunov, JHEP05(2010)010, JHEP07(2013)140

$$|\chi\rangle_{\text{phys}} = \cos\theta|\chi\rangle + \sin\theta|\text{Higgs}\rangle$$
$$\tau \propto 1/\theta^2 \qquad \mathcal{B}(B^+ \to K^+\chi) \propto \theta^2$$

  - Nearly rule out the inflaton parameter space below $2\,m_\tau$

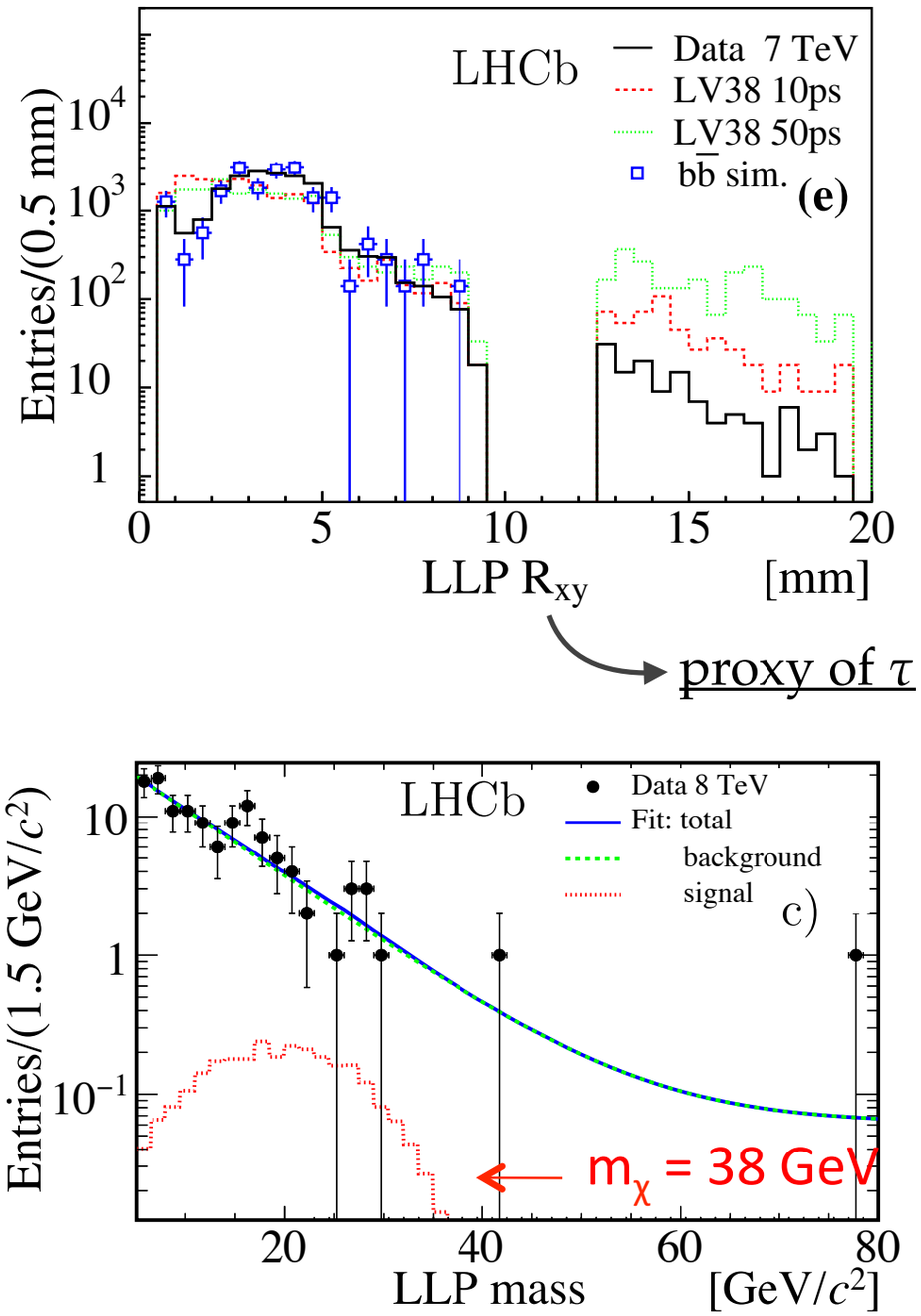



CHARM:
PL 157B, 458 (1985)
NA48/2:
PL B769, 67 (2017)
Cosmology:
JHEP 07(2013)140

# LLP → μ+jets

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

- **Signature**: single displaced vertex with several tracks and a high $p_T$ muon
- **Model**: RPV mSUGRA neutralino decaying to a lepton and two quarks



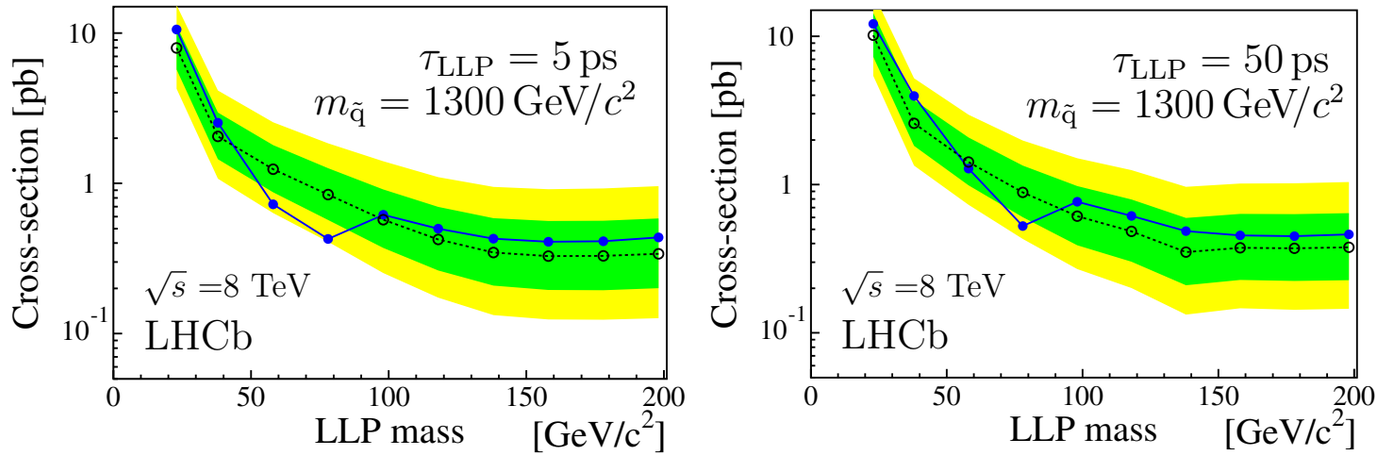

- Analysis strategy:
  - Using 3 /fb at 7 and 8 TeV
  - LLP $m$=[20-80] GeV/c², $\tau$=[5-100] ps
  - Triggering on muon + displaced vertex
  - Background dominated by *bb*
    - tight selection + MVA classifier
  - Number of candidates from fit to candidate LLP mass

# LLP → μ+jets

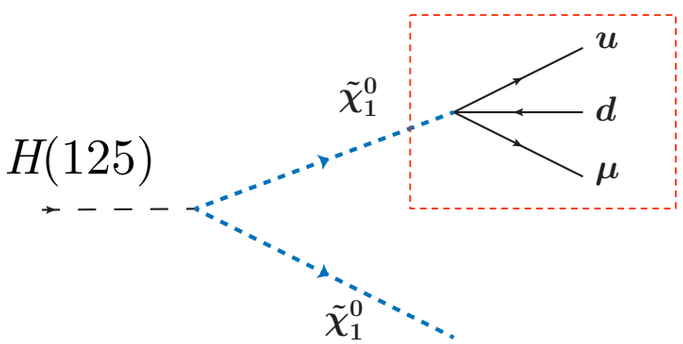
Eur. Phys. J. C (2017) 77:224

## Limits interpreted in various models:

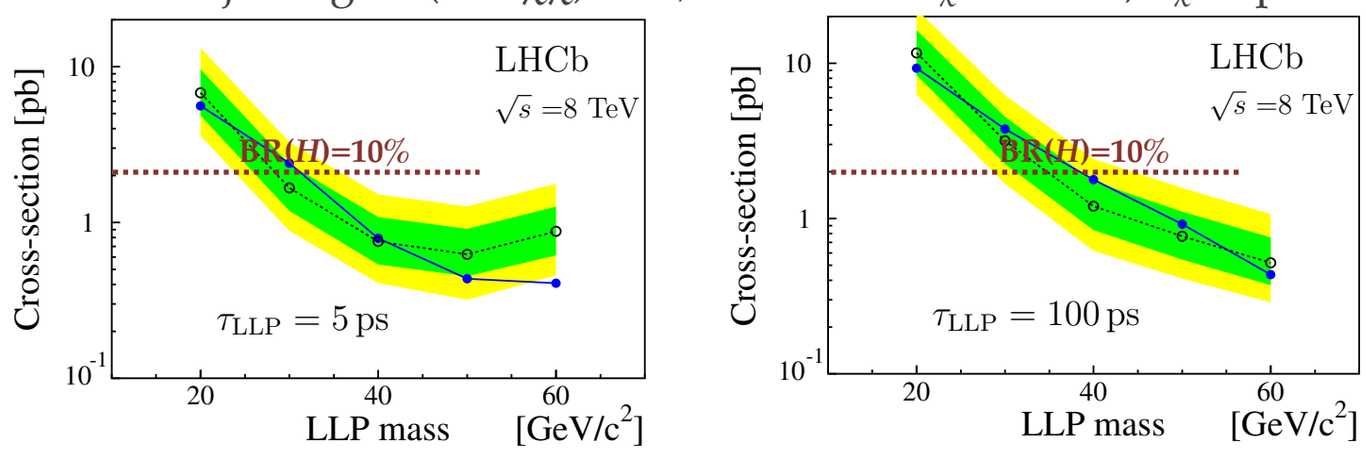
- **R-parity violating mSUGRA MSSM**
  $M_1$= [40-200] GeV → $m_\chi$ = [38-198]
  $M_2$= 2 TeV, $m_g$= 2 TeV, $m_q$= 1.3 TeV
  $\tau_{LLP}$ = [5, 100] ps




- Also simplified topologies:
  - Example: 125 GeV Higgs decay




Rejecting BR($H \to \chi\chi$) > 10% down to $m_\chi$= 30 GeV, $\tau_\chi$= 5 ps



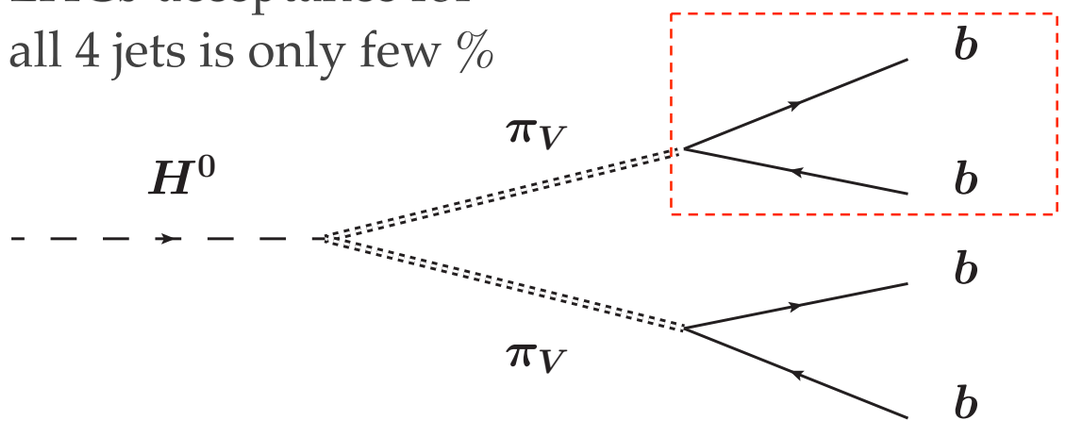

- **Also sensitive to sterile neutrinos**
  —> see **talk** by O.Fischer on Monday

# LLP → jet jet

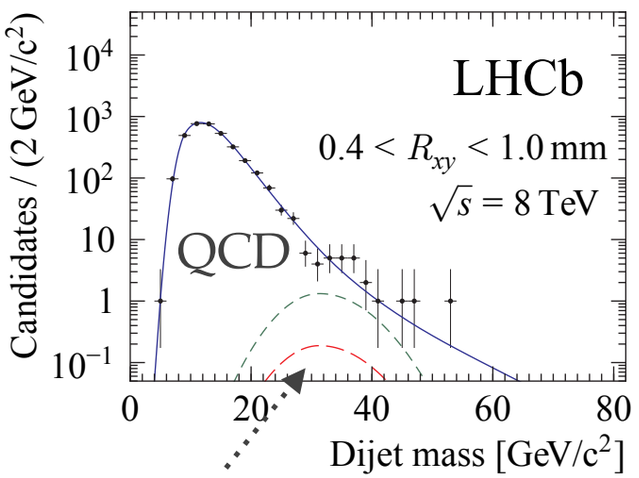
LHCb-PAPER-2016-065 arXiv:1705.07332

- **Signature**: single displaced vertex with two (*b*-) jets (previously searched double)
  EUR. PHYS. J. C (2016) 76: 664
- **Model**: hidden-valley dark pions from SM Higgs decay

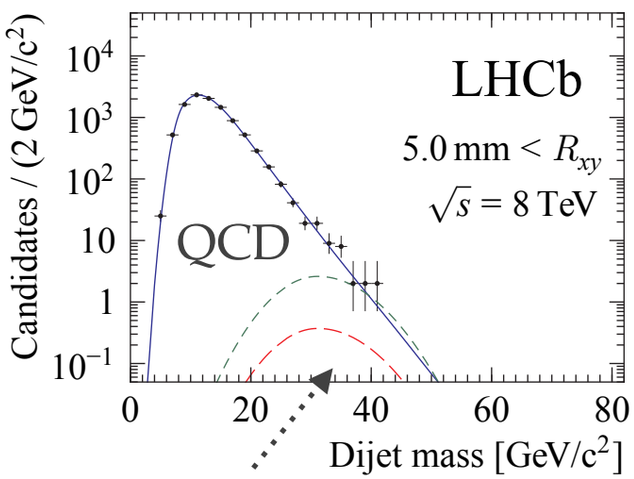
LHCb acceptance for all 4 jets is only few %




- Using 2 /fb of 7 and 8 TeV *pp* data
- Triggering on displaced vertex
- Quality requirement on jets, di-jet pointing, material veto
- Signal from di-jet mass fit in bins of beam-axis displacement $R_{xy}$




$\pi_V$ (35 GeV, 10 ps)
best fit, BR=1

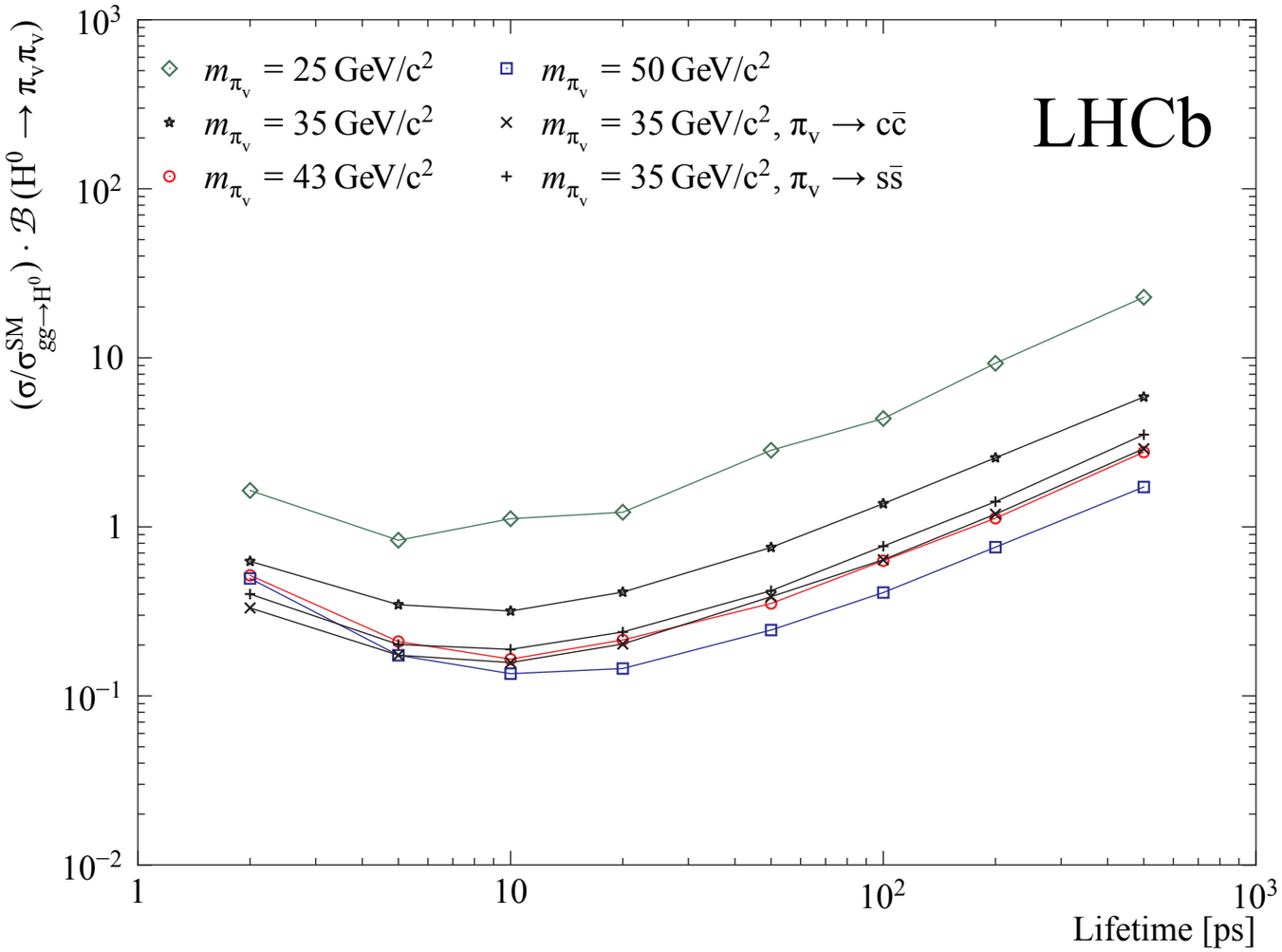



$\pi_V$ (35 GeV, 10 ps)
best fit, BR=1

# LLP → jet jet

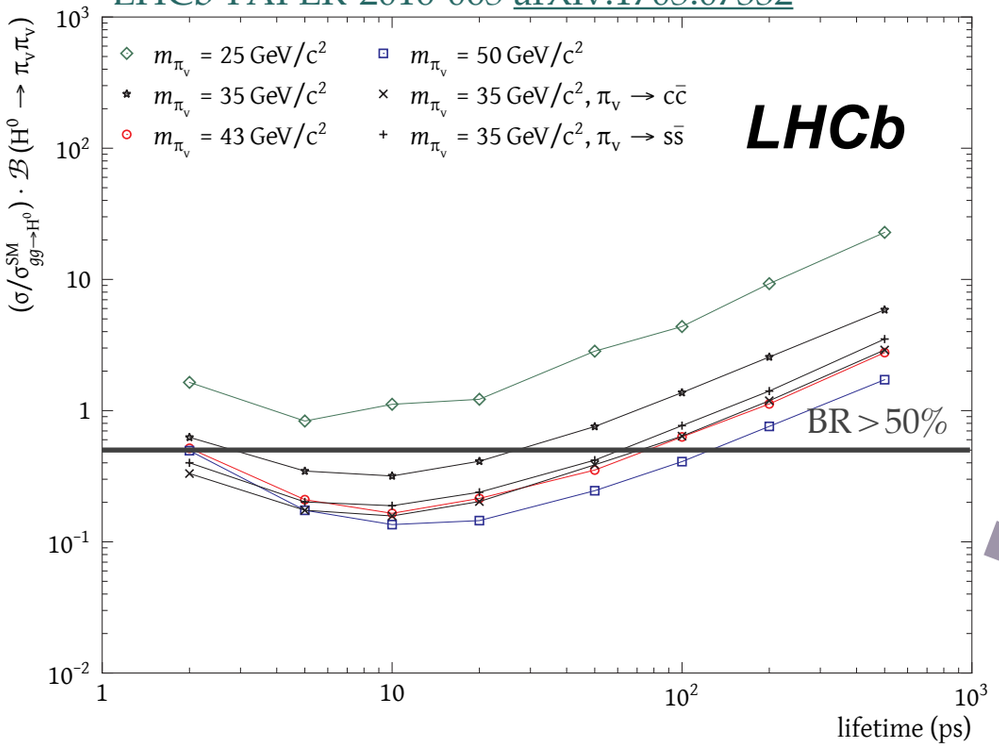
LHCb-PAPER-2016-065 arXiv:1705.07332

- Placing upper limit on SM-Higgs branching ratio to **dark pions**
- Tested the region:
  $m_\pi$=[25-50] GeV, τ=[2-500] ps
- Example: for $m_\pi$= 50 GeV
  exclude BR > 30% for τ=[5-50] ps
  (cτ = [1.5-15] mm)

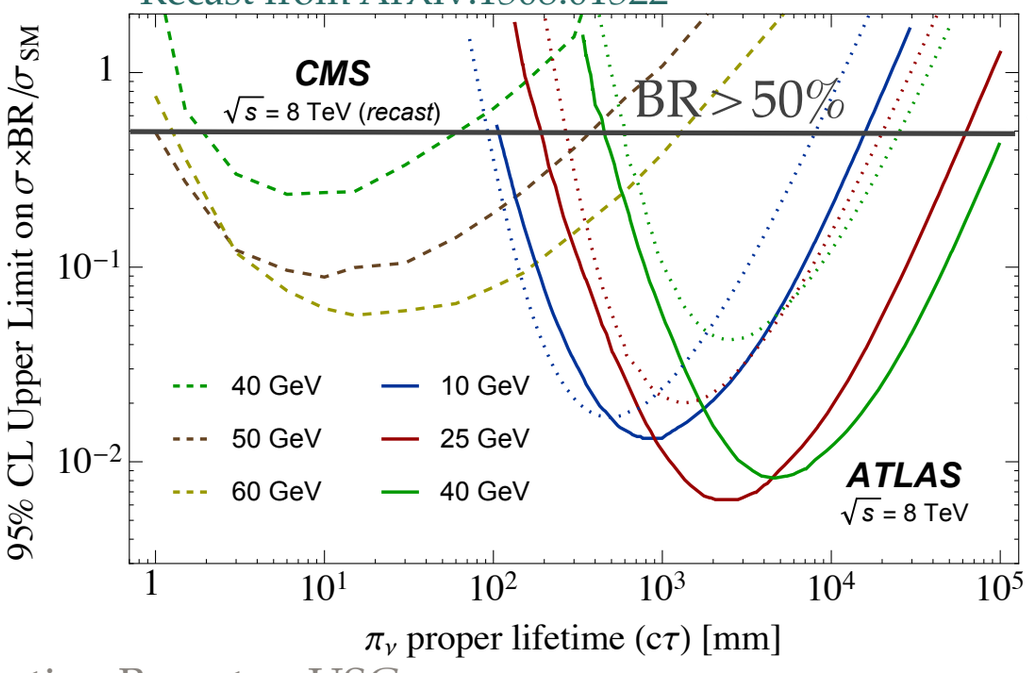


# LLP → jet jet

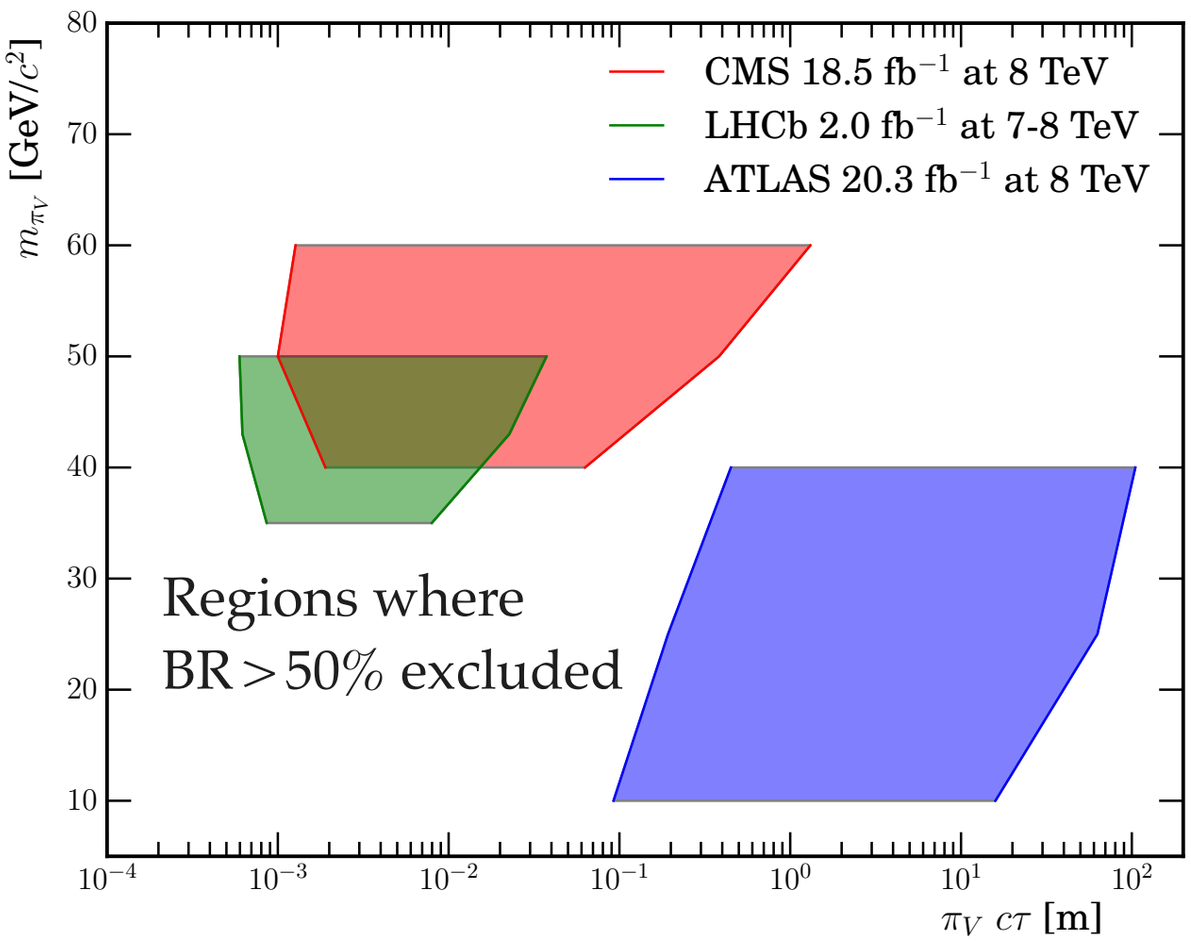
LHCb-PAPER-2016-065 arXiv:1705.07332




Recast from ArXiv:1508.01522




Competitive limit with ATLAS/CMS despite factor 10 less luminosity!

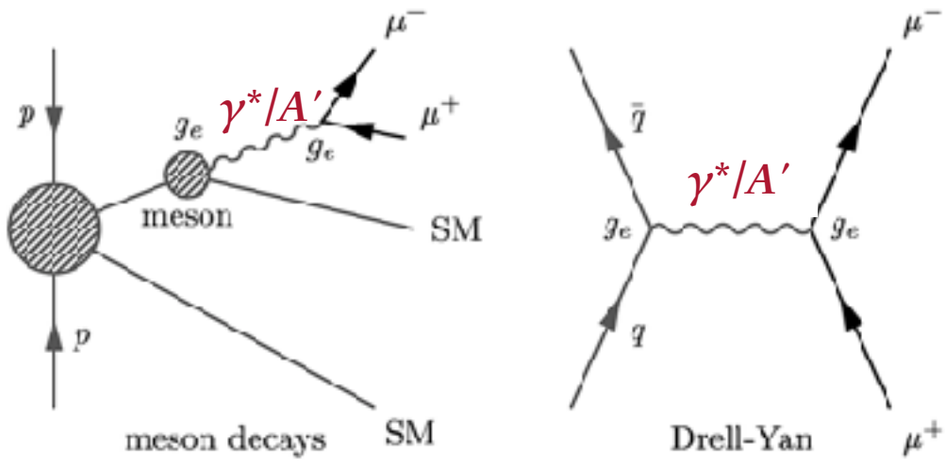



**Bright future at upgraded LHCb!**
expected benefit from online identification of displaced diets

# Dark Photons


LHCb-PAPER-2017-038 (soon in arXiv)

- LHCb has **excellent mass resolution**
  - key with irreducible background (e.g. Drell-Yan)
- **Soft triggers** on $\mu$ $p_T$ (even softer after upgrade)
- New $\mu\mu$ trigger with **online $\mu$-ID**
  - Online calibration of $\mu$-ID
  - Only interesting part of the event to disk (turbo)
    → **no pre-scale down to threshold $2\,m_\mu$**




- Can search for **Dark Photons** ($A'$) in $\mu\mu$
  - Kinetic mixing with off-shell photon ($\varepsilon^2$)
    - inherits production mode
    - can normalise to off-shell photon
    - data-driven analysis!
- **Today presenting first results**
  - 2016 data sample of 1.6/fb at 13 TeV

$$n_{\rm ex}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\rm ob}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\,\epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')]$$

off-shell photon

phase-space

A′ / $\gamma^*$ eff ratio, $\epsilon$=1 for prompt

Need to separate from background

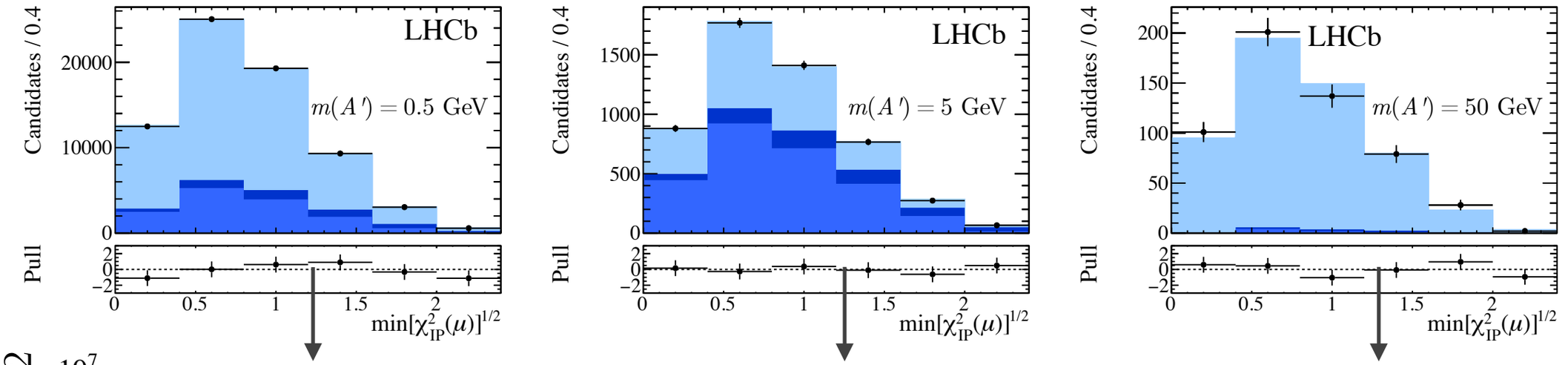
# Dark Photons

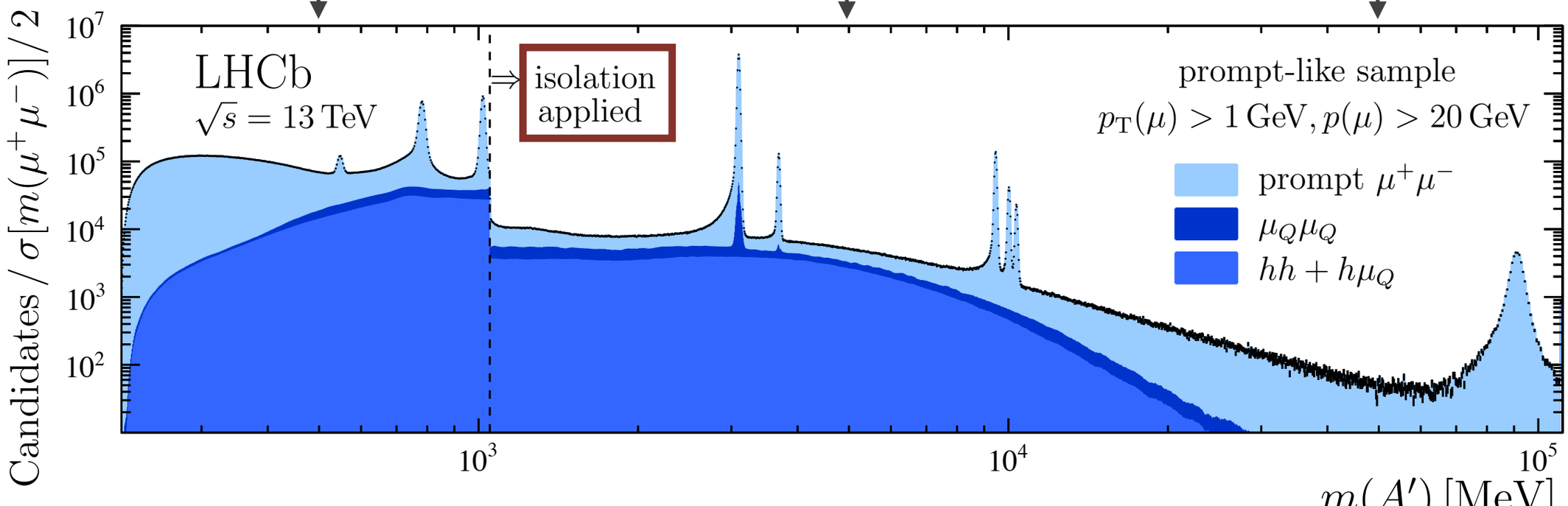

LHCb-PAPER-2017-038 (soon in arXiv)

Using templates for $\min[\chi^2_{\rm IP}]$ (small mass dep)

- prompt $\mu^+\mu^-$ → from data at $m(J/\psi)$ and $m(Z)$
- $\mu_Q\mu_Q$ → from simulation (validated)
- $hh + h\mu_Q$ → from same-sign dimuons (corrected)

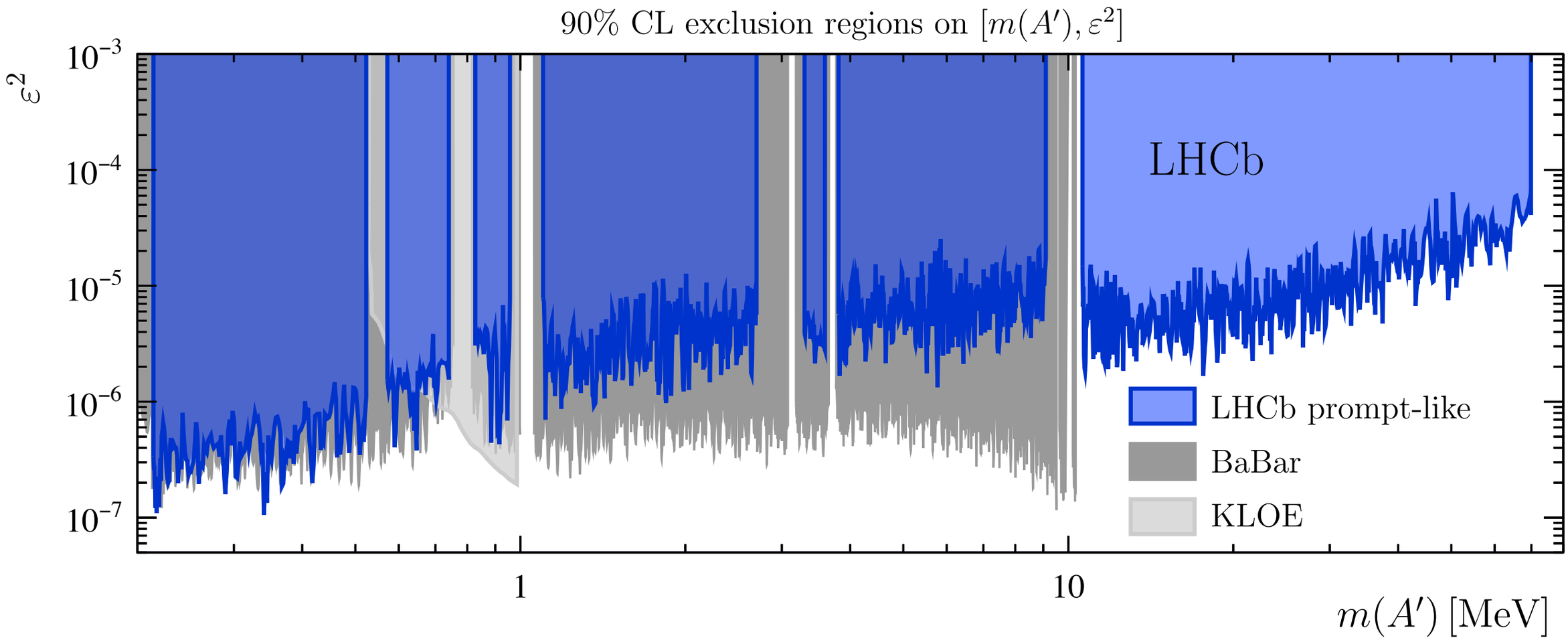
($\mu_Q$ is a muon from a heavy-flavour decay)



# Dark Photons


LHCb-PAPER-2017-038 (soon in arXiv)

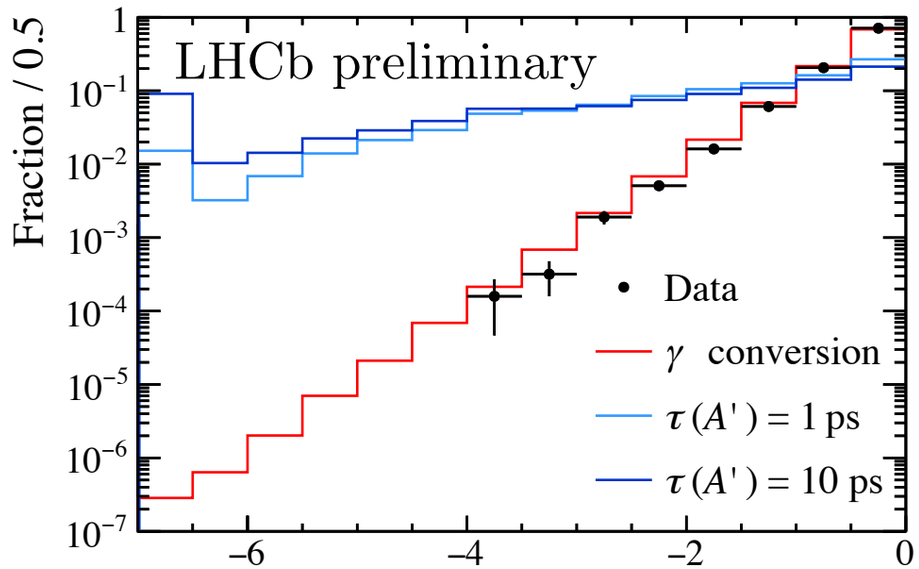


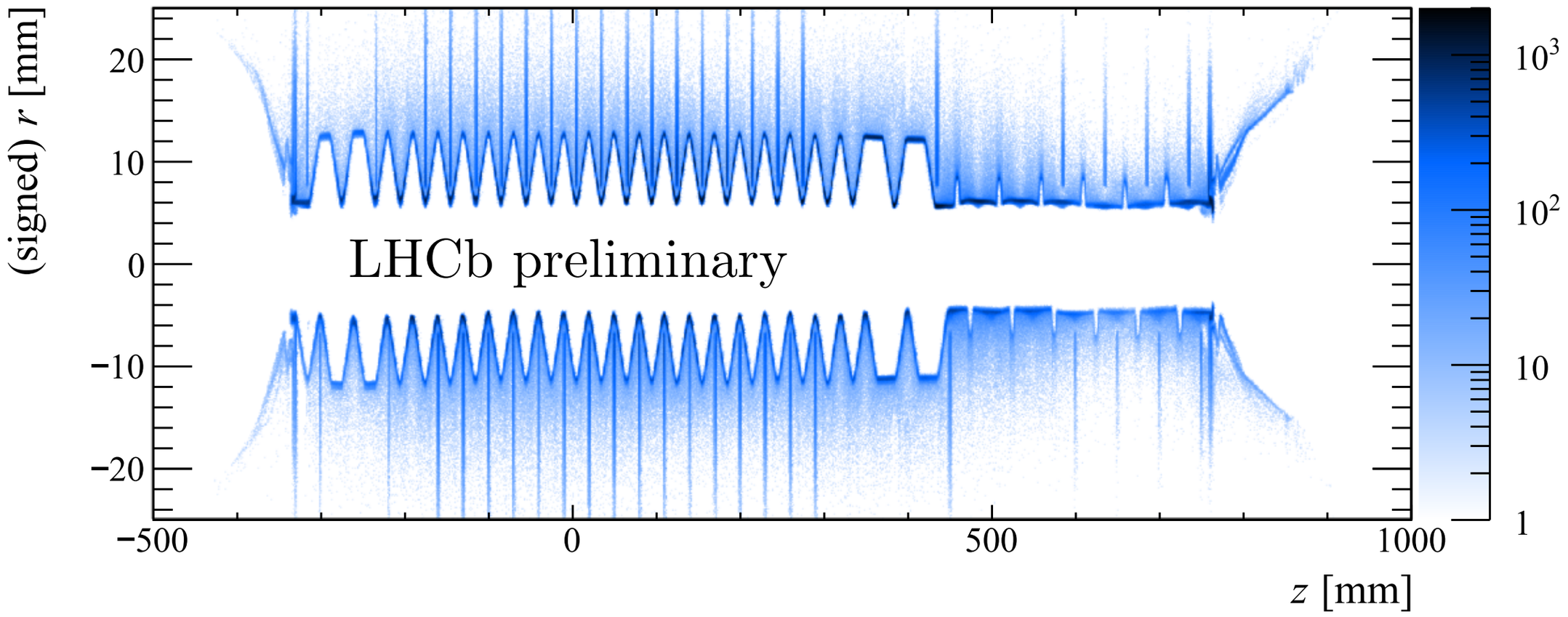

- No significant excess found
- First limit on dark photons for $m(A') > 10\,\text{GeV}$
- Already competitive for $m(A') < 0.5\,\text{GeV}$

# Dark Photons


Detector Performance paper in preparation

- Can also search displaced dark photons
  - Need to reduce background from photon conversions
  - New **material map** based on material interactions from beam-gas collisions

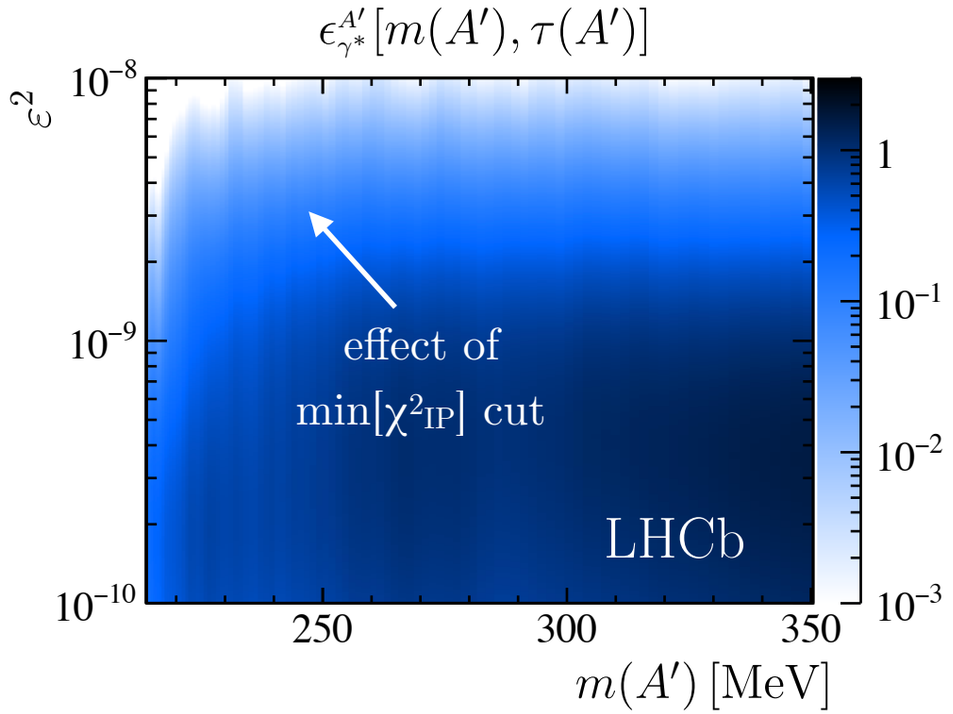


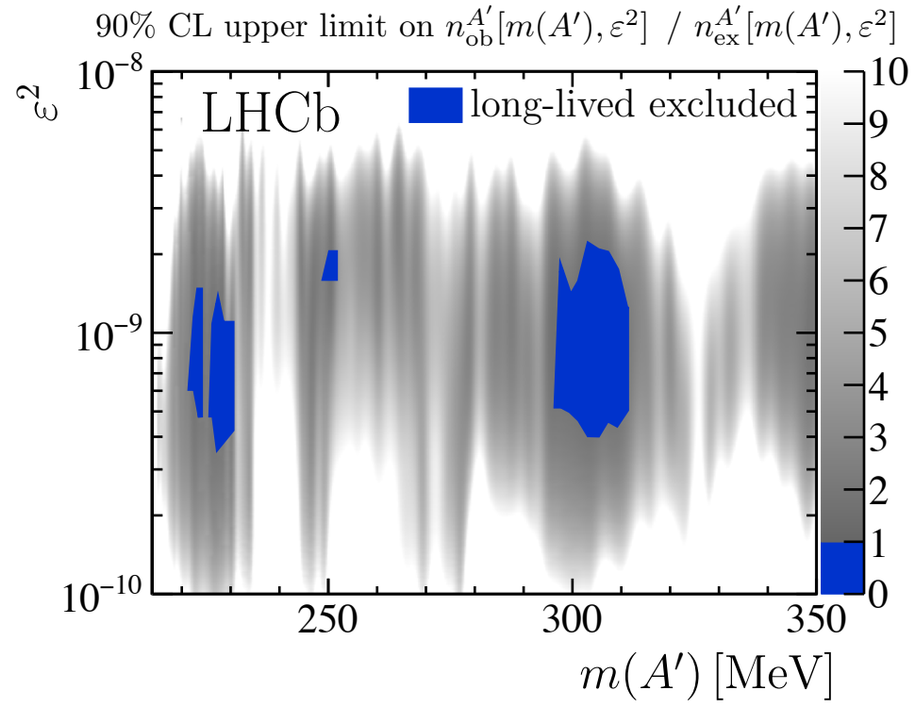



# Dark Photons


LHCb-PAPER-2017-038 (soon in arXiv)

- **Displaced search** in region $214 < m(A') < 350$ MeV
- Even looser online requirements on $p_T(\mu)$
- Other backgrounds:
  - Muons from b-hadron decays
    → isolation decision tree (from $B_s \to \mu\mu$)
  - Mis-id pions from $K_S \to \pi\pi$ tail
    → modelled from PID sideband
- Fit in bins of mass and lifetime
  - Also using consistency of decay topology $\chi^2$
  - Extracting p-values and confidence intervals
- **No significant excess is found**
  - Already excluding a small region of ($\varepsilon^2$, m)
  - First limit ever not from beam-dump!

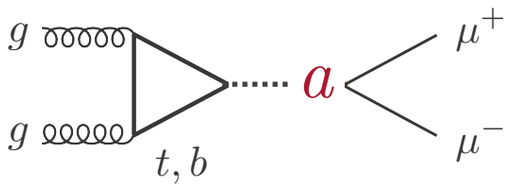


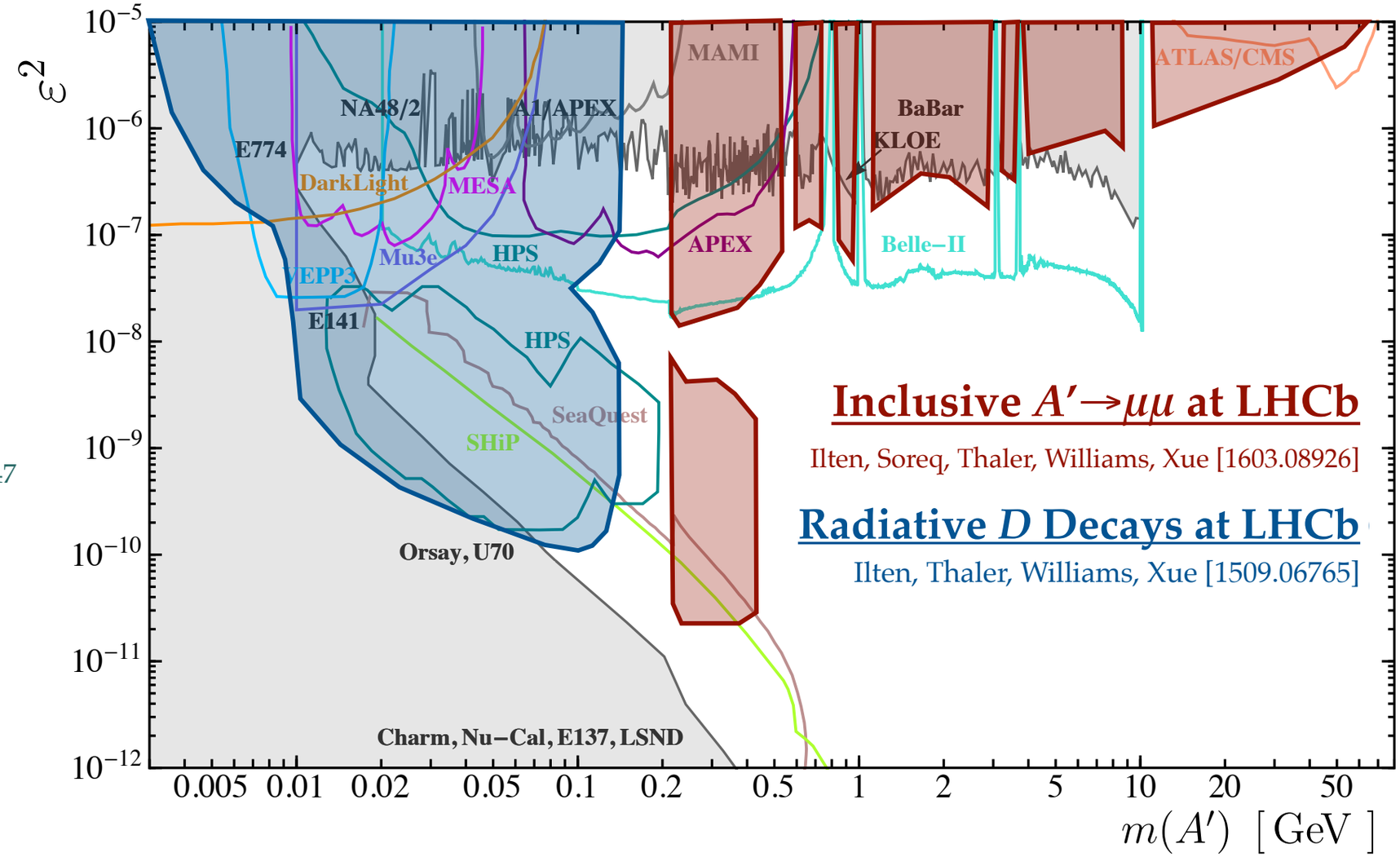
# Future searches

- **Run 3 reach**
- Extend searches model-independently
  - **sensitivity to light Higgs** (e.g. NMSSM)

U.Haisch and J.F.Kamenik PRD 93, 055047

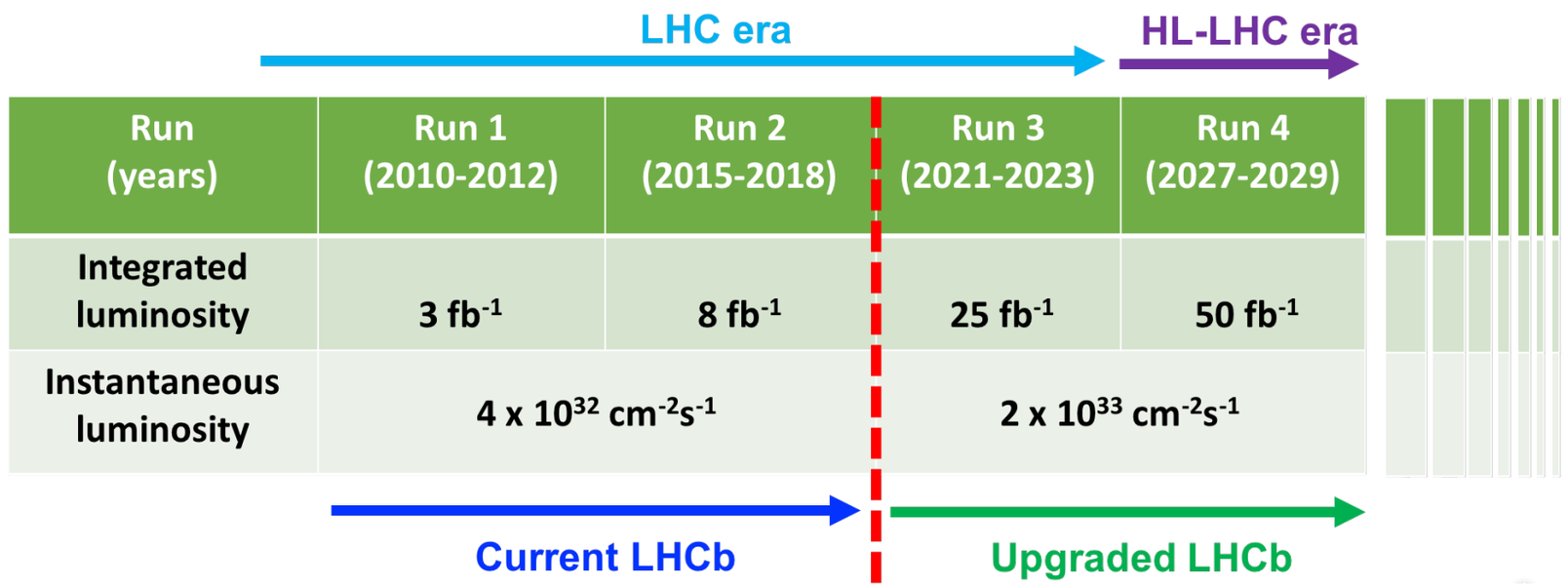



- Search inclusively for $N_{2,3} \to \pi^+ \mu^-$
- Search for $4\mu$



# Conclusions

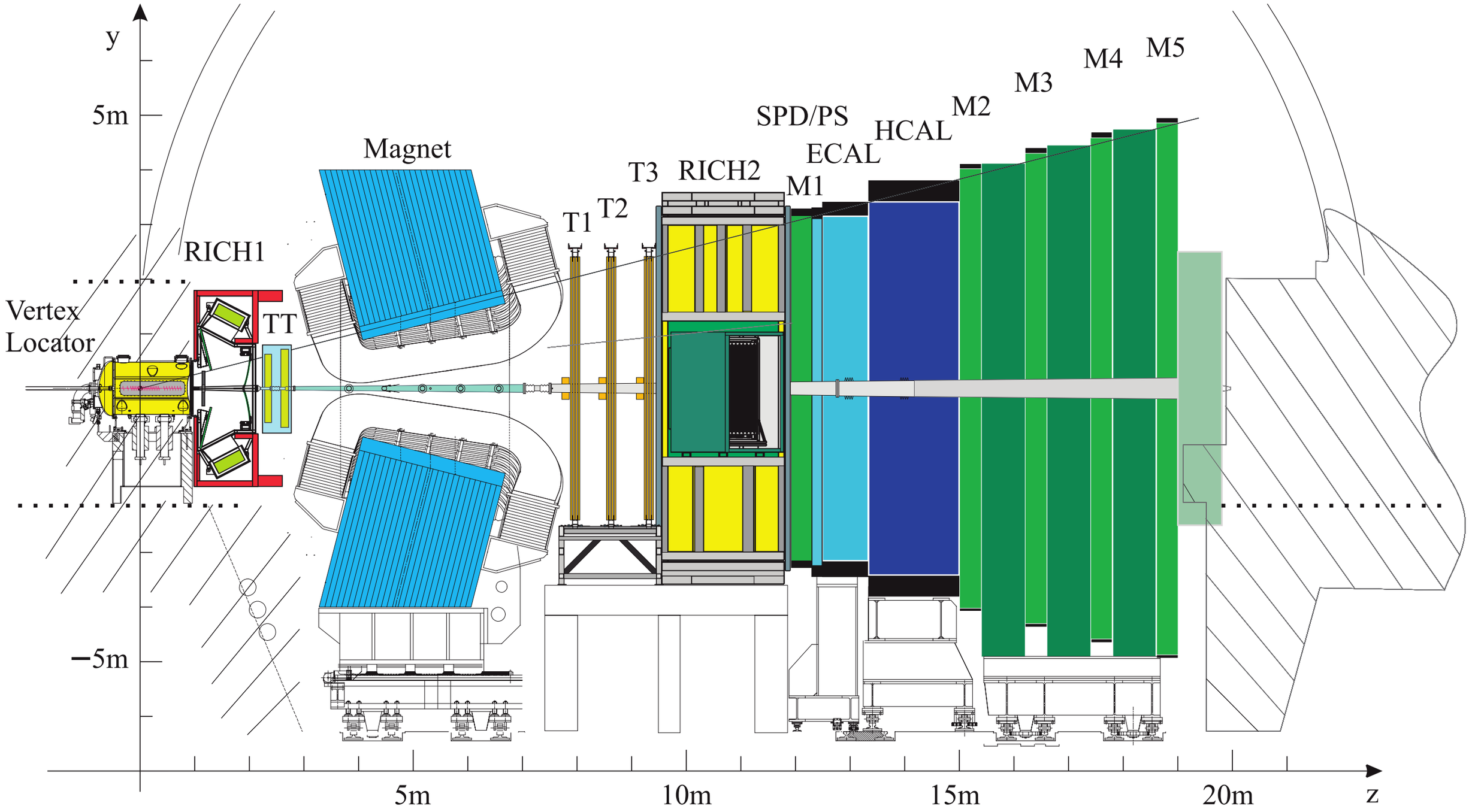
- LHCb has an extensive program of searches **exploring the dark sector**
  - Searches for on-shell new physics from B/D decays
  - Searches for long-lived particles with low mass and short lifetime
  - Searches for dimuon resonances in very large parameter space
- Bright future ahead:
  - 3/fb in Run 1, expect 5/fb in Run 2 (low pile-up)
  - A lot of potential in the upgraded trigger (also 5× luminosity!)



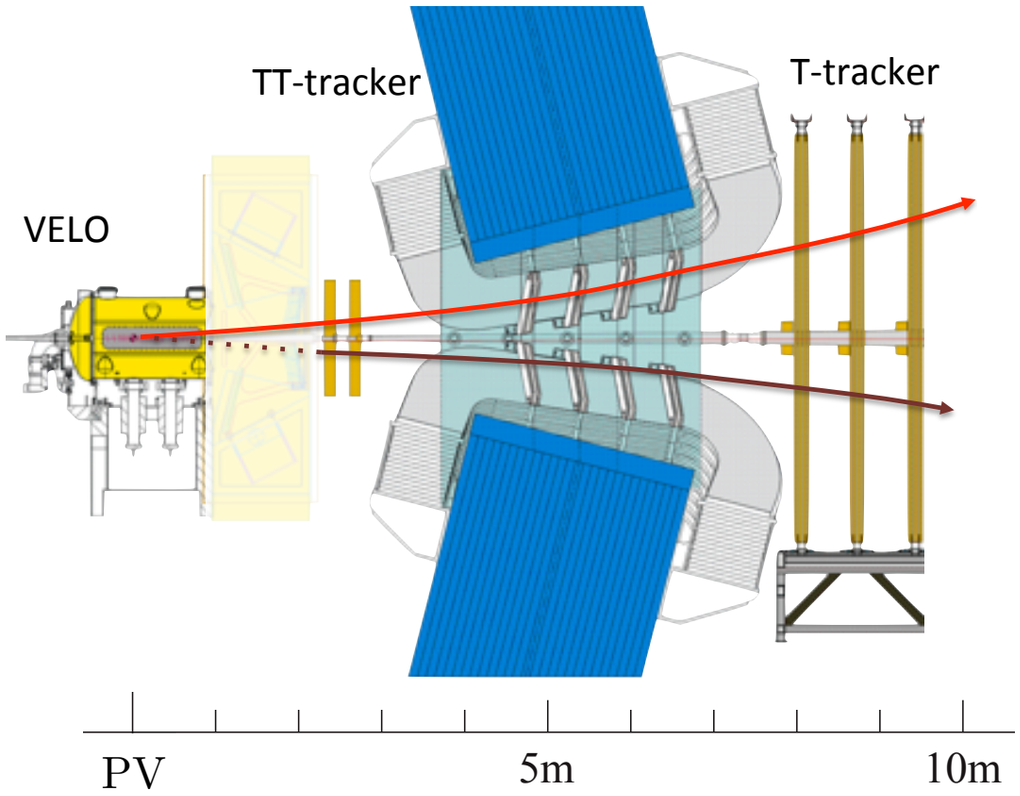
# *BACKUP*

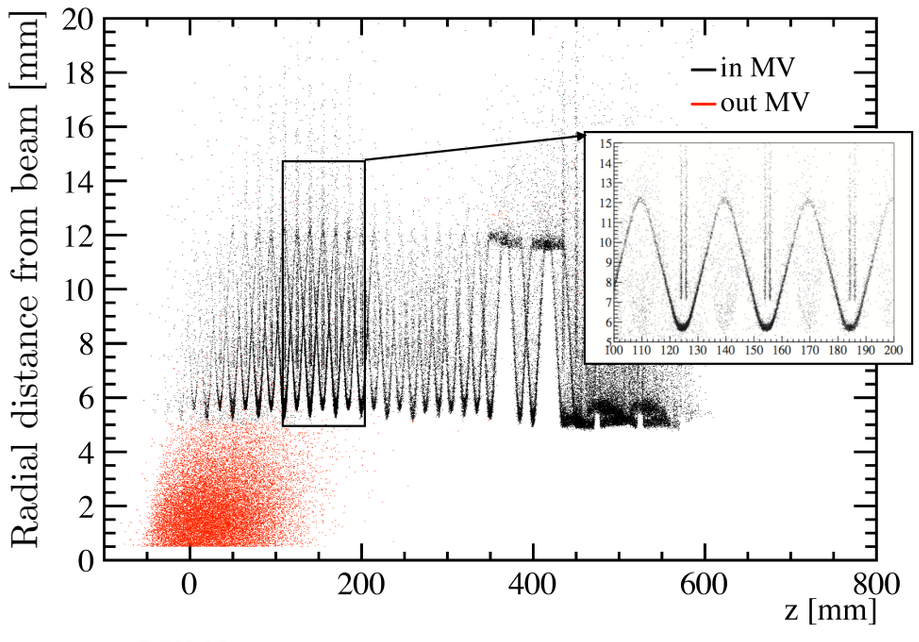
# The LHCb detector

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



# LLP at LHCb




## Tracks from long-lived in LHCb:

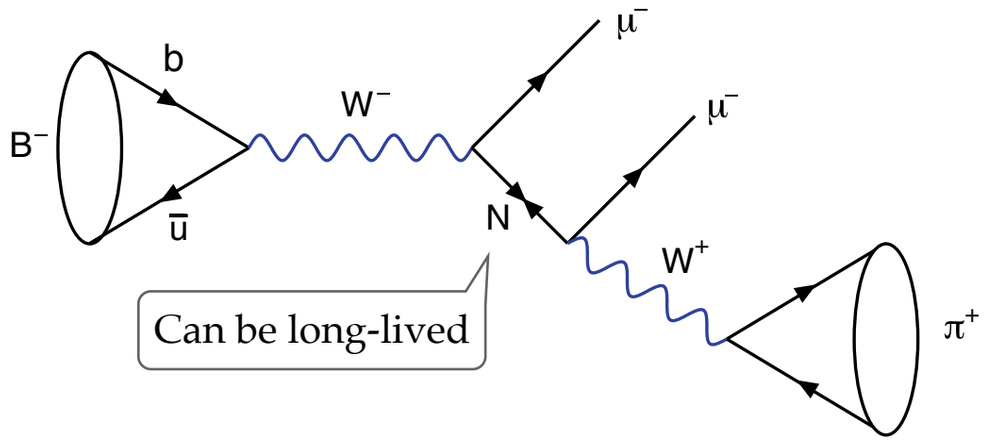
- **Within VELO** (<50 cm)
  - in reality more like <20 cm
- **Up to TT** (<200 cm)
  - Worse vertex and $p$ resolution ($m(\pi\pi)$ resolution 2× larger)
  - Not available in trigger (studies ongoing)

- VELO envelope at ~5 mm from beam
  - Detailed material veto is used
  - **<5 mm**: background mainly from heavy-flavour background
  - **>5 mm**: background mainly from material interaction

# Majorana neutrinos in $B^- \to \pi^+ \mu^- \mu^-$

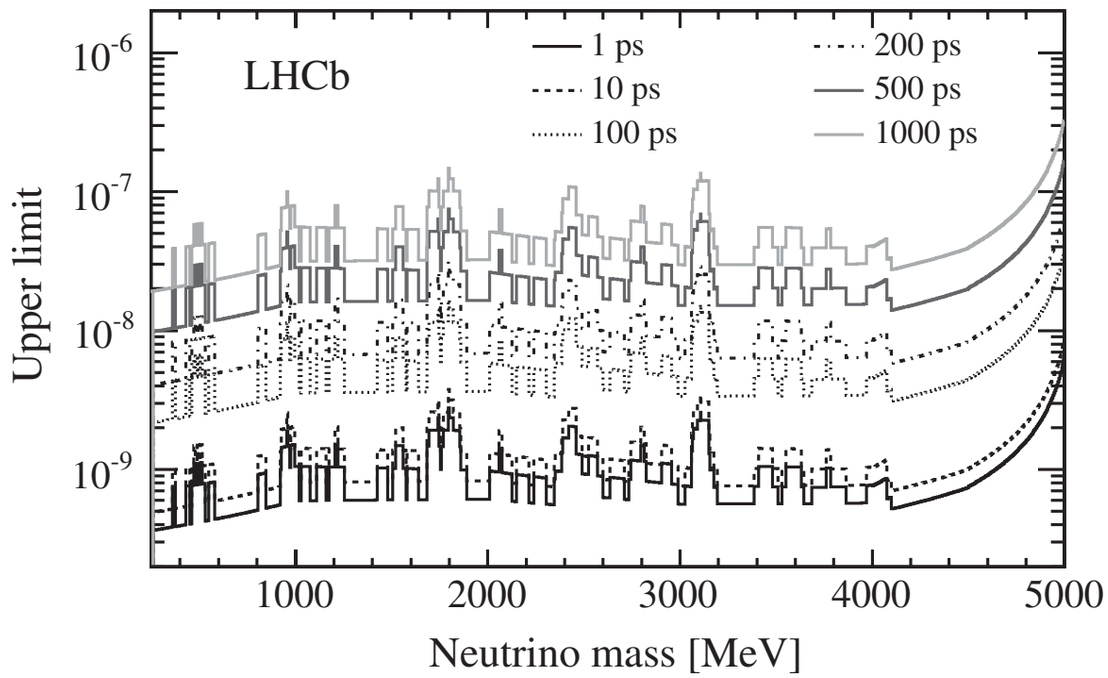
Phys Rev Lett 112 131802 (2014)

- Lepton number violating $B^- \to \pi^+ \mu^- \mu^-$ can proceed via on-shell Majorana neutrinos




- Look for $B$ mass peak, then extract limit as a function of $m_N$
- Limit set on N($\pi\mu$) lifetimes up to 1000 ps
- Constraints on mixing angle $V_{\mu 4}$
  - Recently revisited

    B Shuve, ME Peskin, Phys.Rev. D94 (2016) no.11, 113007
- Searches in other B/D channels foreseen
- Can also search using W→jet $\mu^-\mu^-$



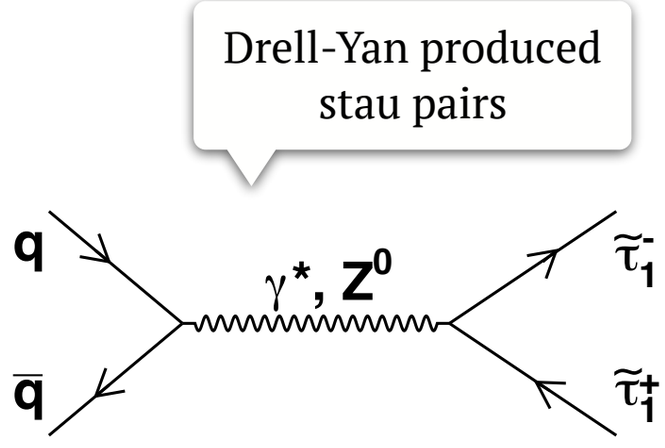
# Charged Massive Stable Particles

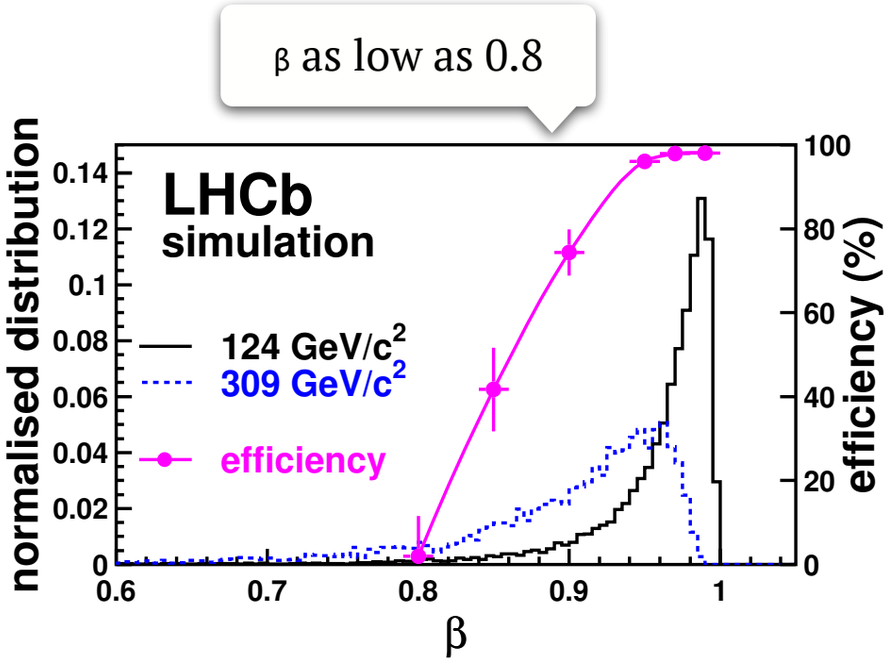
EPJC 75 (2015) 595

- Charged Massive Stable Particles
  - stable = can pass through the $\mu$-stations
- Model considered:
  - SUSY stau can be NLSP in mGMSB
  - long-lived with m>100 GeV/c2

S Dimopoulos et al [NPB488(1997)39]
GF Giudice and R Rattazzi [Phys.Rep. 332(2011)419]

- CMSP can leave a signature as:
  - Smaller energy loss dE/dx
  - Longer Time of Flight
  - Absence of Cherenkov signal
- Several experiments searched for them
  - LEP, Tevatron, HERA, ATLAS/CMS

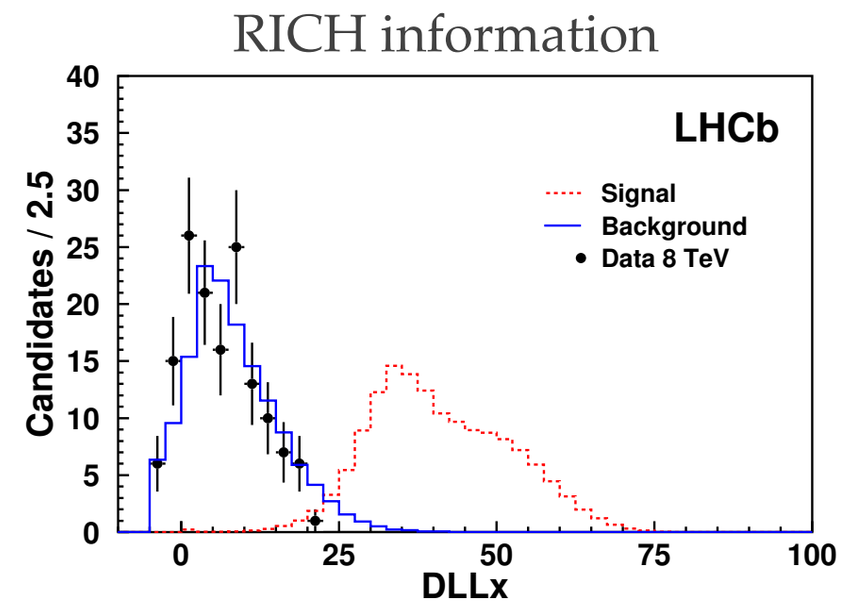


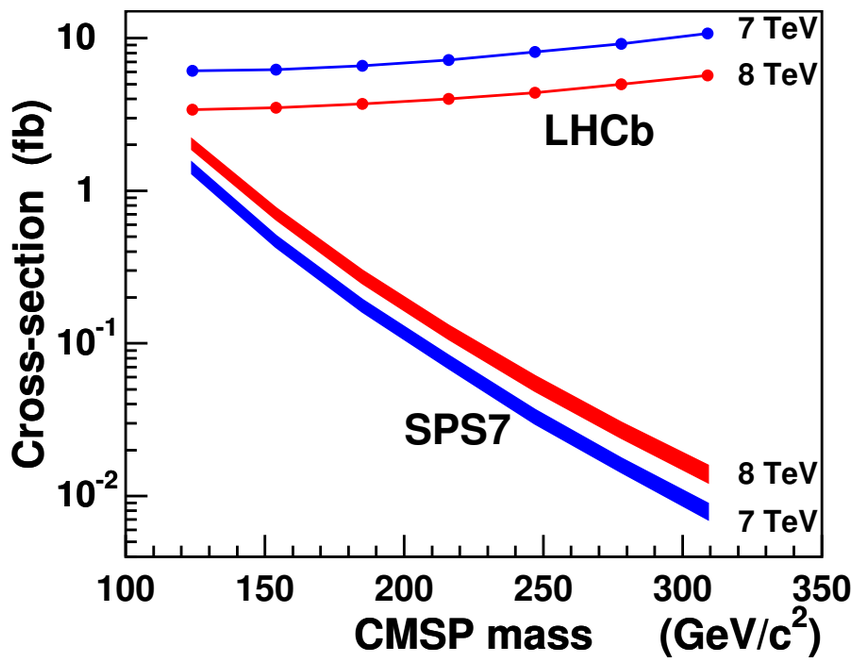
# Charged Massive Stable Particles

EPJC 75 (2015) 595

- Select pair of muon-like tracks in mass range [120, 300] GeV/$c^2$
- Train Neural Network to combine RICH information with d$E$/d$x$ from VELO and calorimeters




- Limit is not competitive with D0 (low mass) and ATLAS (high mass)
- Proof of concept for future searches!
- Possibly move to single CMSP signature and/or to lower masses



# Future: Emerging Jets

- "Emerging jets":
  - Jets with many displaced vertices are smoking gun for dark parton 'shower' (models with composite dark sector)

Schwaller, Stolarski, Weiler, [arXiv:1502.05409]

- LHCb has potential
  - precise jet vertexing
  - sensitive to low mediator mass