Searches for long-lived particles at the LHCb
Second workshop of the LHC LLP Community

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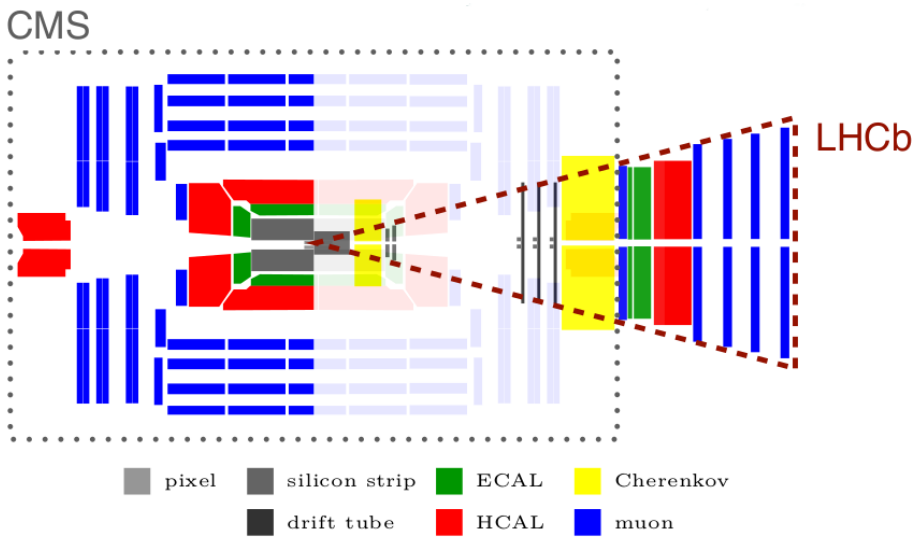
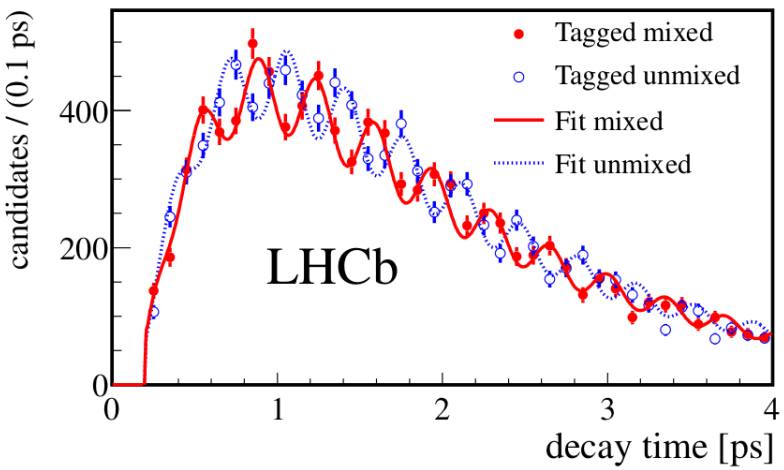
October 18, 2017

The LHCb experiment

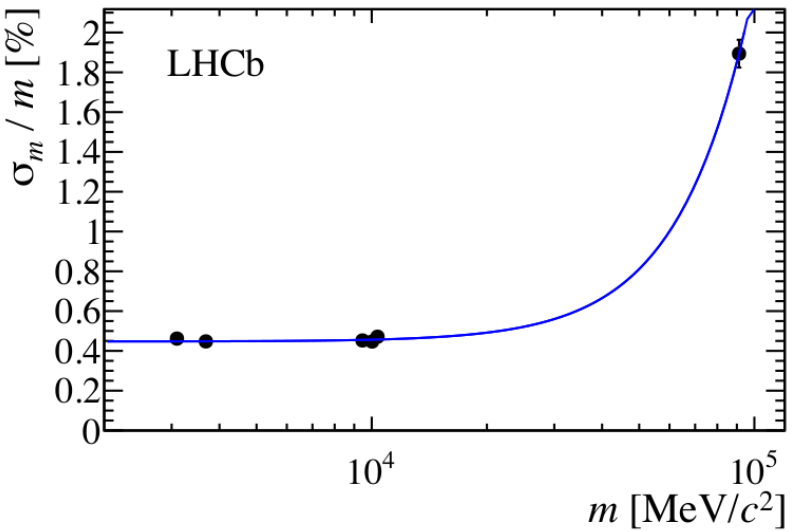
- Fully instrumented in $2 < \eta < 5$. **[IJMP A30 (2015) 1530022]**
- **ParticleID** capabilities (RICH).
- Good **jet reconstruction**:
  → 10 to 20% energy resolution for jets with p_T over 10 GeV/c.
  → b(c) tagging efficiency of 65% (25%) with 0.3% contamination.



- Excellent **vertex** resolution ($B_s^0 \sim 40$ fs):

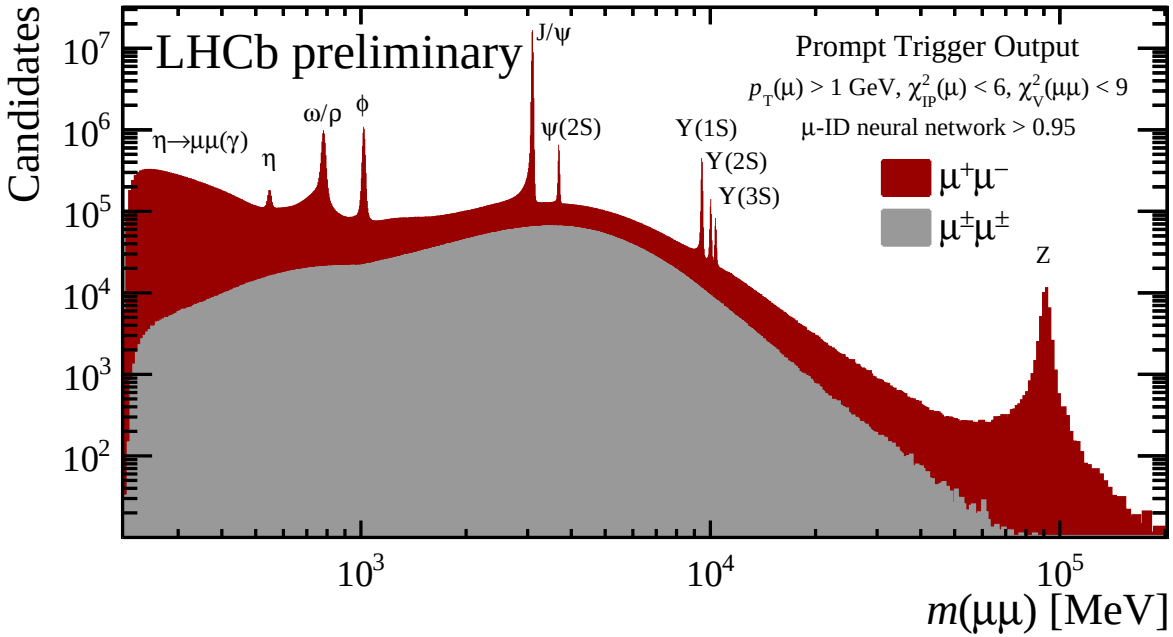


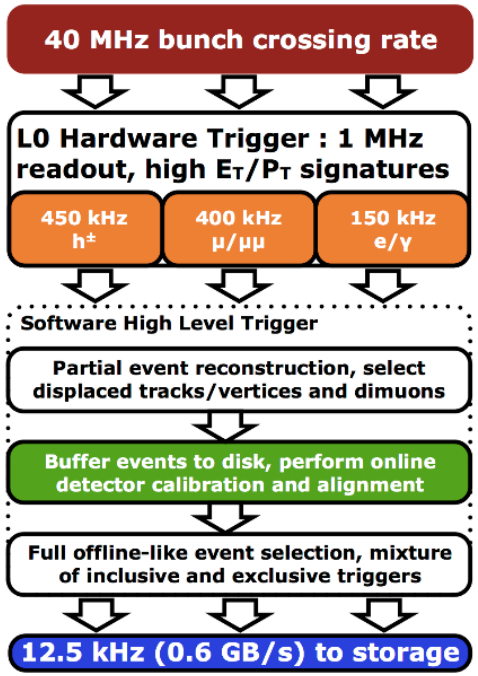
- Excellent **mass** resolution (0.5% in $\mu\mu$):



The LHCb experiment

- Lower luminosity (1/8 of ATLAS/CMS during Run I) $\rightarrow$ **lower pileup**.
- Very **soft** and **versatile** trigger system:





- Hardware level L0 (L1 for the rest):
  $\rightarrow$ 95% efficient for detached di-muon with p_T over 1 GeV/c.
  $\rightarrow$ ECAL (HCAL) triggers at 3.5 (2.5) GeV for electrons (hadrons).
- Software level HLT:
  $\rightarrow$ Topological triggers on detached vertices.
  $\rightarrow$ **Online μ-ID and jets in turbo lines.**

The LHCb experiment

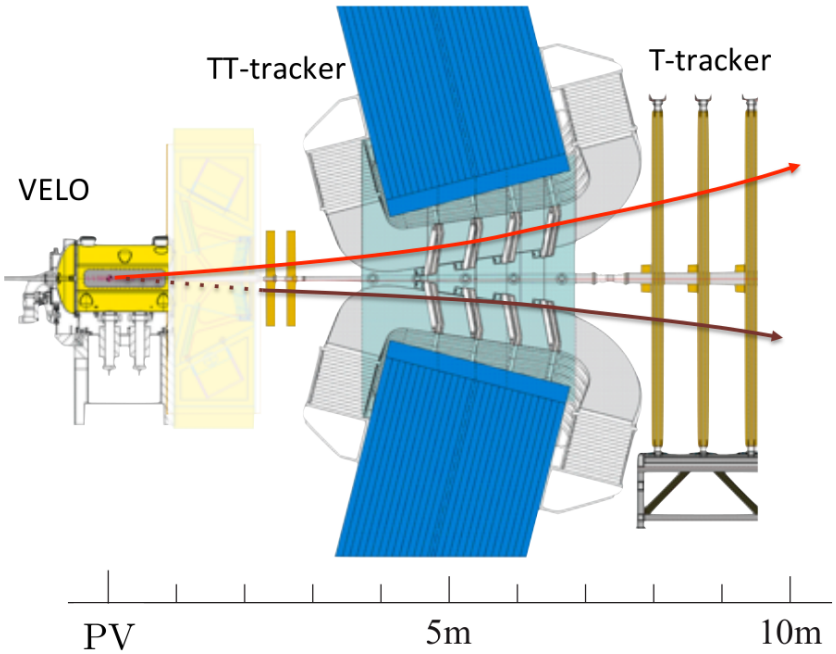
```
> sudo LHC-get exp-upgrade LHCb
```

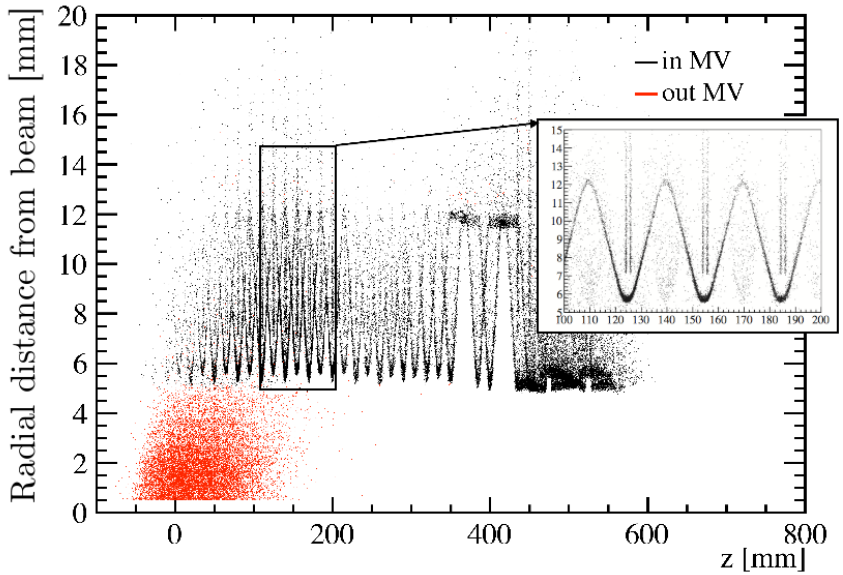
- **Trigger upgrade plans** (real-time readout) – see talk by Jessica on Friday.
- **General LHCb upgrade plans** – see talk by Elena on Friday.

- **CODEX-b proposal** (new detector for LLP at LHCb) – see talk by Dean on **Thursday**.

Direct searches for LLPs at LHCb

- **Long-lived tracks within VELO (below around 50 cm):**
  - In reality more like 20 cm ($\sim$ 700 ps).
  - Presence of a **VELO envelope** at $\sim$ 5 mm from beam:
    $\rightarrow$ Background dominated by heavy flavour below 5 mm.
    $\rightarrow$ Background dominated by **material interactions** above 5 mm.
  - A **detailed material veto map** is used. **[IJMP A30 (2015) 1530022]**
- **Long-lived tracks up to TT (below around 2 m):**
  - Worse vertex and momentum resolution $\rightarrow$ twice the VELO tracks resolution.
  - Not yet implemented in trigger $\rightarrow$ see talk by Elena on Friday.





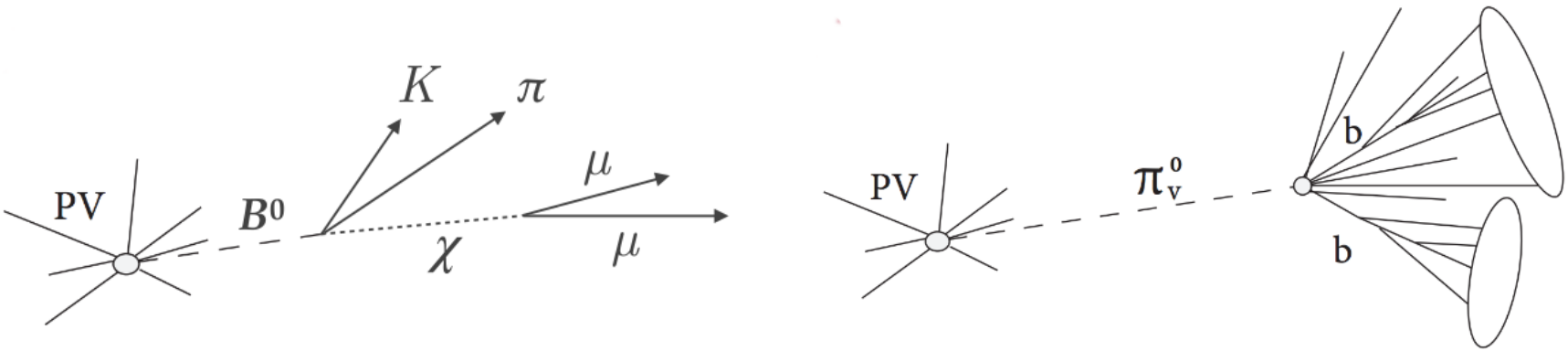
Direct searches for LLPs at LHCb

Unique coverage complementary to ATLAS/CMS:

- Soft trigger and forward acceptance $\rightarrow$ **lower masses**.
- Excellent vertexing capabilities $\rightarrow$ **lower lifetimes** ($\sim$ 1 ps).

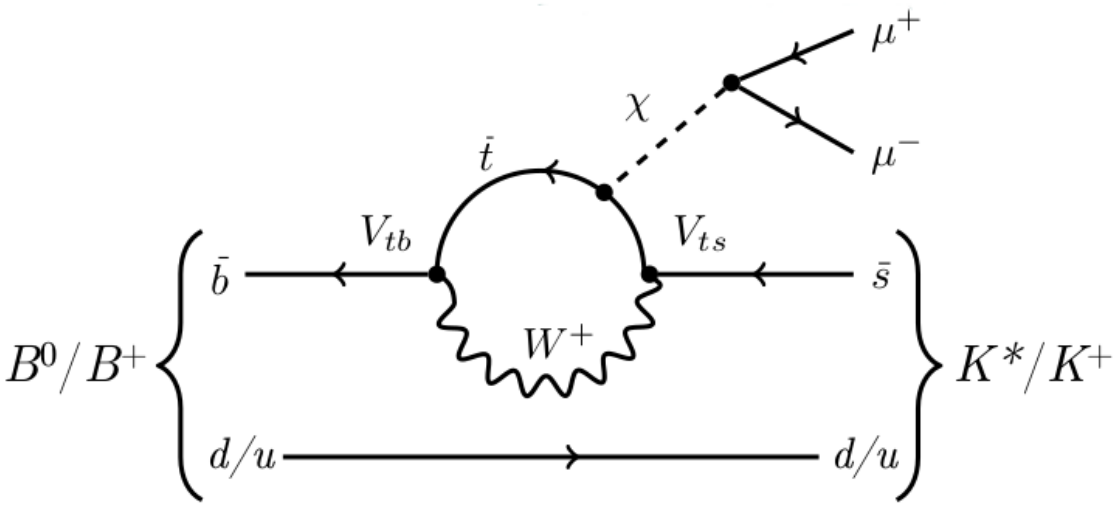
Exploit LHCb capabilities for direct searches:

- Search for LLP produced in B and D decays.
- Search for LLP produced in the *pp* collision.
- Measure detachment of τ leptons.



Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

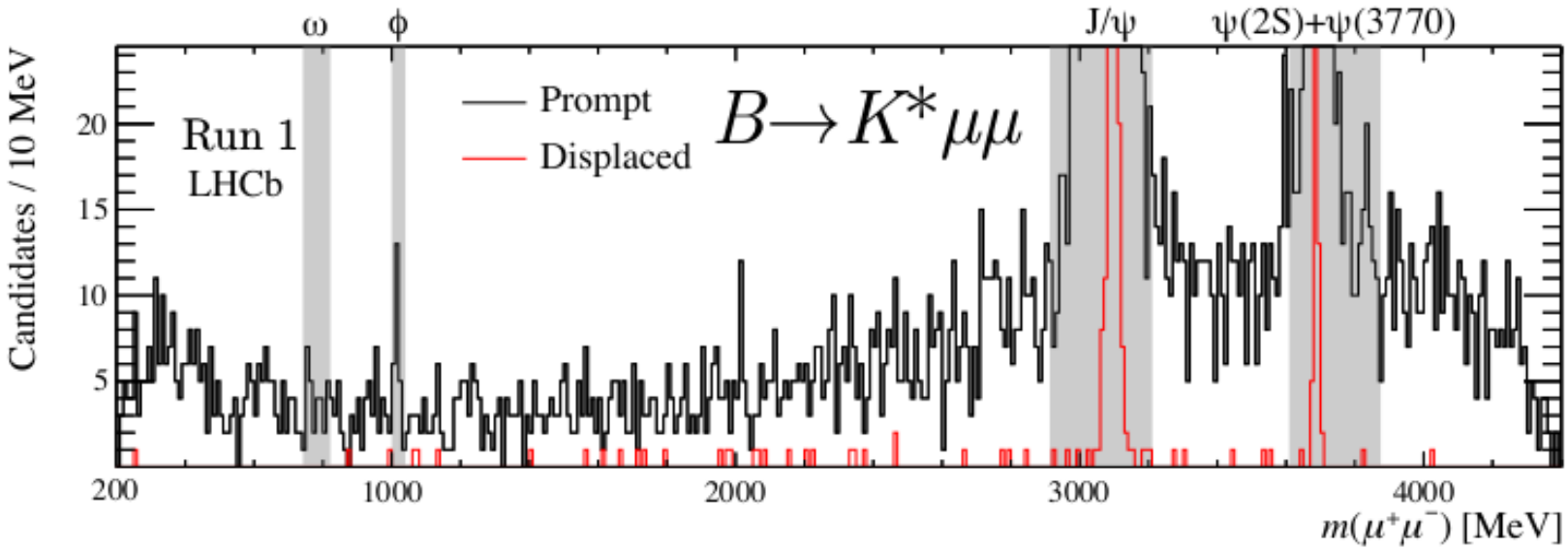
- $\mathrm{B}^0 \to K^{*0}\chi$ **[PRL 115 (2015) 161802]** / $\mathrm{B}^+ \to K^+\chi$ **[PRD 95 (2017) 071101 (R)]**
- Search for hidden-sector bosons $\chi \to \mu^+\mu^-$ in $b \to s$ penguin decays:
  - Axial-vector portal (χ as axion) **[LNP 741 (2008) 3]**
  - **Scalar** (Higgs) portal (χ as inflaton) **[JHEP 05 (2010) 10]**



- 1^{st} dedicated search ($K^{*0}\chi$) over such a large mass range:
  - **Pro:** $K^{*0} \to K^+\pi^-$ vertex leads to better $\tau(\chi)$ resolution and less background.
  - **Con:** $\mathrm{B}^0 \to K^{*0}\chi$ has smaller branching fraction than the $\mathrm{B}^+ \to K^+\chi$ mode.
- Allow for prompt and **detached** di-muon candidates – up to 1000 ps ($\sim$ 30 cm).

Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

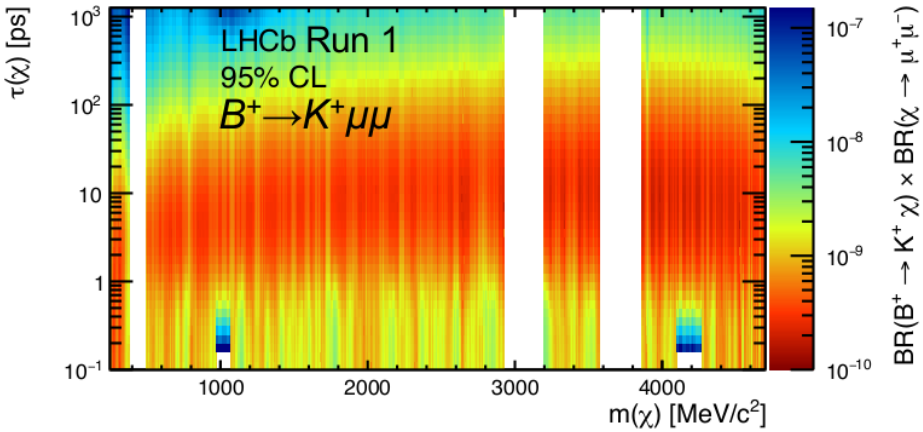
- Full LHCb Run I dataset (3 fb^{-1}) used.
- Look for a narrow di-muon peak (mass resolution between 2 and 9 MeV/c^2).
- Exclude narrow QCD resonances from the search - mass distribution below: **[PRL 115 (2015) 161802]**

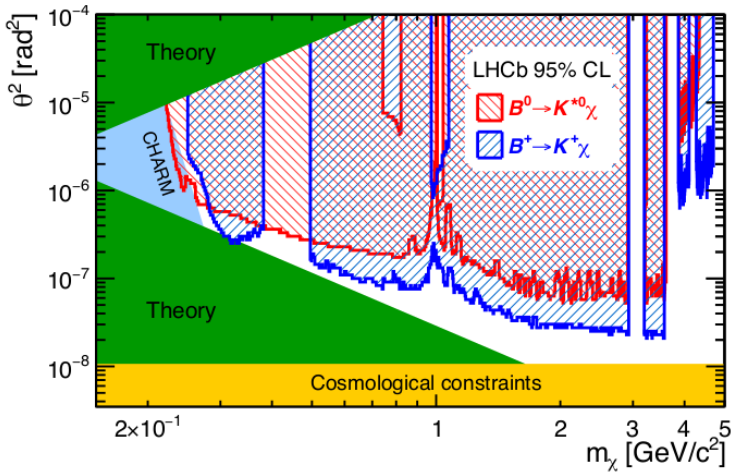


- MVA selection almost independent of χ mass and decay time (uBoost).

Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

- BR normalised to $\mathcal{B}(B^+ \to K^+ J/\psi)$ ($\sim 10^{-4}$) or $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ ($\sim 10^{-7}$).
- Constraints on $\tau(\chi)$ between 0.1 and 1000 ps (left).
- Constraints on mixing angle θ^2 between the Higgs and χ in the inflaton model (right). **[PRD 95 (2017) 071101 (R)]**

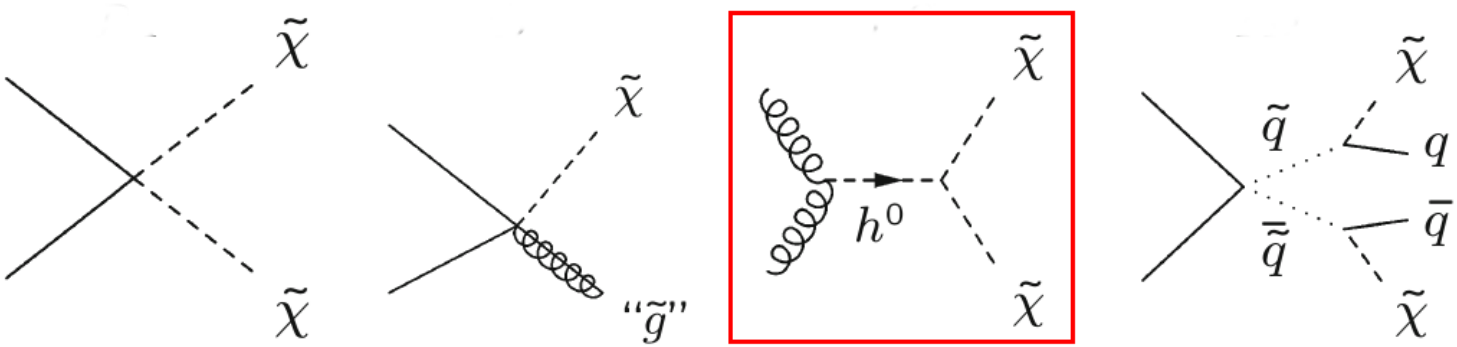




- **No evidence for signal observed.**
- **Large fraction of allowed inflaton parameter space ruled out.**

Massive LLPs decaying semileptonically to μ + jets

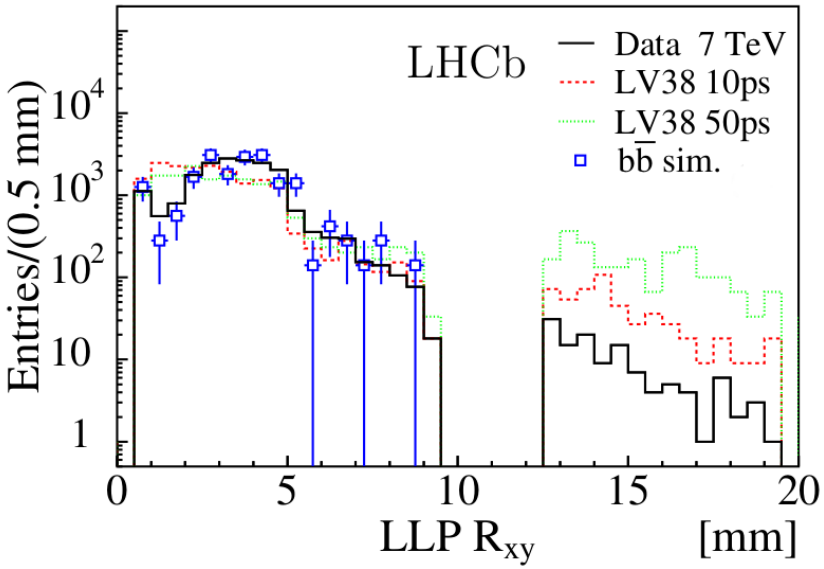
- Massive LLP (5 – 100 ps) into μ + two quarks ($\rightarrow$ jets) **[EPJC (2017) 77:224]**
- Results interpreted in terms of several models:
  - mSUGRA RPV neutralino.
  - Four simplified MSSM topologies:

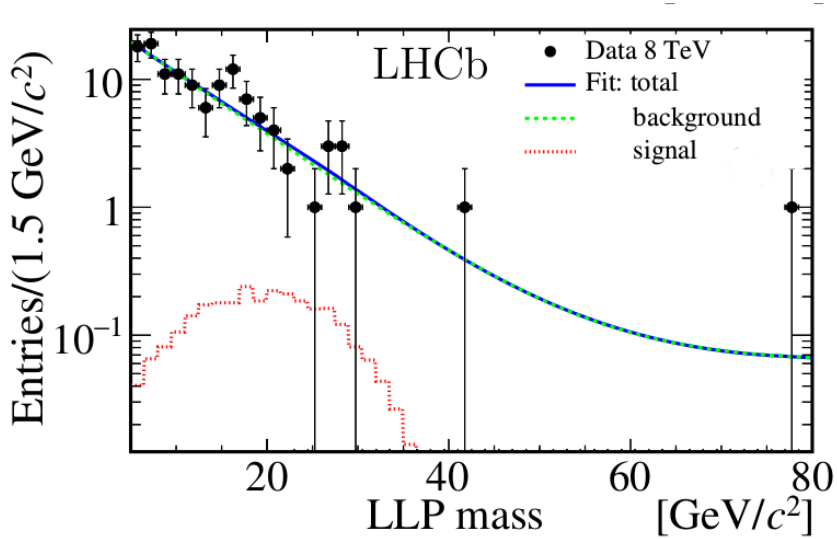


- In particular, **decay of a Higgs-like particle** into two LLPs.

Massive LLPs decaying semileptonically to μ + jets

- Look for a single displaced vertex with several tracks + high p_T muon.
- Background dominated by $b\bar{b}$ events and rejected by a tight selection + MLP. **[EPJC (2017) 77:224]**

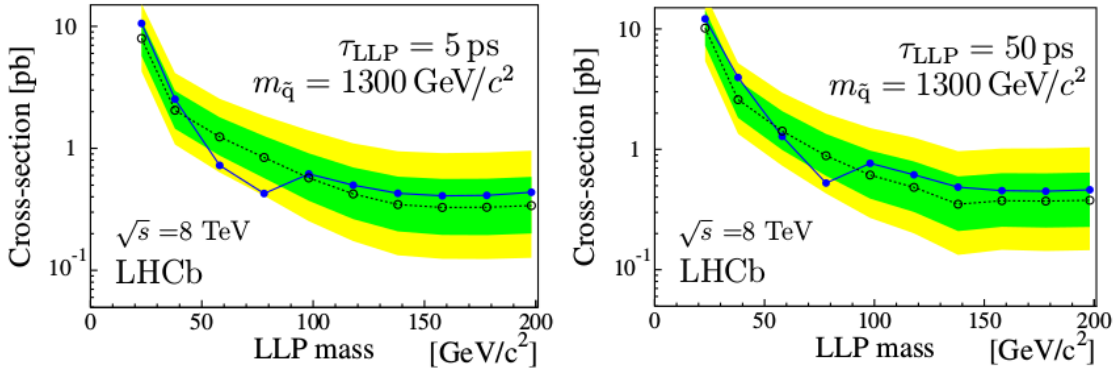




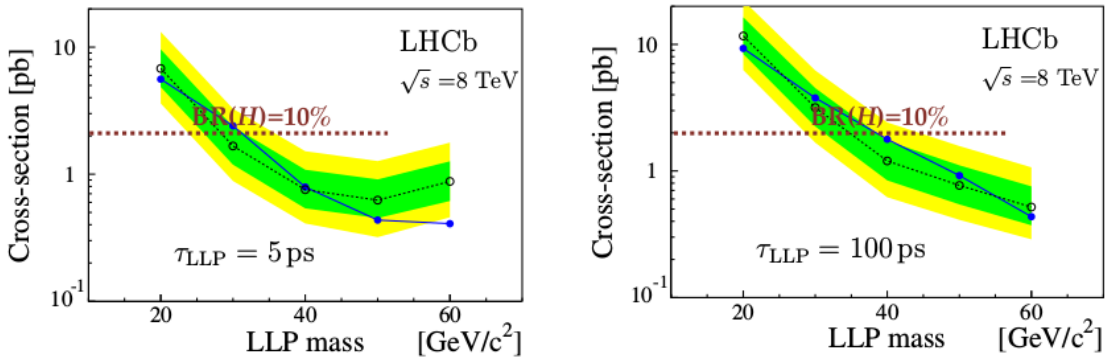
- Radial vertex position (R_{xy}) $\rightarrow$ very discriminant (left plot, mSUGRA RPV).
- Fit (shape from MC) to reconstructed LLP mass (right plot, 38 GeV/c^2).

Massive LLPs decaying semileptonically to μ + jets

- Results interpreted in mSUGRA RPV (default Pythia 6, gluino mass of 2 TeV/c^2): **[EPJC (2017) 77:224]**



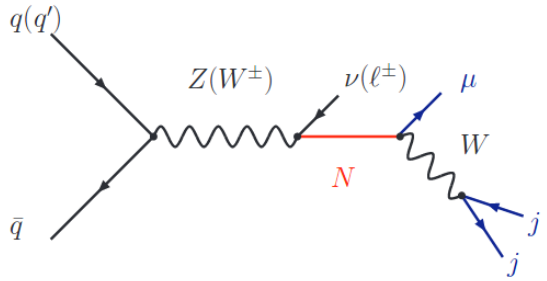
- Results interpreted in SM Higgs into two LLP process:



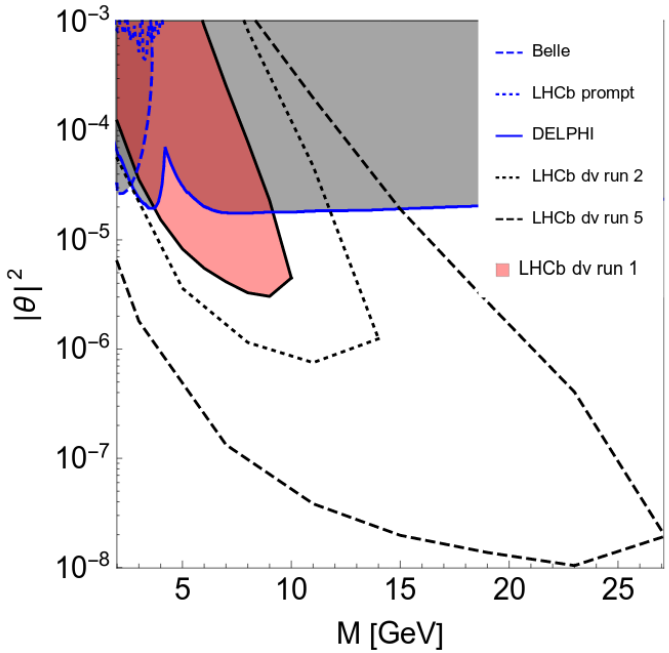
- Stringent limits – rejecting $\mathcal{B}(H^0 \to \chi\chi)$ >10% down to 30 GeV/c^2 (5 ps).
- **No excess observed: results compatible with background-only hypothesis.**

Massive LLPs decaying semileptonically to μ + jets

- Limits from this analysis recasted to look into sterile neutrinos **[arXiv:1706.05990]**



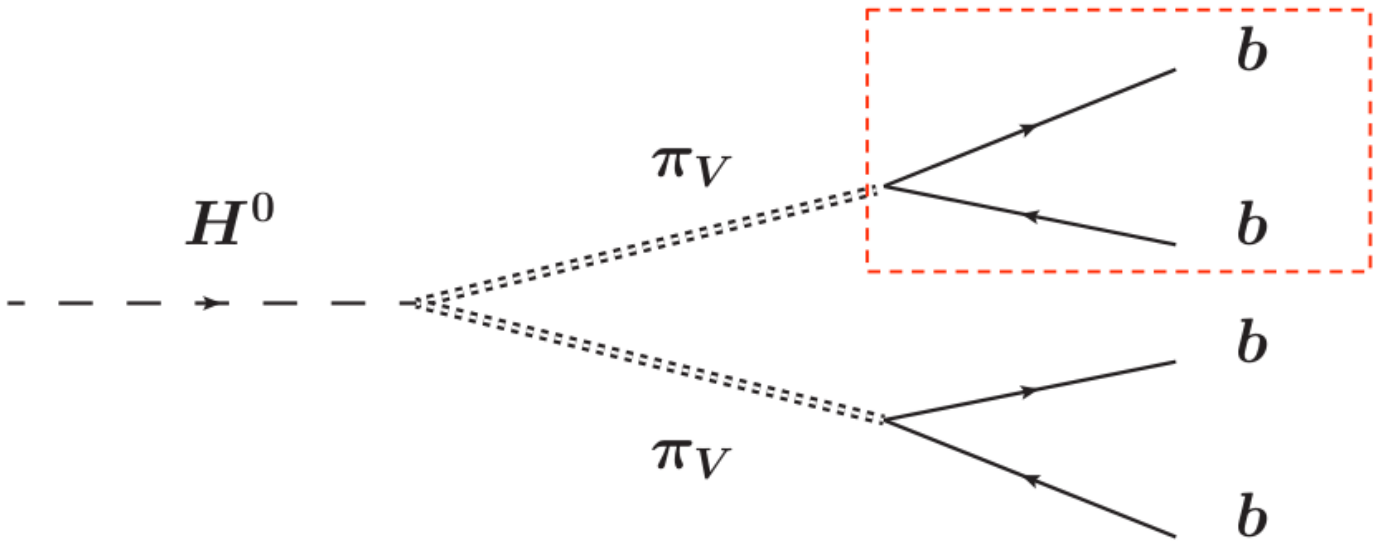
- Could we get best world-limit (5–10 GeV/c^2) with same kind of search?
  $\rightarrow$ See 95% C.L. exclusion plot below.
- Dedicated search with Run II data **in preparation.**



Massive LLPs decaying to jet pairs [LHCb-PAPER-2016-065]

- Search for SM-like $H^0 \to \pi_v \pi_v$ (Hidden Valley π_v), where each $\pi_v \to b\bar{b}$.
- In most of the cases only one of the two π_v decays into the LHCb acceptance.

- Experimental signature is a **single displaced vertex** with two associated jets.
- Explored several masses (25 – 50 GeV/c^2) and lifetimes (2 – 500 ps) of the π_v.

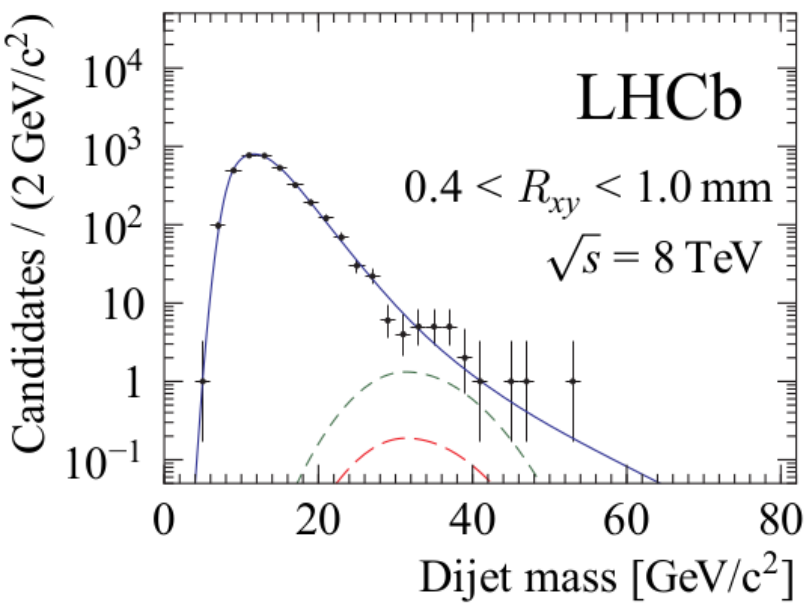


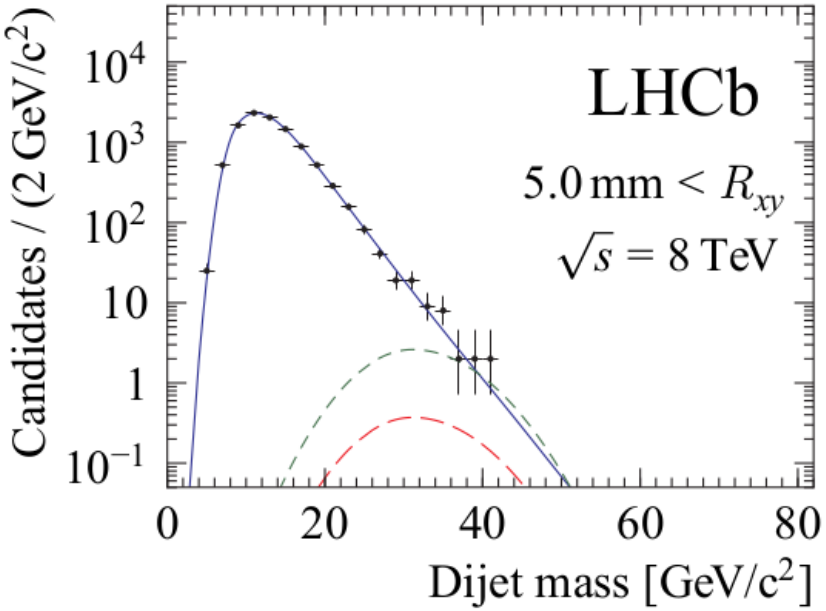
Massive LLPs decaying to jet pairs [LHCb-PAPER-2016-065]

Analysis procedure (full LHCb Run I):

1. Trigger on tracks passing a displaced vertex selection.
2. Reconstruct the displaced vertex and find two associated jets.
3. Quality cuts on jets – di-jet should point back to the candidate vertex.
4. Exclude material interactions + displaced vertices from heavy flavour.
5. Fit the di-jet invariant mass in 6 bins of R_{xy} (0.4 – 50 mm).

Massive LLPs decaying to jet pairs [LHCb-PAPER-2016-065]

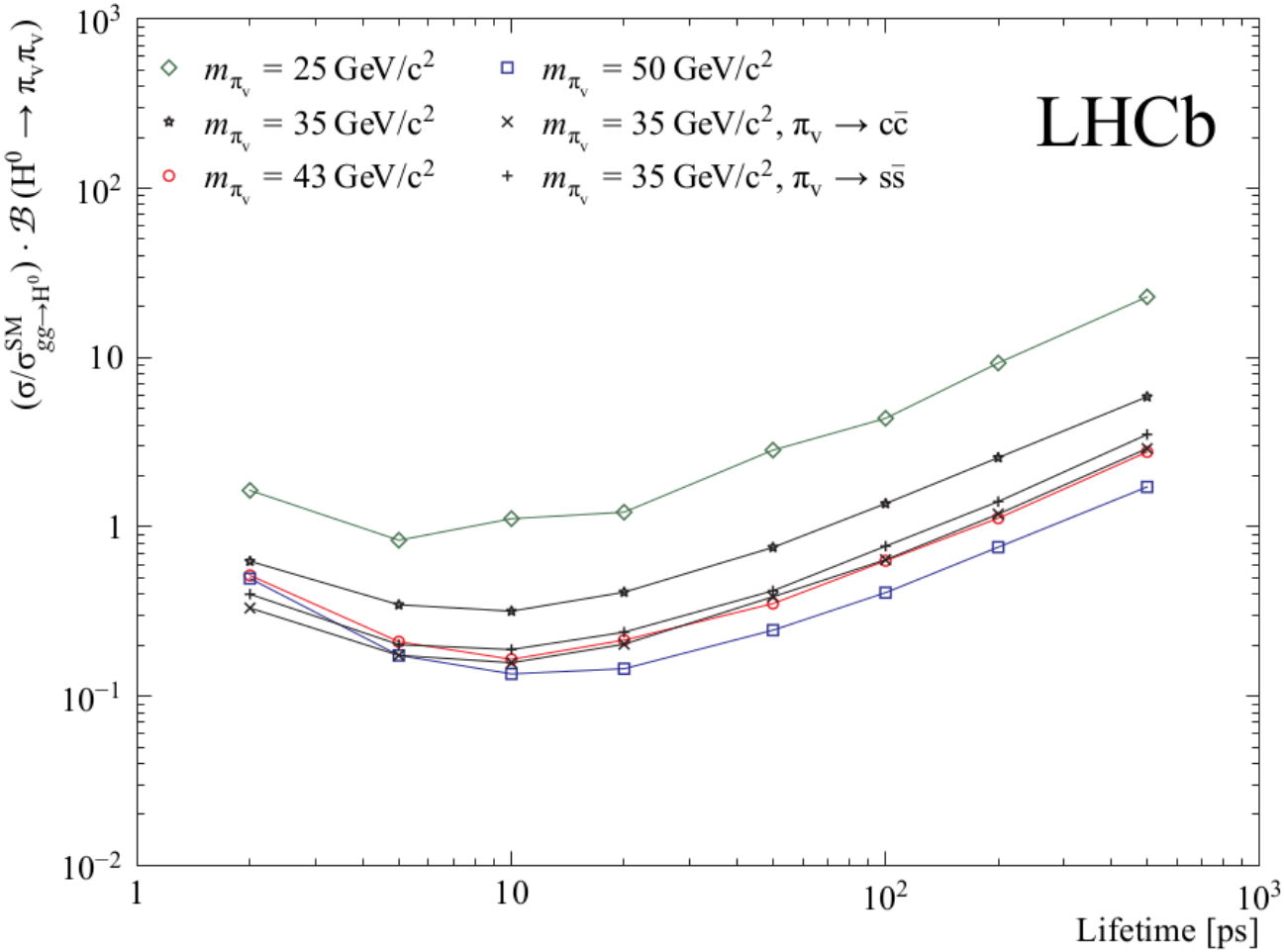




- Background model (material + HF + SM di-jets).
- Signal model (35 GeV/c^2, 10 ps) for $\mathcal{B}(H^0 \to \pi_v \pi_v) = 1$.
- Best-fit signal model (35 GeV/c^2, 10 ps).

Massive LLPs decaying to jet pairs [LHCb-PAPER-2016-065]

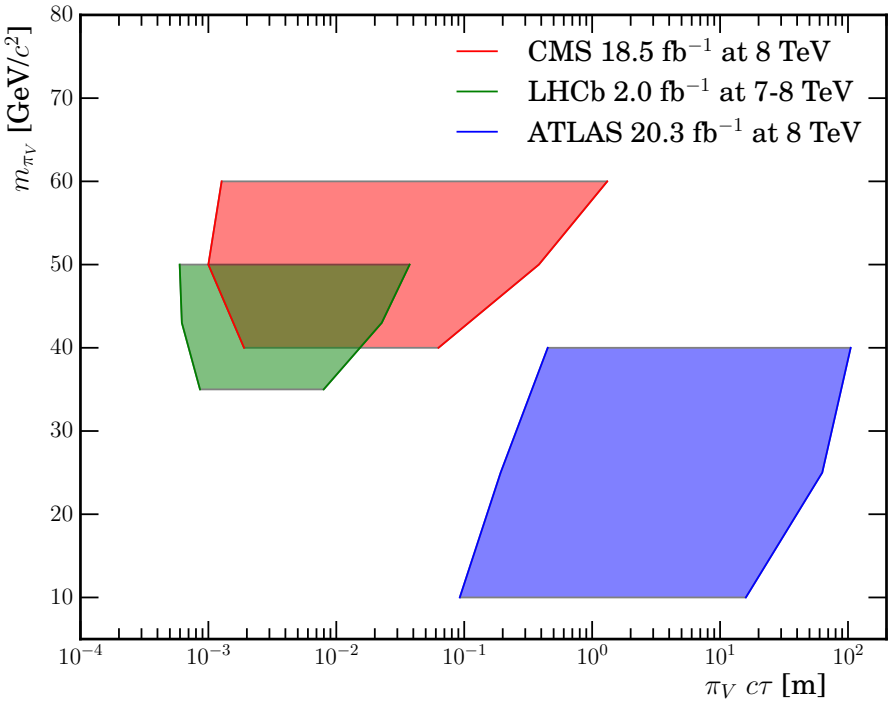
- Limits at 95% C.L. as a function of π_v lifetime for several π_v masses:



- **No excess found** – plan to analyse LHCb Run II (no L0) + go to lower π_v masses.
  → Working on **new dedicated trigger lines for displaced jets** (reach much lower masses).
- Develop a line for emerging jets → confining HV models (dark showers) [arXiv:1708.05389]

Massive LLPs decaying to jet pairs [LHCb-PAPER-2016-065]

- Compare with recasted results from ATLAS and CMS (plot by M. Borsato):



- Parameter space where $\mathcal{B}(H^0 \to \pi_v \pi_v) > 50\%$ is excluded at 95% C.L. is shown.
- Consider similar strategy for lower masses as in the $h^0 \to \chi\chi \to$ hadrons search **[EPJC (2016) 76:664]**

Dark Photons

Search for dark photons at LHCb?

- Excellent **mass** resolution $\rightarrow$ crucial if irreducible background (DY) is present.
- **Soft** trigger on muon **transverse momentum**.
- Online μ-ID in new $\mu\mu$ turbo line $\rightarrow$ **no prescales** down to $\mu\mu$ mass threshold.

Search for dark photons at LHCb!

Search for dark photons produced in 13 TeV pp collisions

LHCb collaboration: R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, A. Alfonso Albero, S. Ali, G. Alkhazov, P. Alvarez Cartelle, A.A. Alves Jr, S. Amato, S. Amerio, Y. Amhis, L. An, L. Anderlini, G. Andreassi, M. Andreotti, J.E. Andrews, R.B. Appleby, F. Archilli, P. d'Argent, J. Arnau Romeu, A. Artamonov, M. Artuso, E. Aslanides, M. Atzeni, G. Auriemma, M. Baalouch, I. Babuschkin, S. Bachmann, J.J. Back, A. Badalov, C. Baesso, S. Baker, V. Balagura, W. Baldini, A. Baranov, R.J. Barlow, C. Barschel, S. Barsuk, W. Barter, F. Baryshnikov, V. Batozskaya, V. Battista, A. Bay, L. Beaucourt, J. Beddow, F. Bedeschi, I. Bediaga, A. Beiter, L.J. Bel, N. Beliy, V. Bellee, N. Belloli, K. Belous, I. Belyaev, E. Ben-Haim, G. Bencivenni, S. Benson, S. Beranek, et al. (737 additional authors not shown)

(Submitted on 8 Oct 2017)

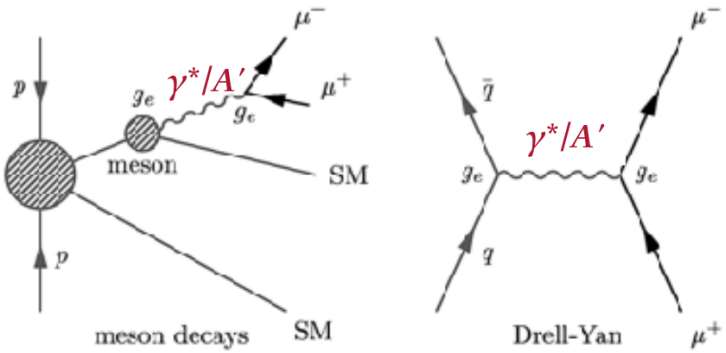
Searches are performed for both prompt-like and long-lived dark photons, A', produced in proton-proton collisions at a center-of-mass energy of 13 TeV, using $A' \rightarrow \mu^+\mu^-$ decays and a data sample corresponding to an integrated luminosity of 1.6 fb^{-1} collected with the LHCb detector. The prompt-like A' search covers the mass range from near the dimuon threshold up to 70 GeV, while the long-lived A' search is restricted to the low-mass region $214 < m(A') < 350$ MeV. No evidence for a signal is found, and 90% confidence level exclusion limits are placed on the γ-A' kinetic-mixing strength. The constraints placed on prompt-like dark photons are the most stringent to date for the mass range $10.6 < m(A') < 70$ GeV, and are comparable to the best existing limits for $m(A') < 0.5$ GeV. The search for long-lived dark photons is the first to achieve sensitivity using a displaced-vertex signature.

Comments: All figures and tables, along with any supplementary material and additional information, are available at this https URL
Subjects: **High Energy Physics - Experiment (hep-ex)**
Report number: LHCb-PAPER-2017-038, CERN-EP-2017-248
Cite as: **arXiv:1710.02867 [hep-ex]**

Dark Photons

Search for dark photons decaying into a pair of muons:

- Kinetic mixing of the dark photon (A') with off-shell photon (γ^*) by a factor ε:
  1. A' inherits the production mode mechanisms from γ^*.
  2. $A' \to \mu^+\mu^-$ can be normalised to $\gamma^* \to \mu^+\mu^-$.
  3. No use of MC $\to$ no systematics from MC $\to$ **fully data-driven analysis!**
- Separate γ^* signal from background and measure its fraction.
- **Prompt-like** search (up to 70 GeV/c^2) $\to$ **displaced** search (214 – 350 MeV/c^2).
  - A' is long-lived only if the mixing factor is really small.
- Used 1.6 fb^{-1} of 2016 LHCb data (13 TeV) **[LHCb-PAPER-2017-038, arXiv:1710.02867]**



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

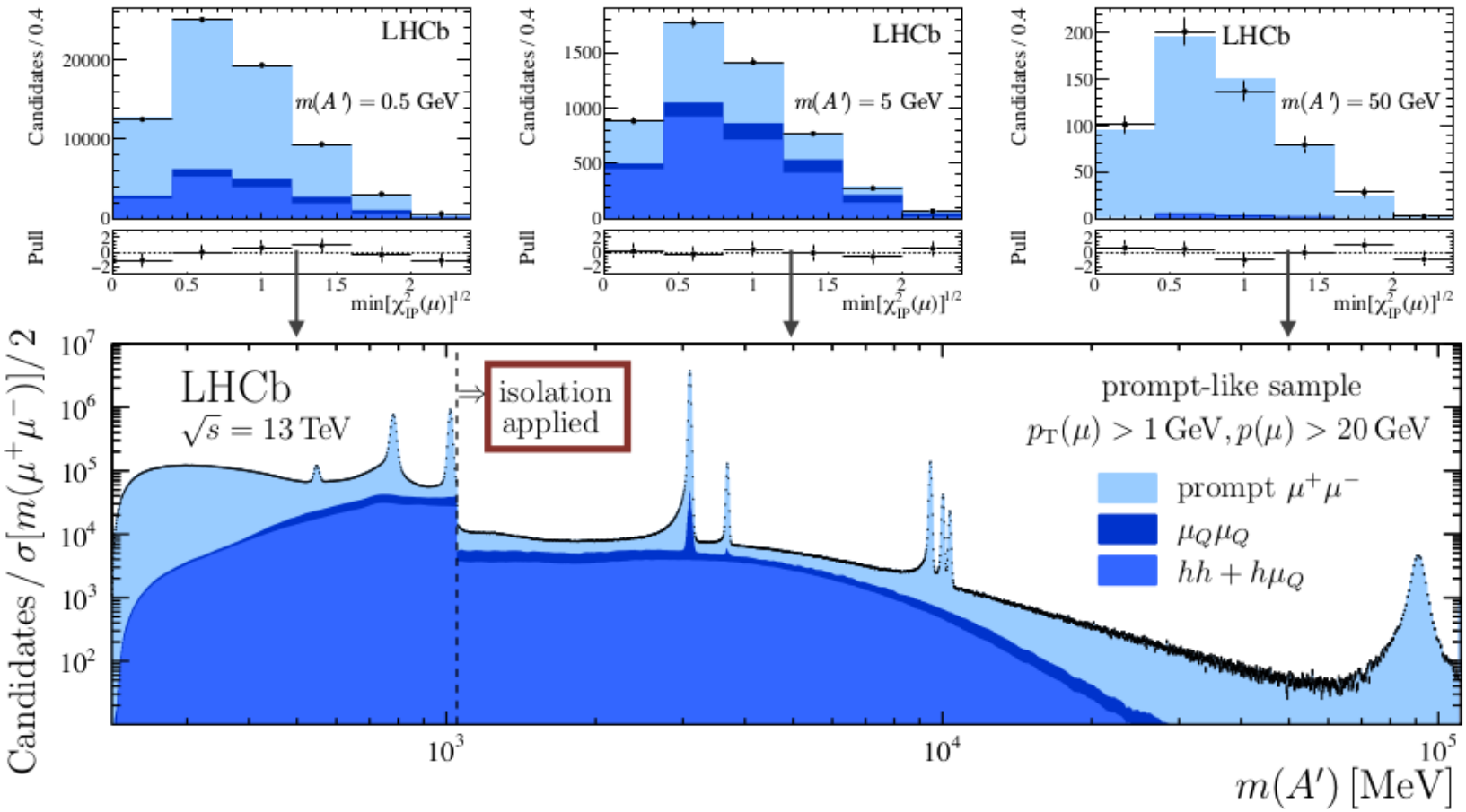
off-shell photon | phase-space | A′/γ* eff ratio, ϵ=1 for prompt

Dark Photons – prompt-like search [LHCb-PAPER-2017-038]

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

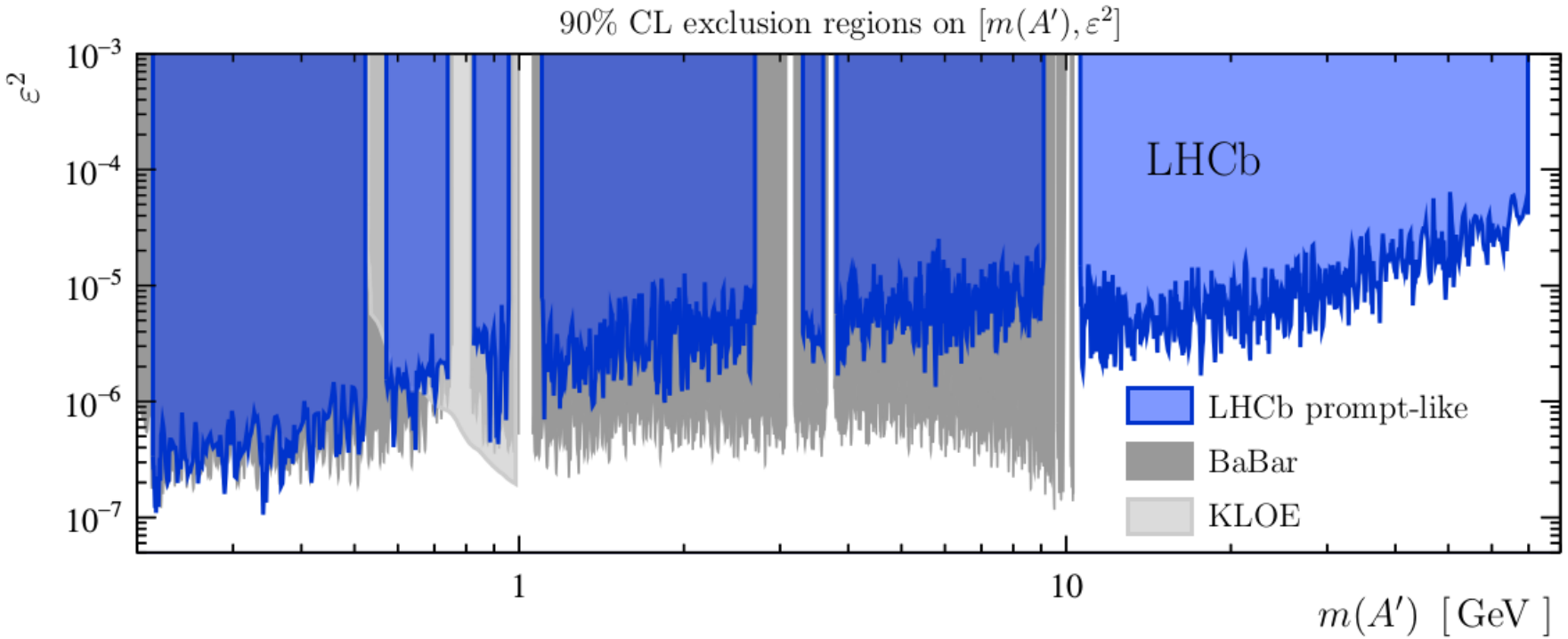
- prompt $\mu^+\mu^-$ → from data at $m(J/\psi)$ and $m(Z)$
- $\mu_Q\mu_Q$ → from simulation (validated)
- $hh + h\mu_Q$ → from same-sign dimuons (corrected)

(μ_Q is a muon from a heavy-flavour decay)



(shamelessly stolen from Martino's talk at Flavour and Dark Matter workshop)

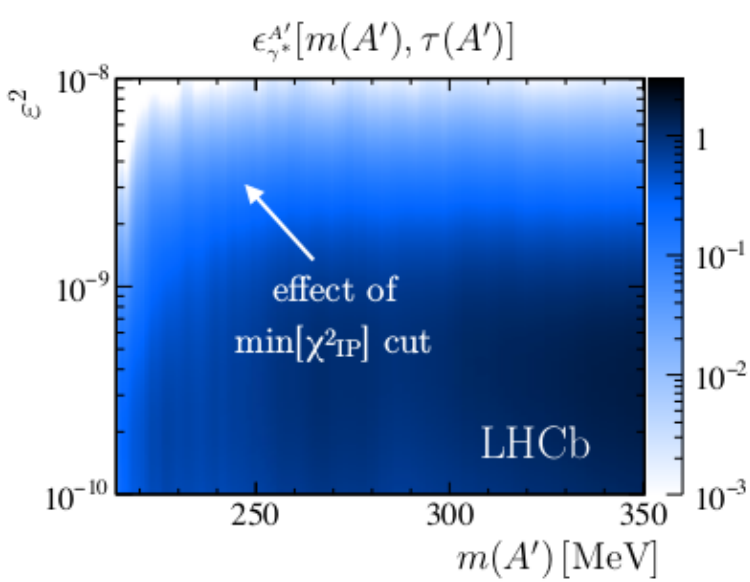
Dark Photons – prompt-like search [LHCb-PAPER-2017-038]

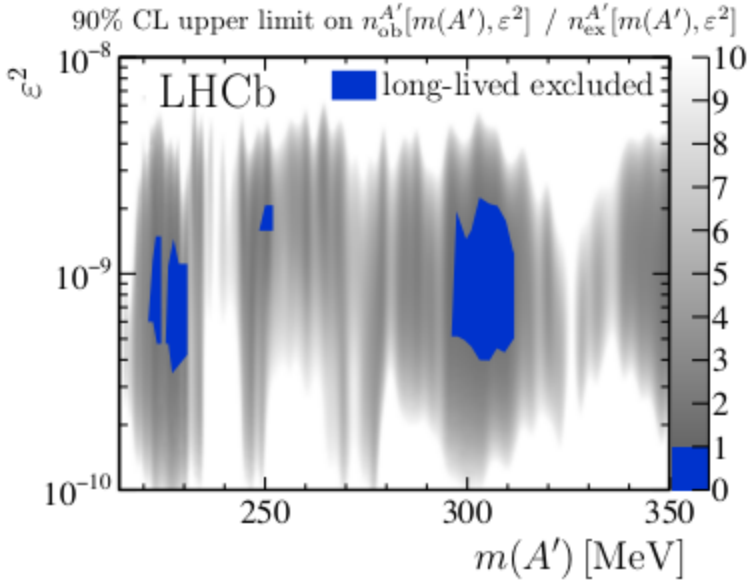


- **No significant excess found.**
- **First limits above dark photon masses of 10 GeV/c^2.**
- **Also – competitive limits below 0.5 GeV/c^2!**

Dark Photons – displaced search [LHCb-PAPER-2017-038]

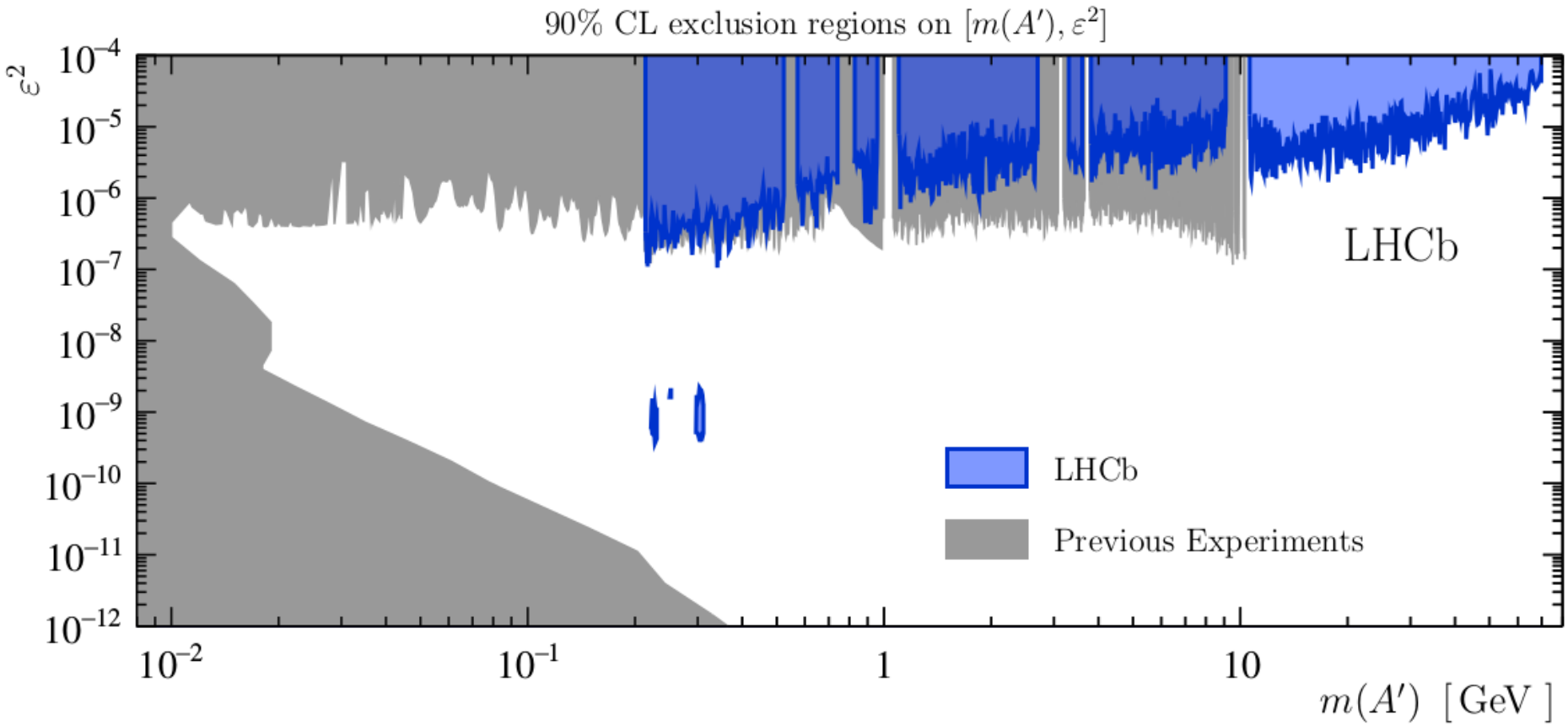
- Looser requirements on muon tranverse momentum.
- Material background mainly from photon conversions at VELO region.
- Isolation decision tree from $B_s^0 \to \mu^+\mu^-$ search:
  $\to$ Supress μ from b-hadron decays + mis-identified π from $K_S^0 \to \pi^+\pi^-$ tail.
- Fit in bins of mass and lifetime – use consistency of decay topology χ^2.
- Extract p-values and confidence intervals from the fit:





- **No significant excess found** – small parameter space region excluded.
- First limit ever **not from beam dump!**

Dark Photons – summary [LHCb-PAPER-2017-038]

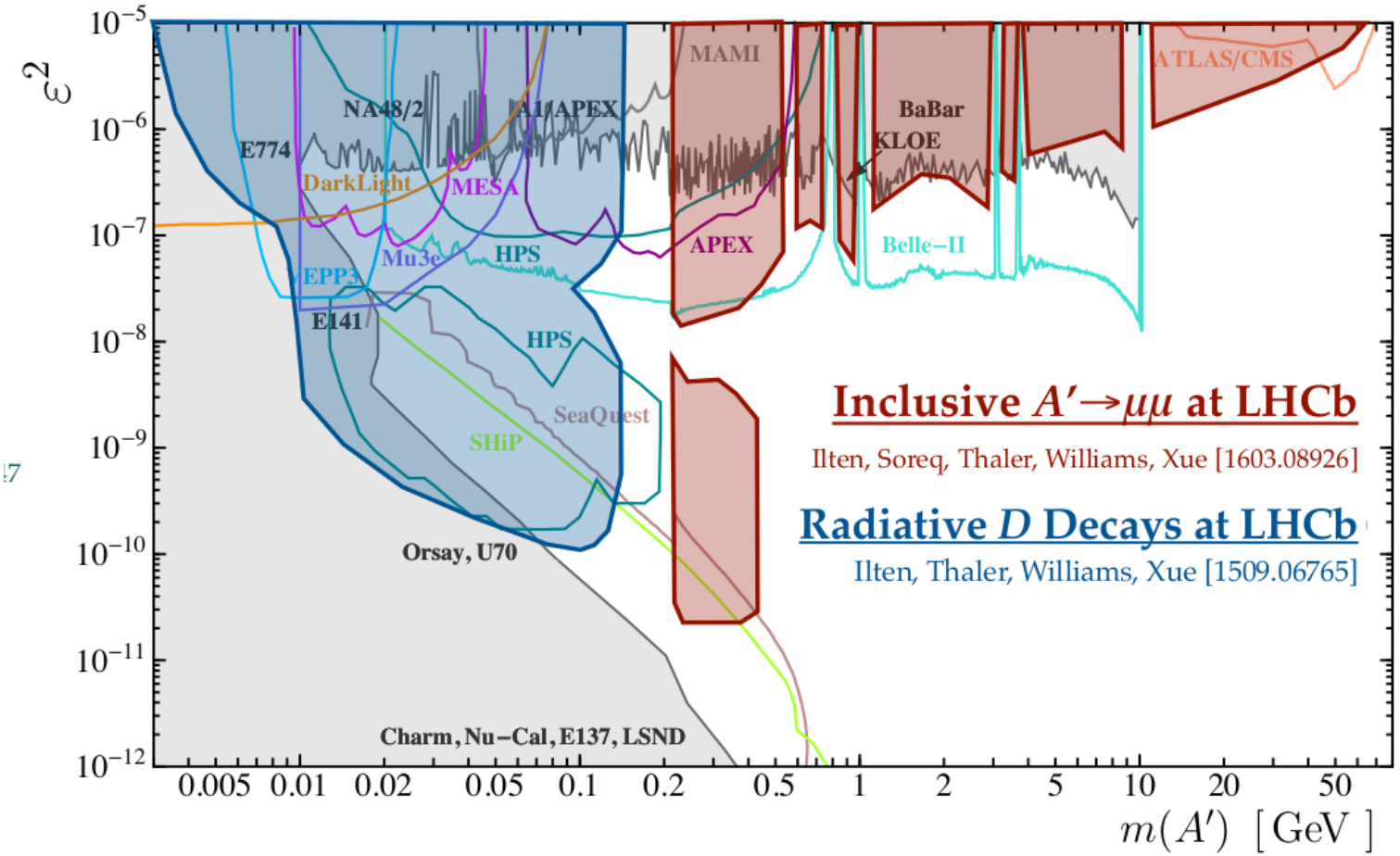


Search for dark photons at LHCb:

- No significant excess found.
- First limits above prompt-like dark photon masses of 10 GeV/c^2.
- Competitive limits for prompt-like dark photon masses below 0.5 GeV/c^2.
- First limit for a small displaced dark photon low mass region not from beam dump.

Dark Photons – the future

- Extend searches model-independently
  $\rightarrow$ i.e. light NMSSM Higgs via ggF **[PRD 93 (2016) 055047]**
- Search inclusively for four muons,
- Search for $N_{2,3} \rightarrow \pi^+ \mu^-$, etc.
- Prospected reach for **Run III:**



Conclusions

Our present:

- Collected 3.0 fb^{-1} during the full Run I.
- Collected so far 3.1 fb^{-1} during Run II (2015 – 1$^{\text{st}}$ October 2017).
- LHCb proved to have already entered the LLPs game – some results shown in this talk:
  - Hidden-sector bosons (inflatons) from B decays,
  - Neutralinos (mSUGRA RPV, from SM-like Higgs decay),
  - Hidden Valley π_v from SM-like Higgs decays,
  - Dark photons from B-meson decays and Drell-Yan.

Conclusions

Our future:

- Expect to collect 5.0 fb^{-1} during the full Run II – only if 16L2 allows us to, of course...
- A lot of potential in Run III triggers (see talks by Jessica & Elena) + also $\times 5$ luminosity.
- Plenty of prospects fom existing results and ideas of new searches:
  - HV π_v searches at lower masses, lower lifetimes, more realistic models (dark showers).
  - Extend dark photon searches model-independently, inclusive searches.
  - Majorana neutrinos from B decays ($b \to c$ transitions) – less CKM suppression.
  - Majorana neutrinos from W decays – already on-going!
  - e in final states – sensitive to lower masses (no sensitivity anywhere else at the LHC).
  - Fractional charge particles, monopoles, quirks – sensitivity studies needed!

Conclusions

Take-home message:

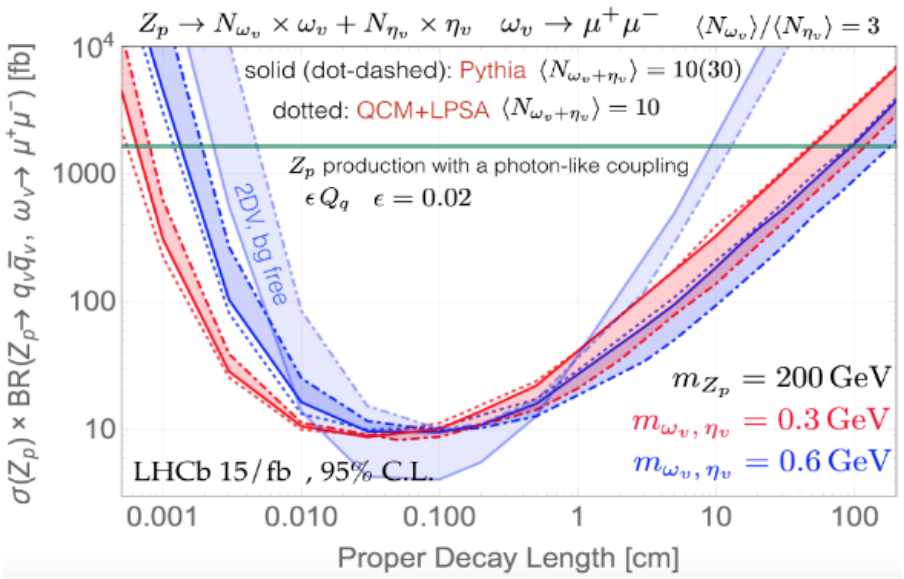
- Our experiment proved to be competitive in a wealth of signatures and regions.
- Plan to extend our LLPs programme to complementary regions w.r.t. other experiments.
- There is an increasing interest in LLP searches in LHCb:
  $\rightarrow$ Even a proposal for a new compact detector for exotics – CODEX-b (see talk by Dean).
- We are looking forward to ideas for new signatures and techniques:
  $\rightarrow$ **Do not hesitate to contact us if interested!**

Is there anything beyond the Standard Model?

Thanks for your attention!

Backup

Confining HV at LHCb [arXiv:1708.05389]



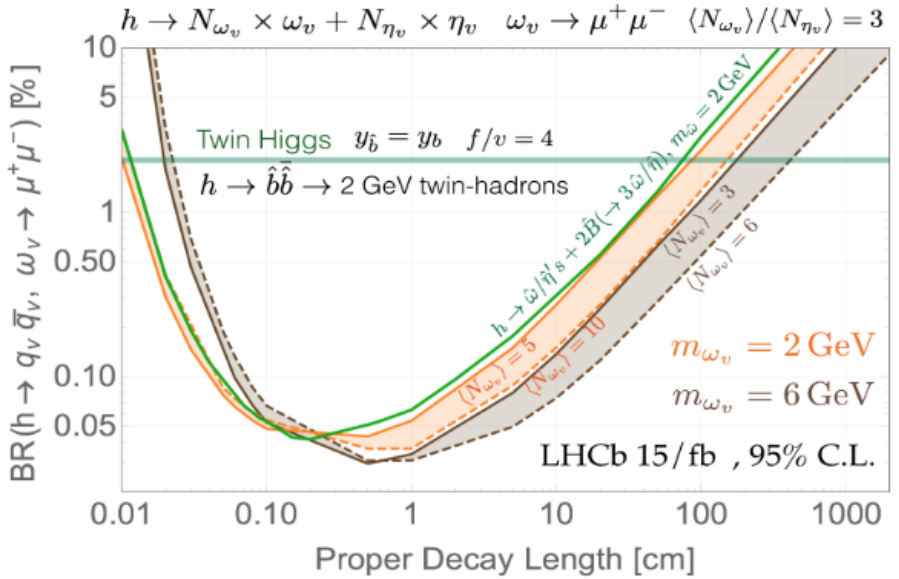


FIG. 1: Left panel: Z_p cross section reach. Green line: cross section for a photon-like coupling, suppressed by $\epsilon = 0.02$. Right panel: Projected upper bounds on BR($h \to$ twin bottom quarks) using the 1 DV search. This process produces lighter twin mesons $\hat{\omega}/\hat{\eta}$ followed by $\hat{\omega} \to \mu^+\mu^-$. Horizontal green line: prediction in a variation of the Fraternal Twin Higgs model (see text); in this context ω_v is a mixture of c' and s'. Green curve: reach for the corresponding decay topology (see text for details).

Confining HV at LHCb [arXiv:1708.05389]

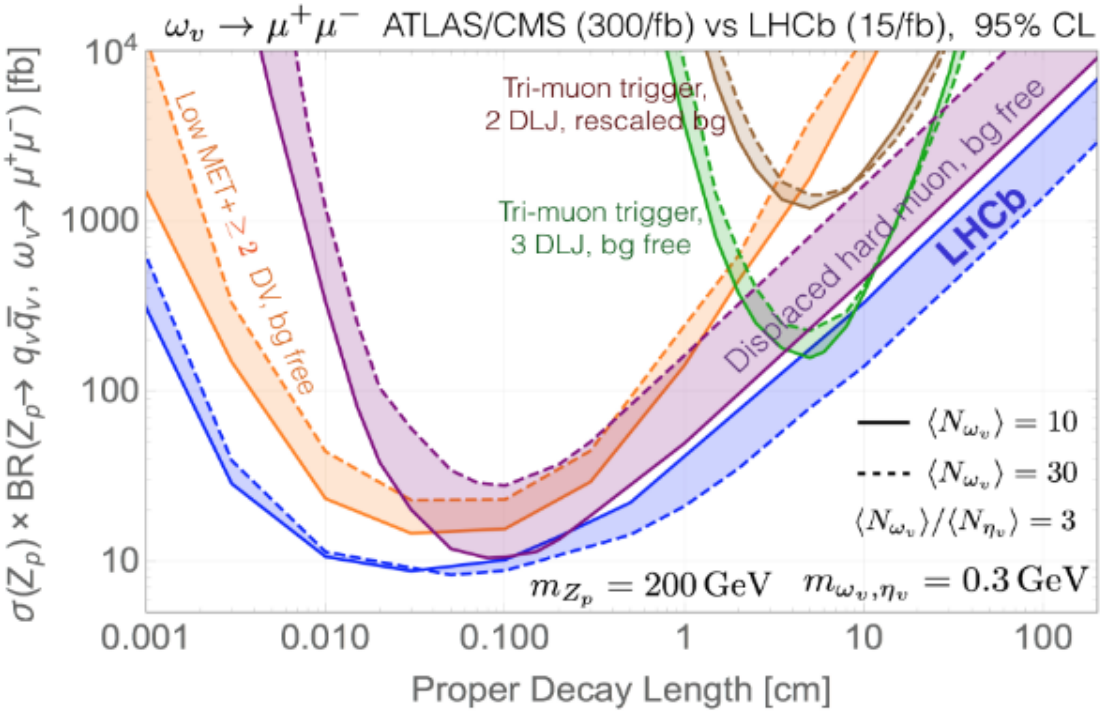


FIG. 2: Projected bounds from various ATLAS/CMS displaced muons search strategies, see text for details. The brown curve represents an extrapolation of a current analysis, while the green curve represents only a minor modification. The orange and purple projections have aggressive assumptions about backgrounds and will likely weaken following detailed detector simulations. The band widths correspond to $10 \leq \langle N_v \rangle \leq 30$. The blue band is derived from the LHCb search proposed in this work.

Confining HV at LHCb [arXiv:1708.05389]

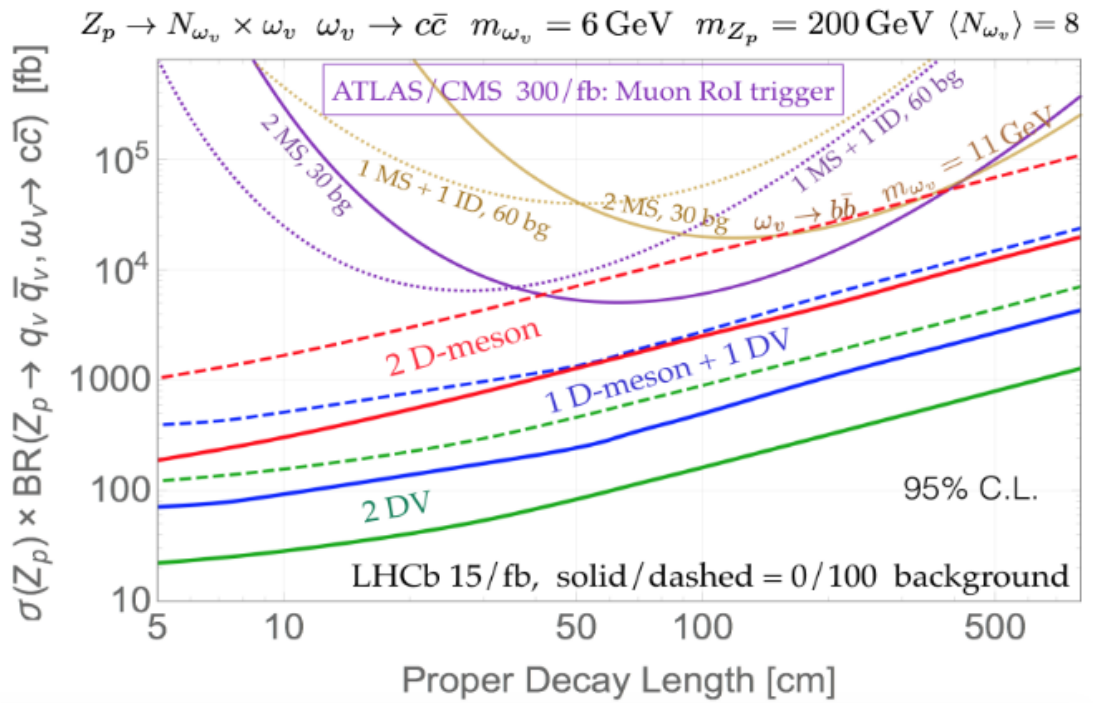


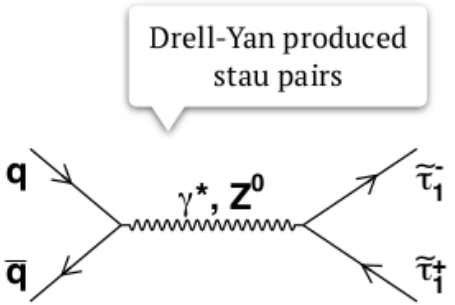
FIG. 3: Projected bounds from various displaced $c\bar{c}$ search strategies, see text. Purple curves: ATLAS/CMS reach estimate for DV decays into ≥ 5 charged tracks, with either two DV in the muon spectrometer (solid) or one DV in the inner detector and one in the muon spectrometer (dotted). Brown: analogous ATLAS/CMS reach for $\omega_v \to b\bar{b}, m_{\omega_v} = 11$ GeV.

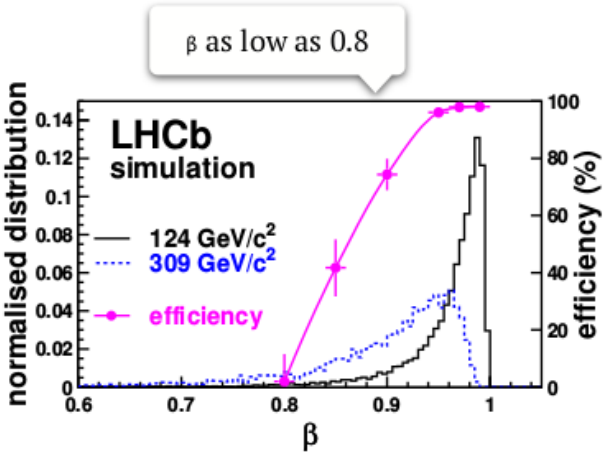
Charged Massive Stable Particles

EPJC 75 (2015) 595

- Charged Massive Stable Particles
  - stable = can pass through the μ-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





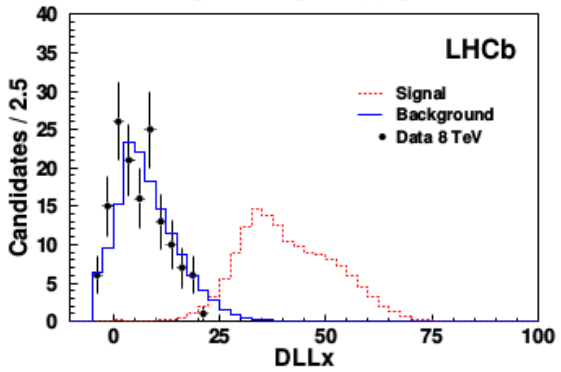
(shamelessly stolen from Martino's talk at previous LLP workshop)

Charged Massive Stable Particles

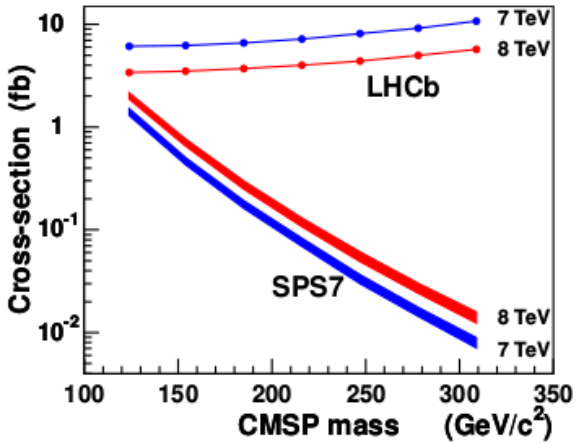
EPJC 75 (2015) 595

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

RICH information



- 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



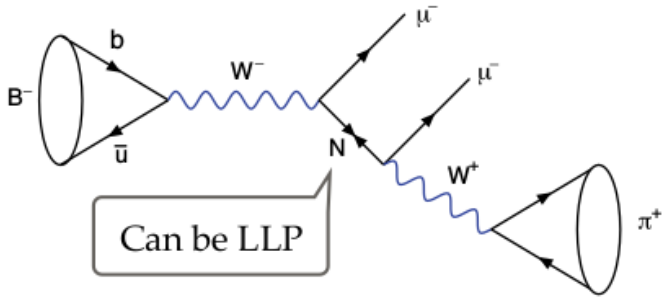
(shamelessly stolen from Martino's talk at previous LLP workshop)

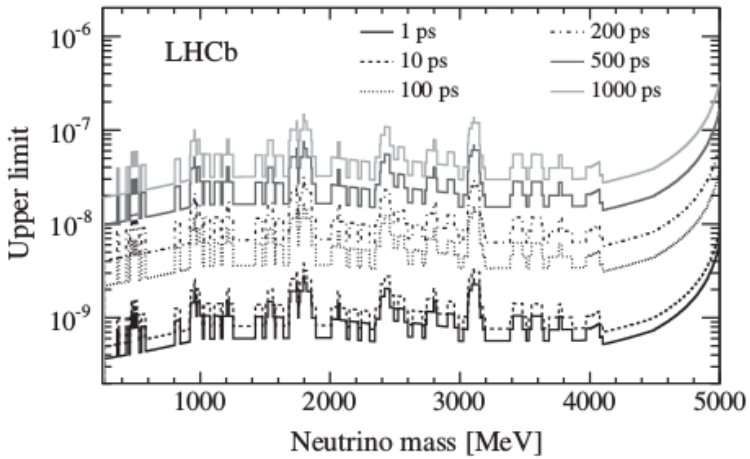
Majorana neutrinos in $B \to \pi \mu^+ \mu^+$

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 $\mu^+ \mu^+$





(shamelessly stolen from Martino's **talk** at previous LLP workshop)

- "Revision of the LHCb Limit on Majorana Neutrinos" **[arXiv:1607.04258]**

Dark showers:

- Dark parton showers motivated by models with a composite dark sector.
- Production of v-hadrons (neutral) in cascade, some of them decaying to visible particles.
- In terms of its experimental signature, an "emerging jet" is produced.
- **LHCb has potential** (future studies): sensitive to **low mediator masses**, good jet vertexing.