Searching for Long Lived Particles at LHCb

Federico Leo Redi (EPFL) - on behalf of the LHCb Collaboration
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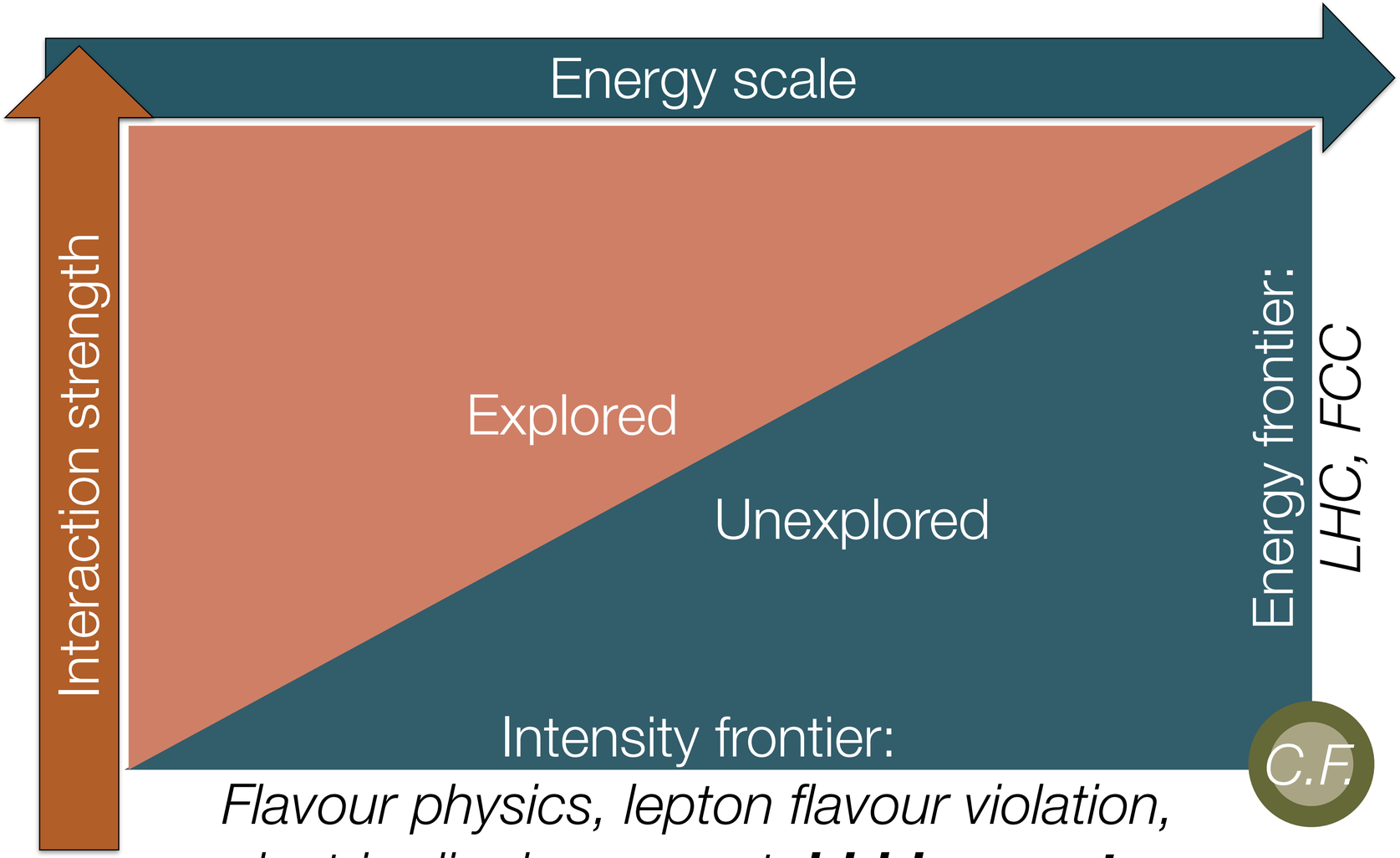
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Introduction

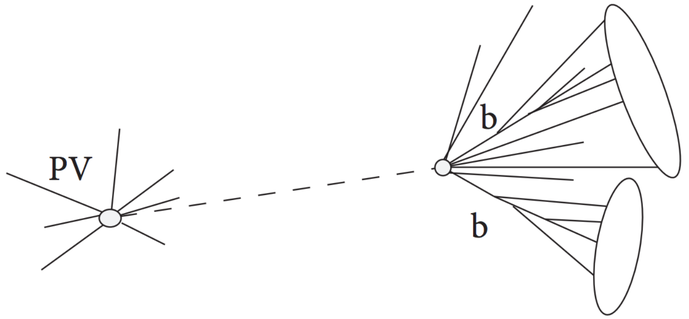
- Naturalness does not seem to be a **guiding principle** of Nature
- There are some **anomalies in flavour physics** which (if true) seem again to point out that our theory prejudice was wrong
- We should therefore not forget that **we have a 2D** problem (Mass VS Coupling)
- Low coupling → Long Lived

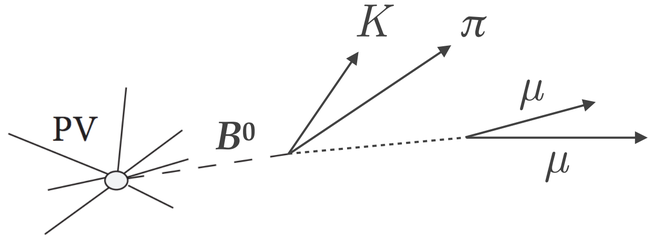


Landscape today

- The intensity frontier is a **broad** and **diverse**, yet **connected**, set of science opportunities
  - Light Dark Matter (**LDM**)
    Portals to Hidden Sector (**HS**) (dark photons, dark scalars)
    Axion Like Particles (**ALP**)
    Heavy Neutral Leptons (**HNL**)
- In this talk, I will concentrate on HS particles, specifically **Long Lived Particles (LLP)** at LHCb.
- **Landscape**: LHC results in brief:
  - Parameter space for popular **BSM** models is **decreasing rapidly**, but only < 5% of the complete HL-LHC data set has been delivered so far
  - NP discovery **still may happen**!
  - **LHCb** reported intriguing hints for the violation of lepton flavour universality
    - In $b \to c\mu\nu$ / $b \to c\tau\nu$, and in $b \to se^+e^-$ / $b \to s\mu^+\mu^-$ decays
    - **Clear evidence of BSM** physics if substantiated with further studies (possibly by **BELLE II**)

Exploring the dark sector



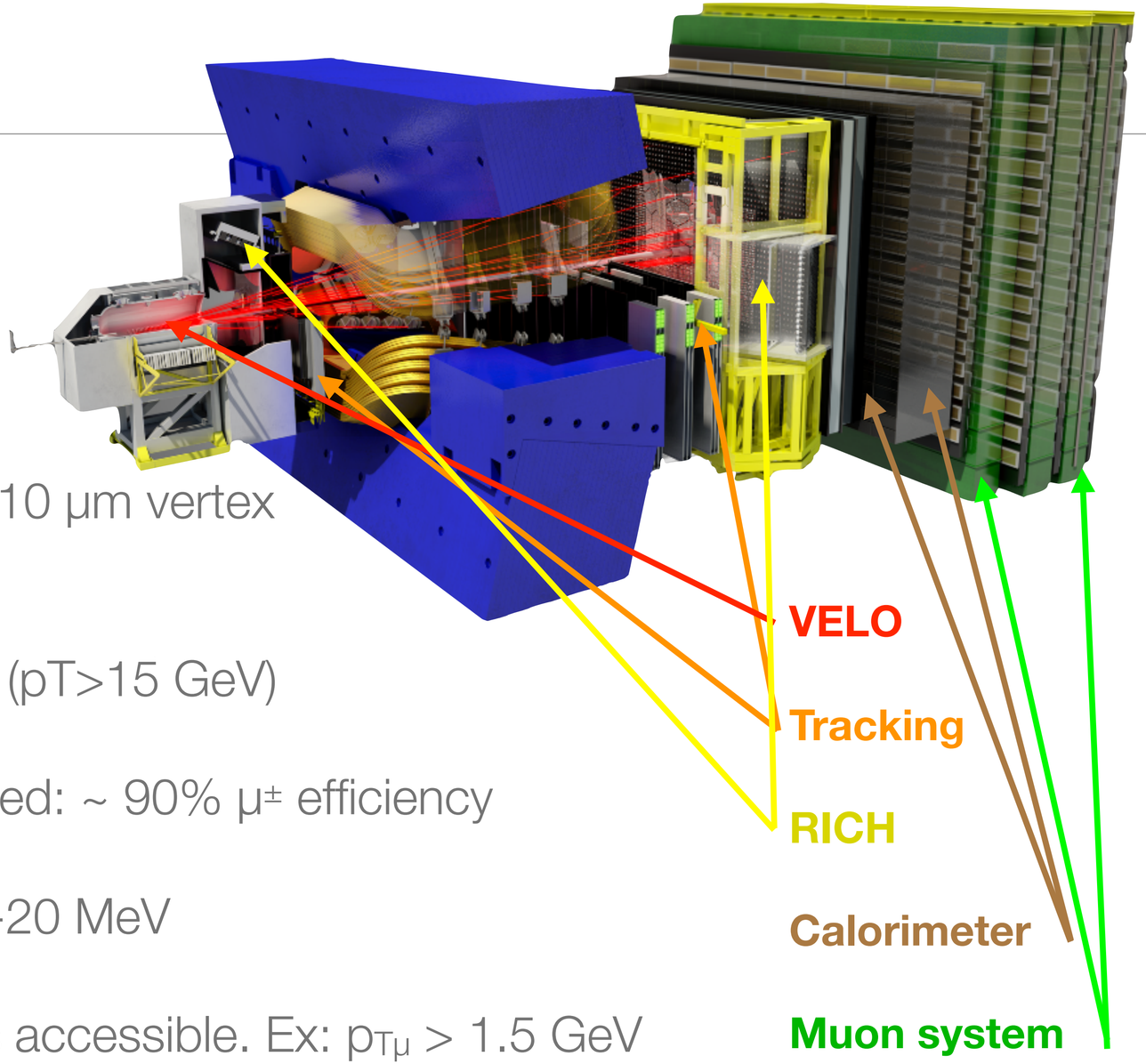


- In the dark sector: $L = L_{SM} + L_{mediator} + L_{HS}$
  - Hidden Sector decay rates into SM final states is suppressed
    Branching ratios of O(10^{-10})
    Long-lived objects
    Interact very weakly with matter
- Experimental challenge is **background suppression**
- **Full reconstruction** and **PID** are essential to minimise model dependence
- **Two** strategies of searching for mediators at accelerators:
  - Not decaying in the detector (missing energy and scattering technique)
  - **Decaying in the detector** (reconstruction of decay vertex)
- **Two** means of production:
  - Produced in pp collisions (displaced di-jets and di-leptons)
  - Produced in B/D decays (displaced di-leptons)

Bonus: Dark bosons:
PRL 115, 161802 (2015)
PRD. 95, 071101 (2017)

The LHCb detector / 1

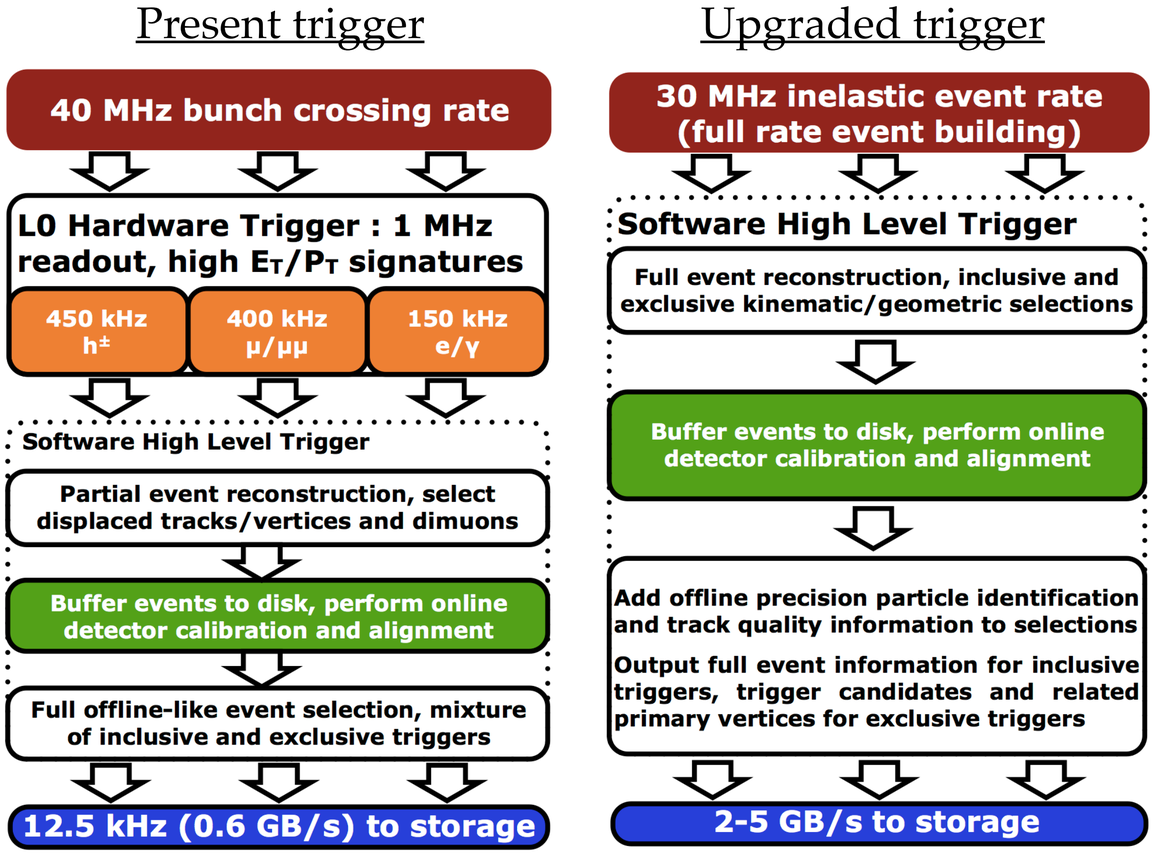
- **LHCb** is a dedicated flavour experiment in the f**orward region** at the LHC (1.9 < η < 4.9) (~1°-15°)
- **Precise vertex reconstruction** ~ 10 μm vertex resolution in transverse plane
- Jet reconstruction efficiency > 80% (pT>15 GeV)
- **Muons** clearly identified and triggered: ~ 90% $\mu^{\pm}$ efficiency
- Great **mass resolution**: typically 7-20 MeV
- **Low p_T trigger** means low masses accessible. Ex: $p_{T\mu} > 1.5$ GeV



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

The LHCb detector / 2

- Lower luminosity (and low pile-up)
  - **~1/8** of ATLAS/CMS in **Run 1**
  - **~1/20** of ATLAS/CMS in **Run 2**
- **Real-time reconstruction** for all charged particles with pT > 0.5 GeV
- Real-time calibration & alignment
- **Full real-time** reconstruction for all particles available to select events
- We go from 1 TB/s (post zero suppression) to 0.7 GB/s (mix of full + partial events)
- LHCb will move to a **trigger-less readout system** for LHC Run 3 (2021-2023), and process
  5 TB/s in real time on the CPU farm



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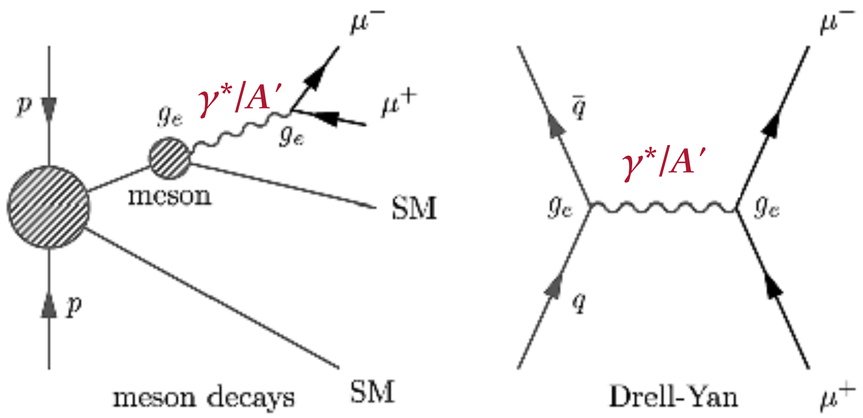
Searching for Dark Photons / 1

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

- Search for dark photons decaying into **a pair of muons**
- Used **1.6 fb^{-1}** of 2016 LHCb data (13 TeV)
- Kinetic mixing of the dark photon (A′) with **off-shell photon** (γ^*) by a factor ε:
  - A′ inherits the production mode mechanisms from γ^*
  - A′ → $\mu^+\mu^-$ can be **normalised** to $\gamma^* \to \mu^+\mu^-$
  - No use of MC → no systematics from MC → fully **data-driven** analysis
- Separate γ^* signal from background and measure its fraction
- Prompt-like search (up to 70 GeV/c^2) → displaced search (214-350 MeV/c^2)
  - A′ is long-lived only if the mixing factor is really small



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

off-shell photon

phase-space

A′/γ^* eff ratio, ϵ=1 for prompt

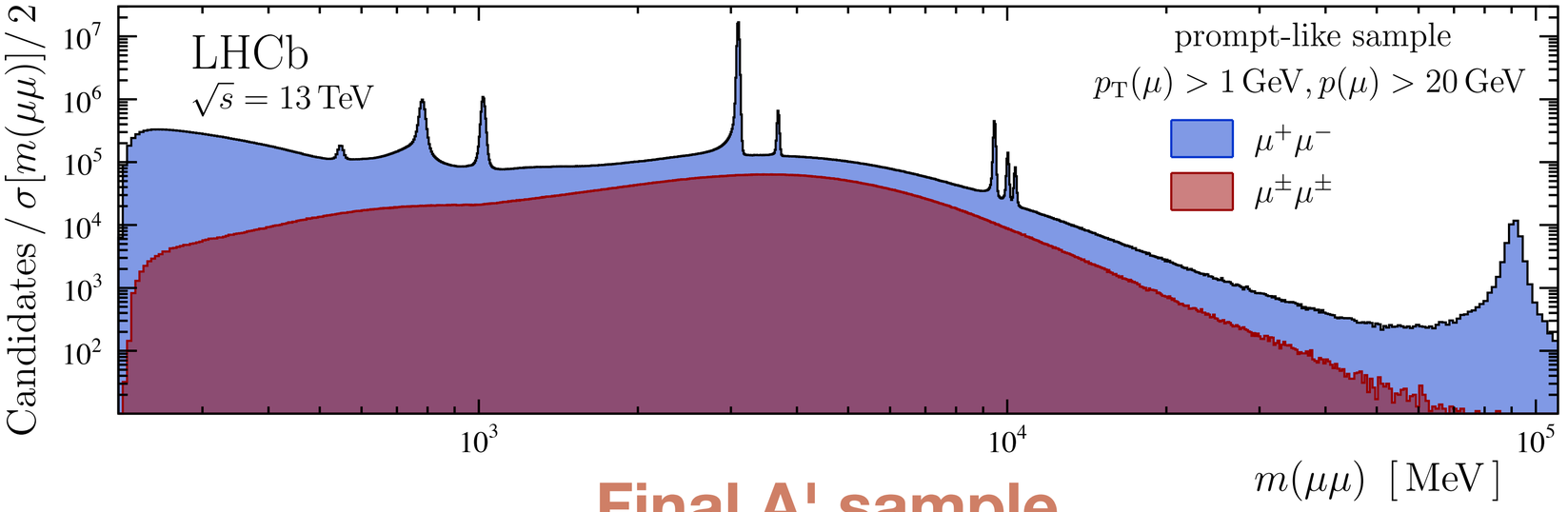
Need to separate from background

Searching for Dark Photons / 2

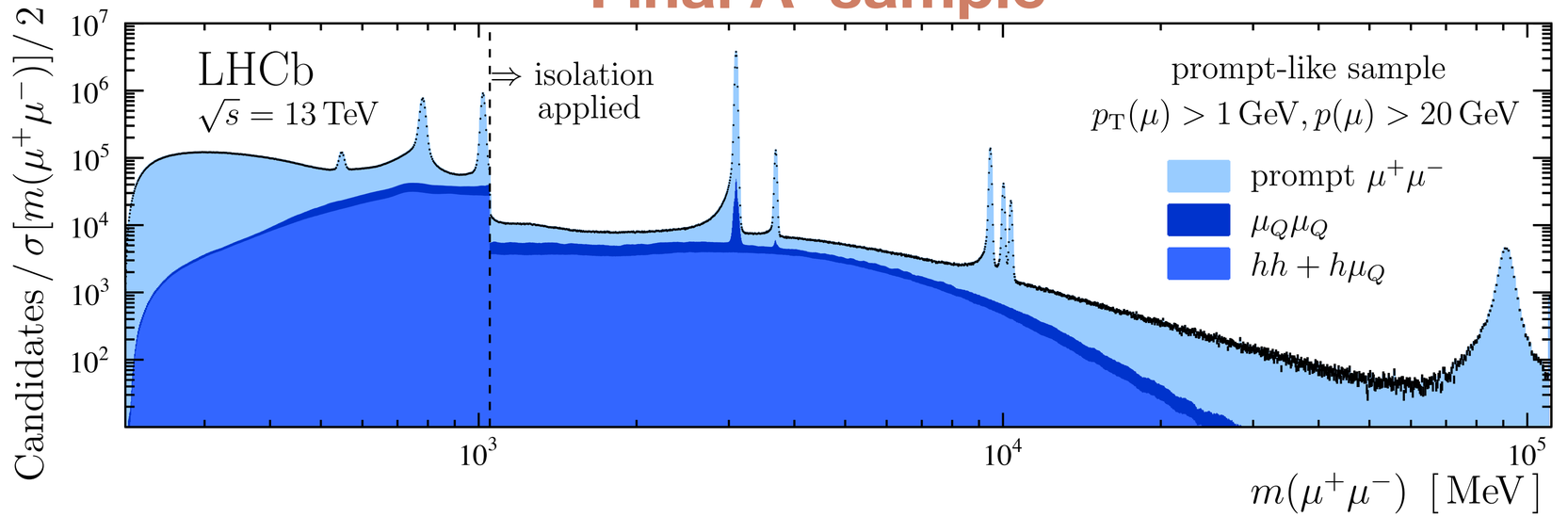
Phys. Rev. Lett. 120, 061801 (2018)

- Suppressing misidentified (non-muon) backgrounds and reducing the event size enough to record the **prompt-dimuon sample**
- Accomplished these by moving to **real-time calibration** in Run 2
- Hardware trigger is still there, and only ~10% efficient at low pT

Trigger output



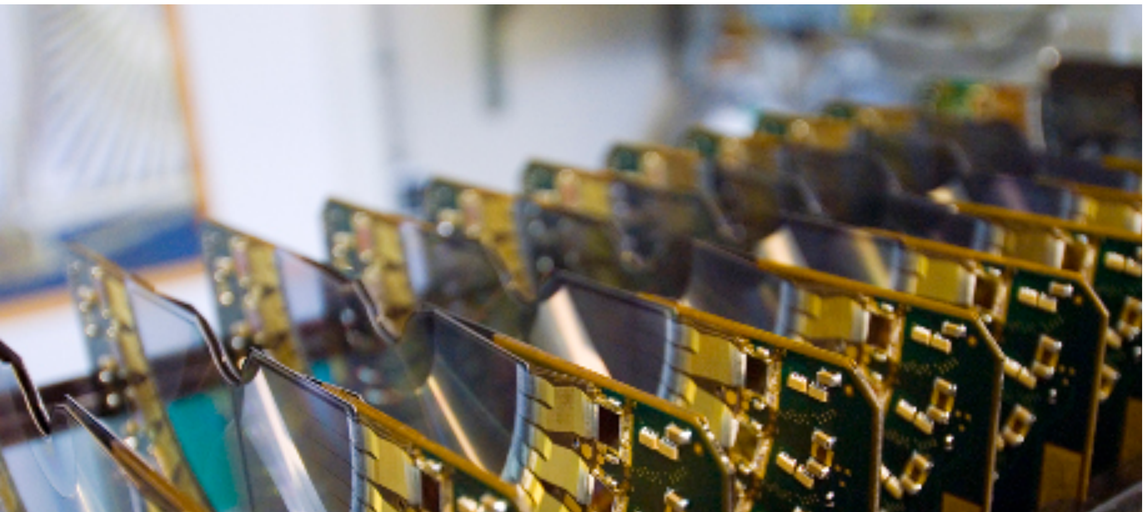
Final A' sample

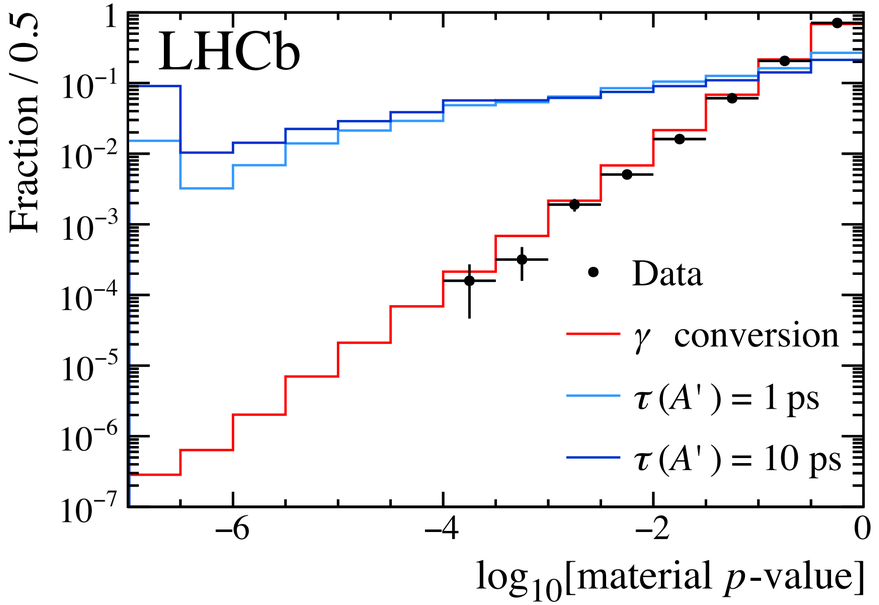


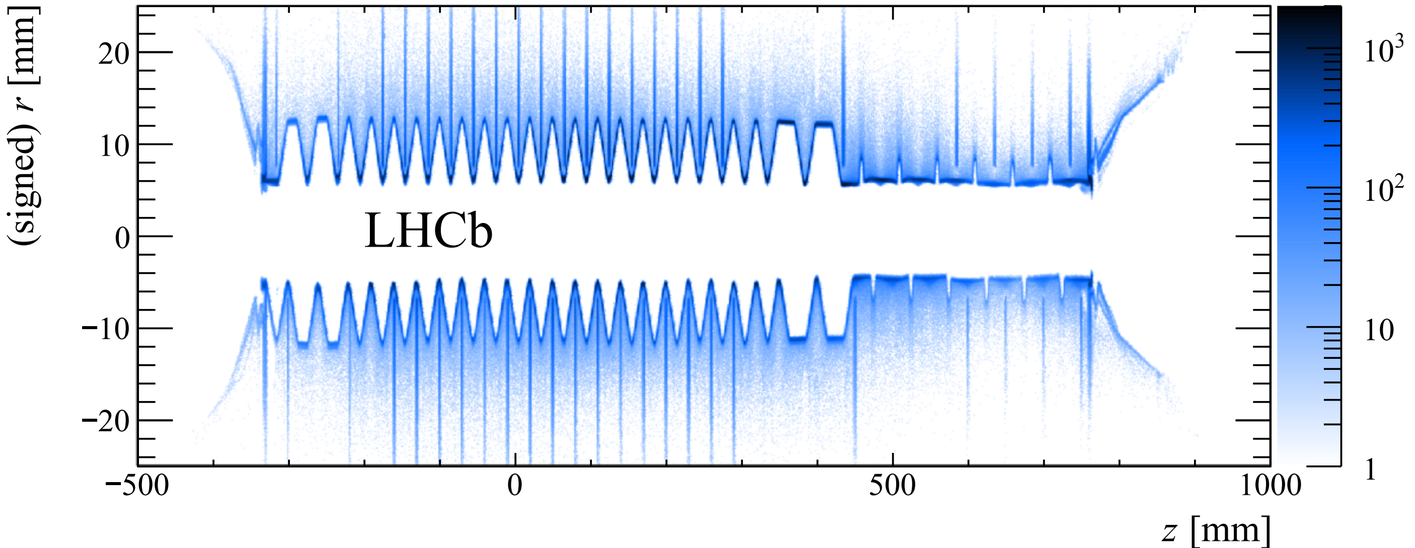
Searching for Dark Photons / 3

JINST 13, P06008 (2018)

- Background dominated by **material interactions** for displaced searches at LHCb
- Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles
- LHCb data calibration process can align active sensor elements, an **alternative approach** is required to fully map the VELO material



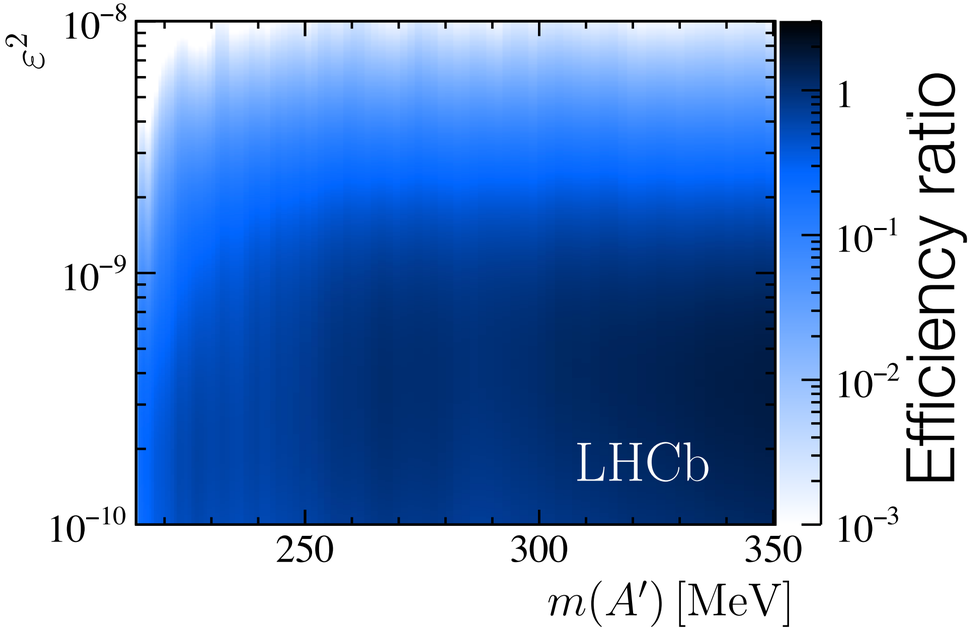


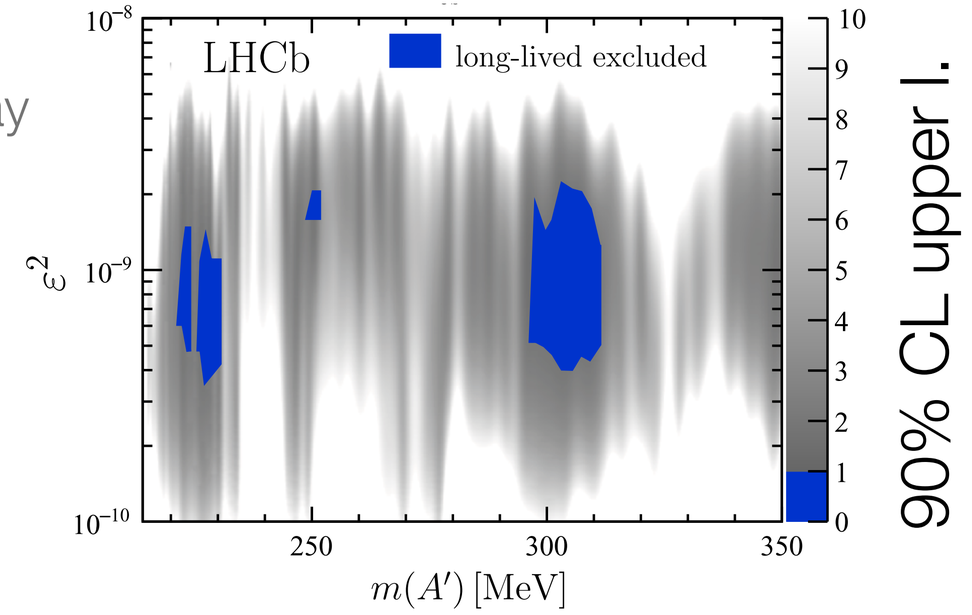


Phys. Rev. Lett. 120, 061801 (2018)

Search for Dark Photons / Displaced

- (**Prompt**: no excess is measured)
- **Looser requirements** on muon transverse momentum
- **Material background** mainly from photon conversions
- Isolation decision tree from $B^0_s \to \mu^+\mu^-$ search
  - Suppress events with additional number of tracks, i.e. μ from b-hadron decays
- 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**

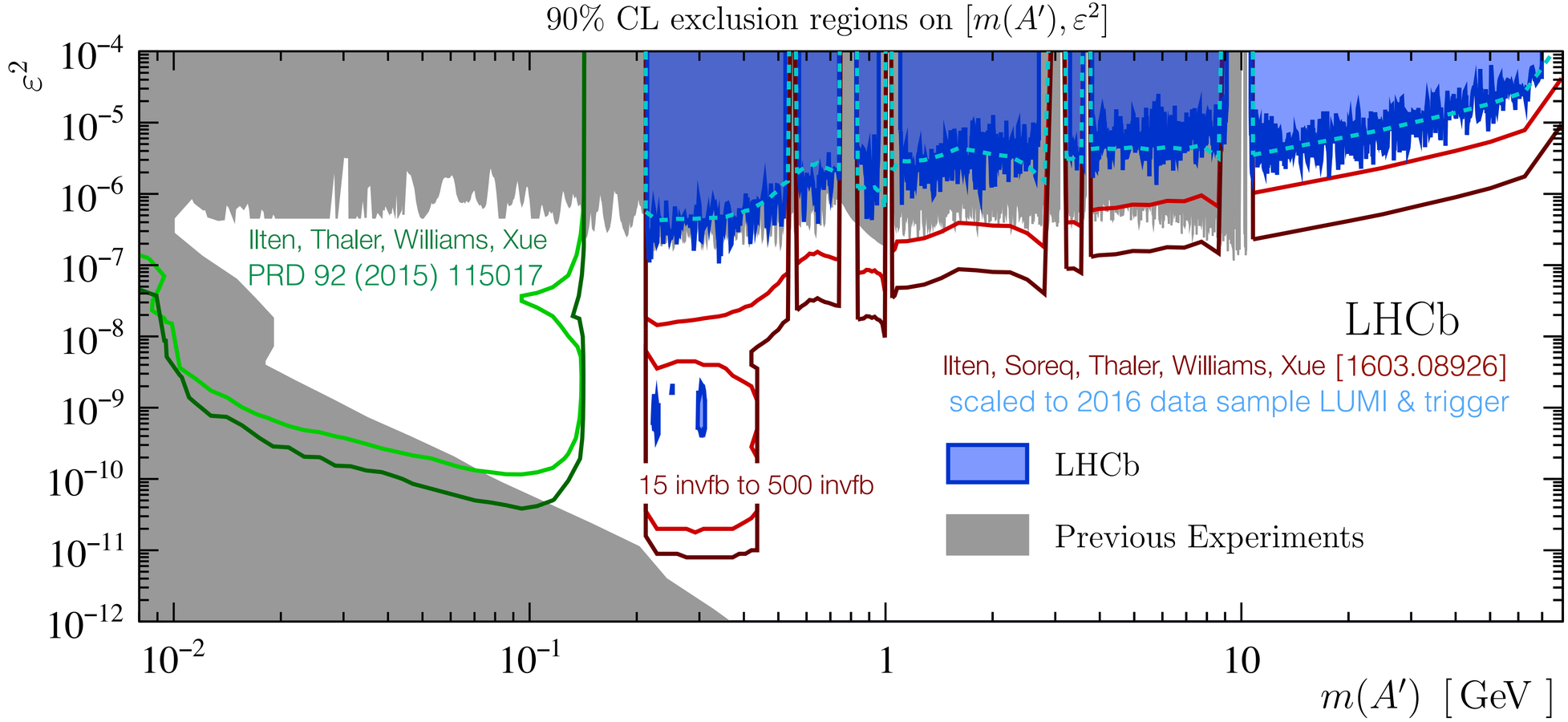




Search for Dark Photons / Results

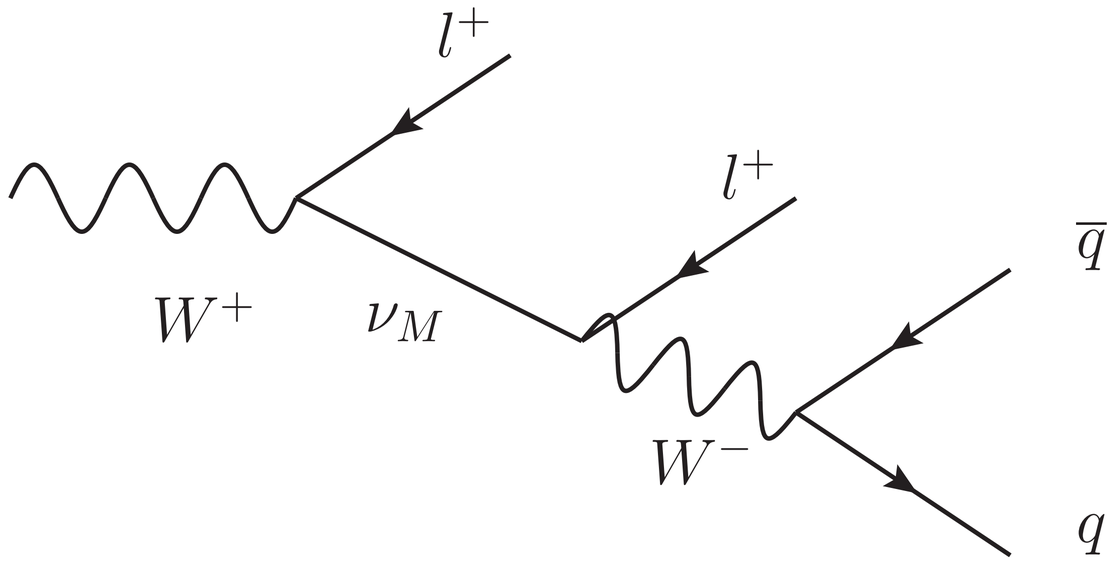
Phys. Rev. Lett. 120, 061801 (2018)

- The 2016 dimuon results are consistent with (better than) predictions for prompt (long-lived) dark photons as discussed in [1603.08926]. We implemented huge improvements in the 2017 triggers for low masses, so plan quick turn around on updated dimuon search - then onto electrons.



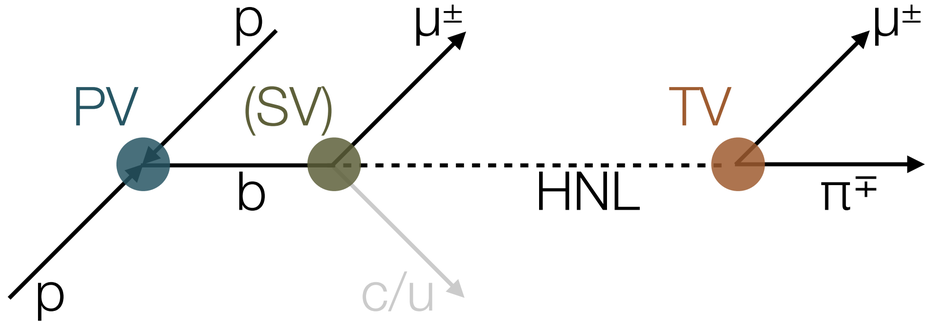
Off-shell Majorana neutrinos at LHCb / 1

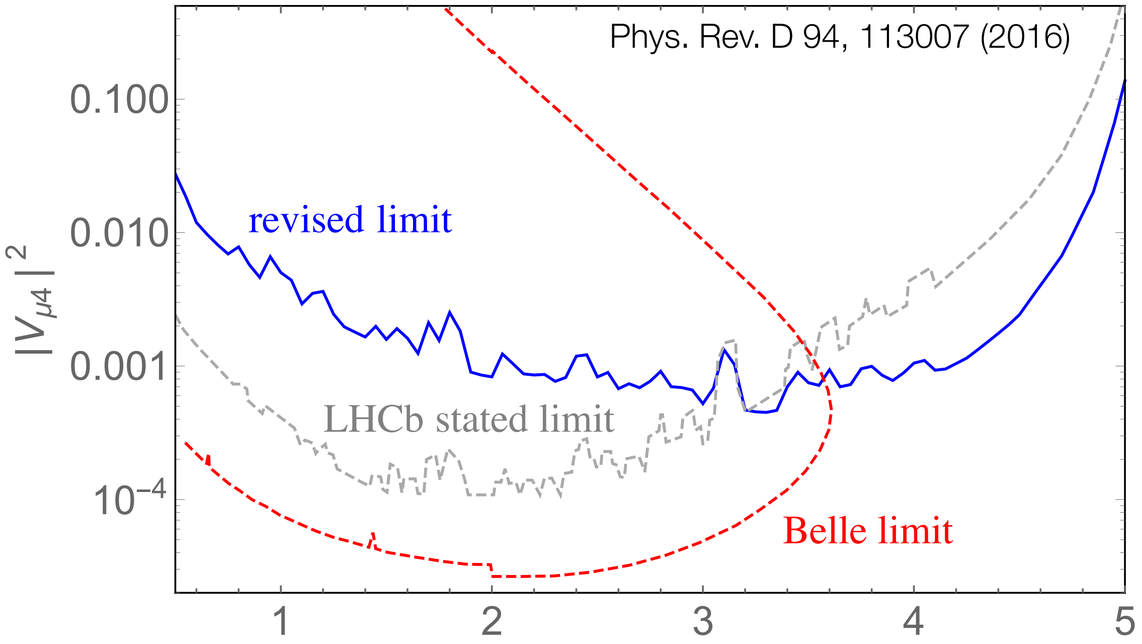
- Searches for the decays of heavy mesons to final states with **two same sign leptons**
- Complementary to other searches, such as in neutrino-less double β decay (only coupling to e^-)
- LHCb searches (will) constrain models like the type-I seesaw model with **three right-handed neutrinos (**e.g. HNL of Shaposhnikov et al.)
- Very stringent limits are possible for rare **B** and **D** decays
- Particularly true for **off-shell** Majorana neutrinos
  - Phys.Rev.Lett. 112 (2014) 131802:
    h = π, with 3.0 fb–1 (7 TeV and 8 TeV)
  - Phys.Rev. D85 (2012) 112004:
    h = D, D∗, Ds and D0π, with ~40 pb–1 (7 TeV)
  - Phys.Rev.Lett. 108 (2012) 101601:
    h = K or π, with ~36 pb–1 (7 TeV)

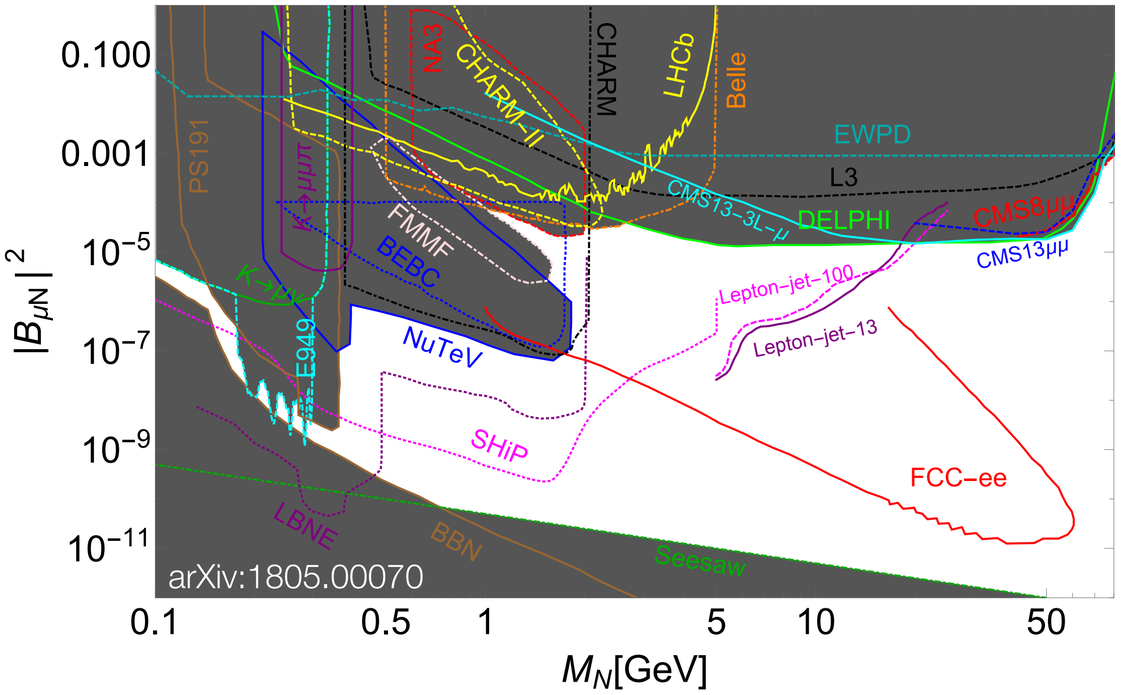


Off-shell Majorana neutrinos at LHCb / 2

- Theoretical interpretation is **extremely** challenging
- LHCb and Belle limits **revised** in:
  Phys. Rev. D94, 113007 (2016)
  Phys. Rev. D95, 099903 (2017)
- Analysis of inclusive production of Majorana neutrinos is **completed** on Run 1 and ongoing on Run 2
- Possibility to explore further (mixing with e^-, opposite sign muons…)



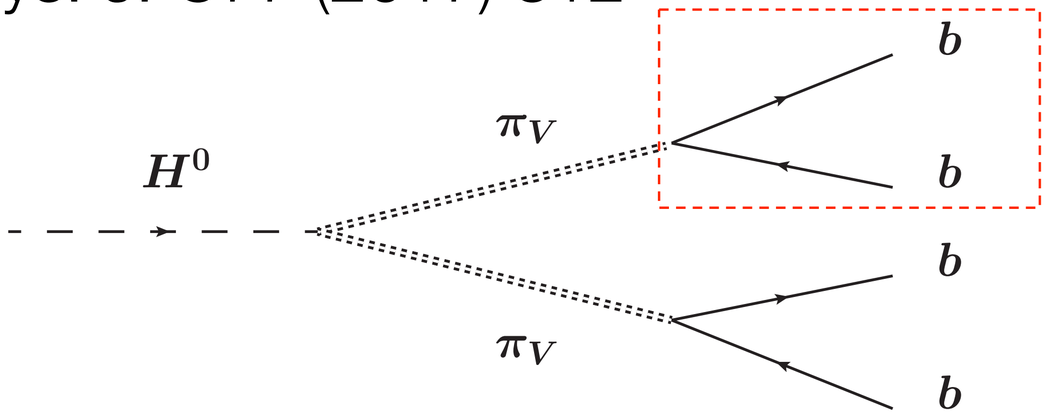


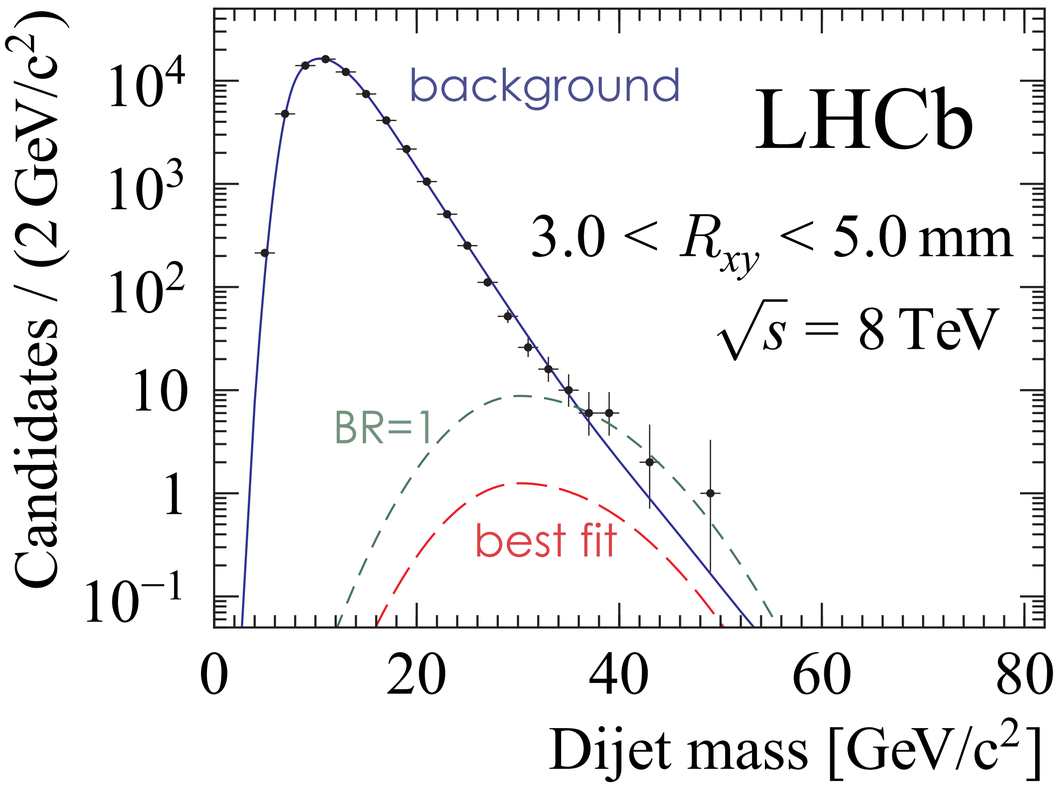


Eur. Phys. J. C77 (2017) 812

Massive LLP decaying to jet pairs / 1

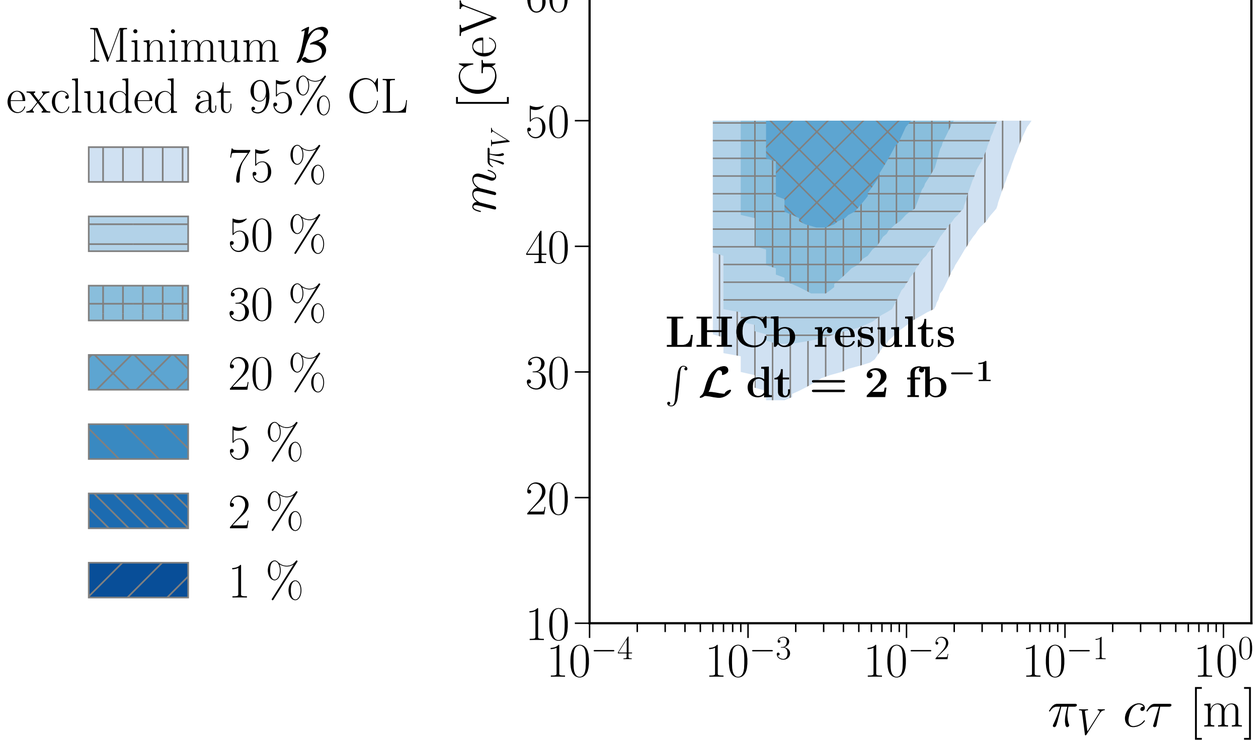
- Search for LLP, SM Higgs boson acts as a portal, hidden-valley pion (π_V)
- Experimental signature is a **single** displaced vertex with **two** associated jets, trigger on displaced vertex
- Uses 2 invfb of 7 and 8 TeV data
- Quality requirement on jets and di-jet pointing
- **Material veto** + selection optimised as a function of t**ransverse distance from beam axis** (R_{xy})
- Search uses **6 bins** of R_{xy}

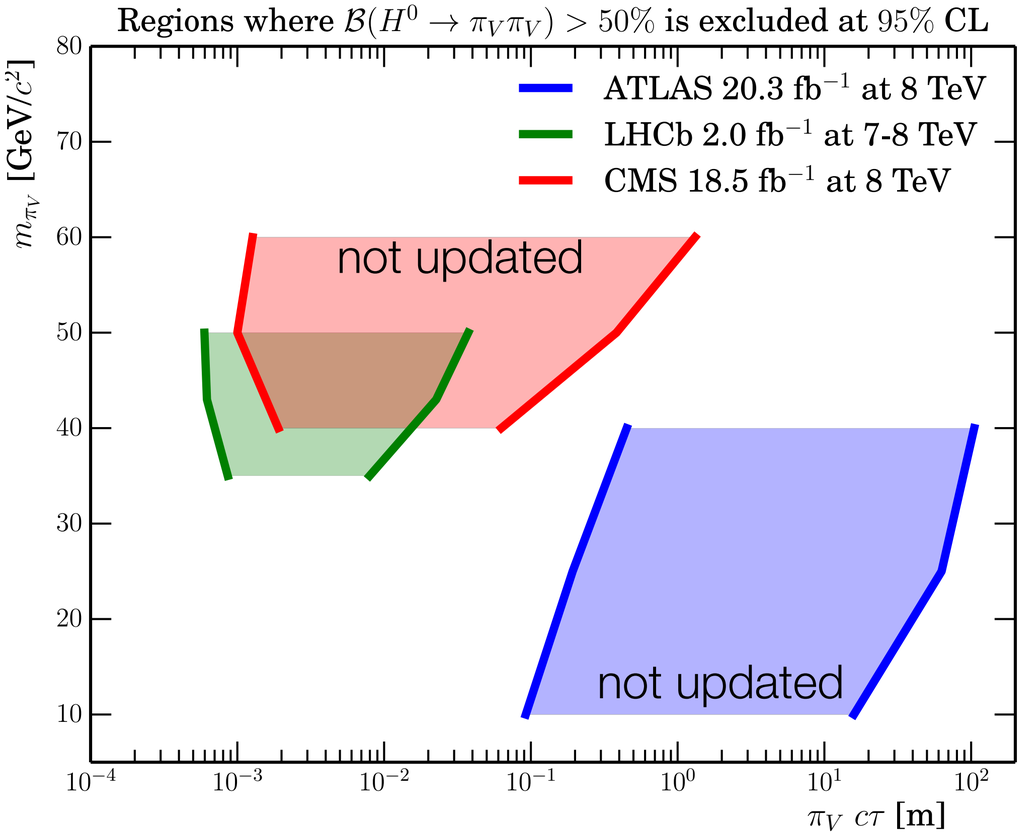




Massive LLP decaying to jet pairs / 2

- Published on Run 1; Done for Run 2; Prospect for Run 3 published soon





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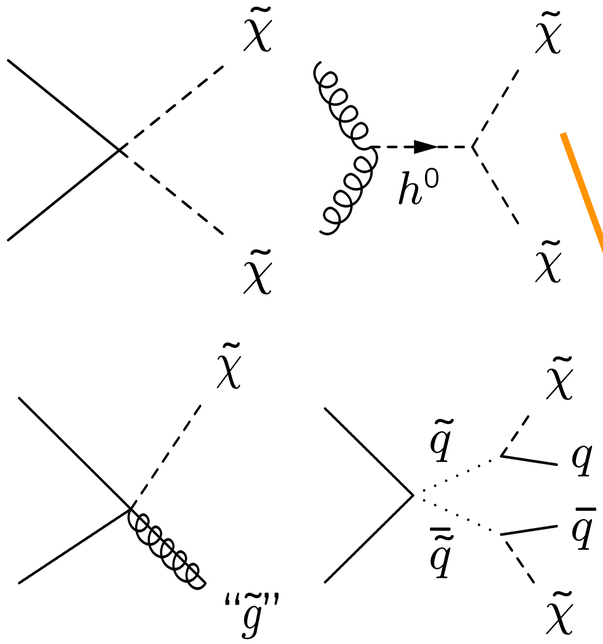
LLP Decaying Semileptonically

- Massive LLP into μ and quark pair (to jets pair)
- Uses full Run 1 dataset mass in range 20-80 GeV/c2. Lifetime in range 5-100 ps
- Background dominated by combinatorial strong MVA and tight selection
- Several models:
  mSUGRA RPV neutralino, Majorana neutrino, simplified topologies
- No excess is observed, rejecting BR(H→χχ)>10% down to m_χ=40 GeV, τ_χ=100 ps



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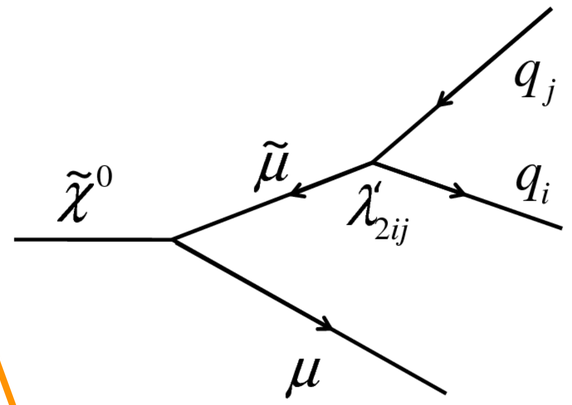
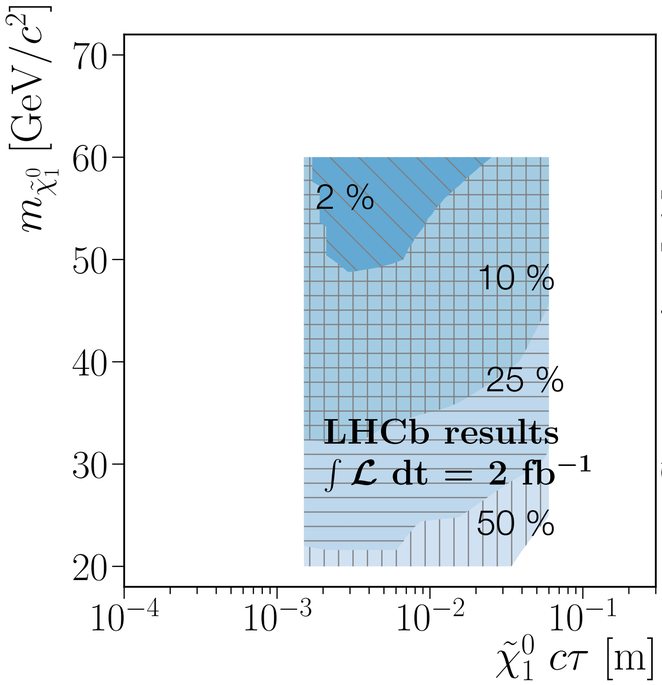
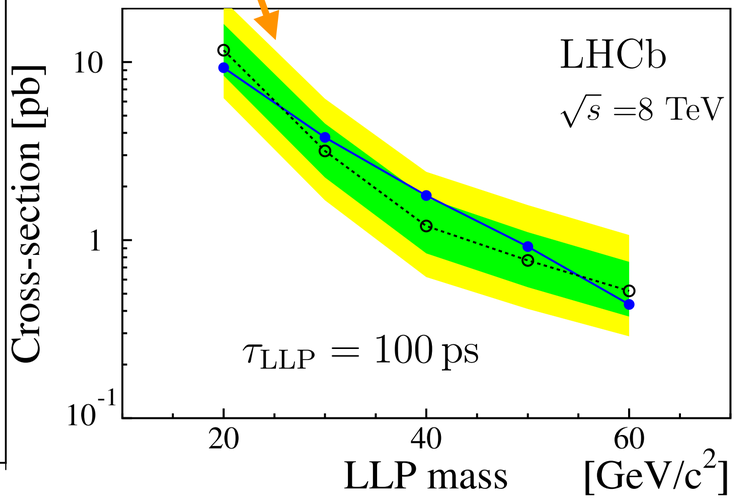






Conclusions

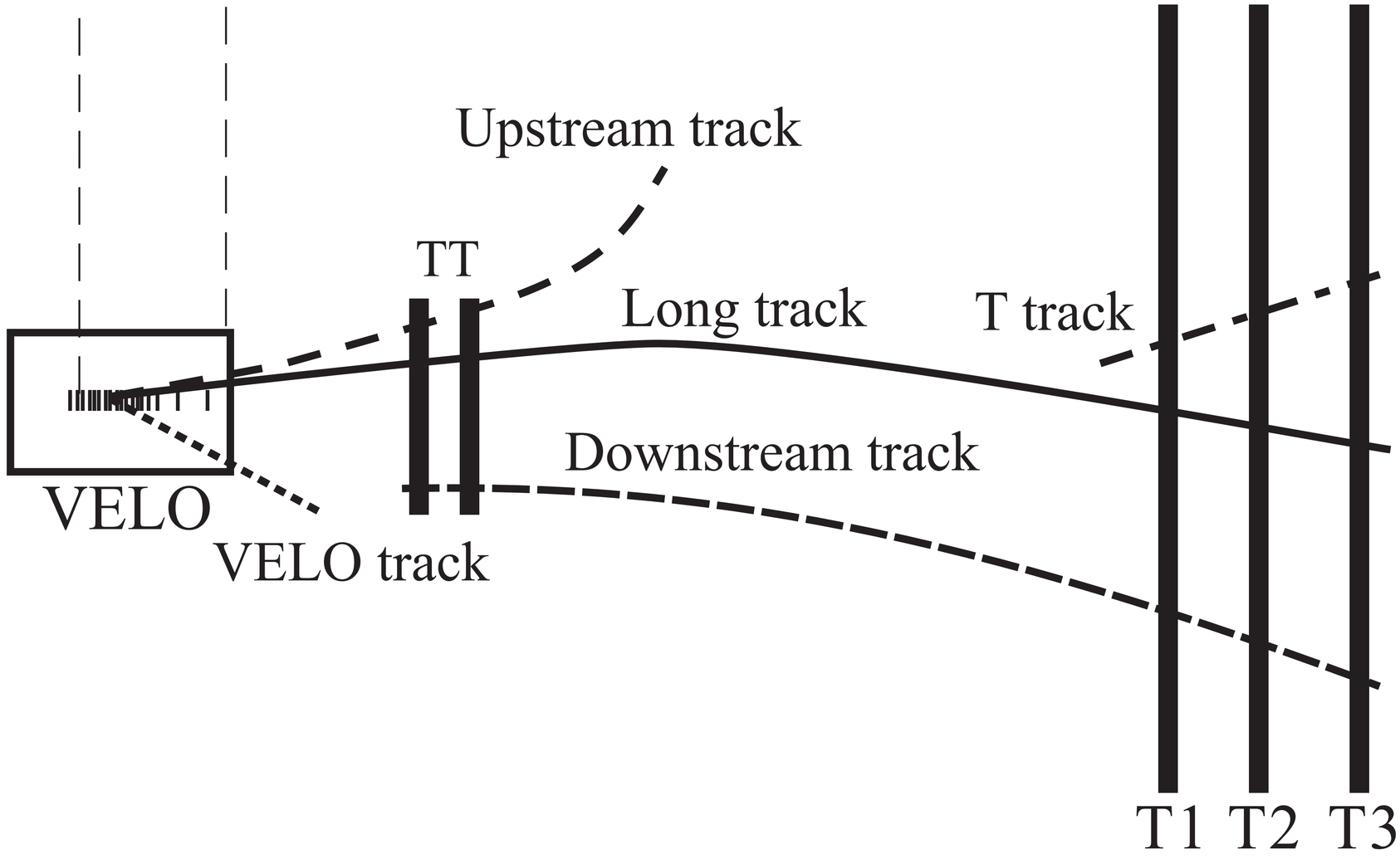
- LHCb has an **extensive program** of searches even beyond flavour physics
  - Searches for **on-shell** new physics from heavy flavour decays
  - Searches for **long-lived** particles with low mass and short lifetime
  - Searches for **dimuon resonances** in very broad parameter space
- Bright future ahead:
  - 3 fb-1 in Run 1, 6 fb-1 in Run 2 (with larger cross-sections)
  - A lot of potential in the upgraded trigger (also 5× luminosity)

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
LS2		**RUN III**			LS3			**RUN IV**			LS4		**RUN V**	
LHCb 40 MHz Upgrade Phase I		L = 2e33			LHCb Consolidation			L = 2e33; 50 invfb			LHCb Upgrade Phase II (proposed)		L = 2e34; 300 invfb (proposed)	

Thanks

Federico Leo Redi

LCHb track types



Search for Dark Photons / Prompt

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

- No significant excess found - exclusion regions at 90% C.L.
- First limits on masses above 10 GeV & competitive limits below 0.5 GeV