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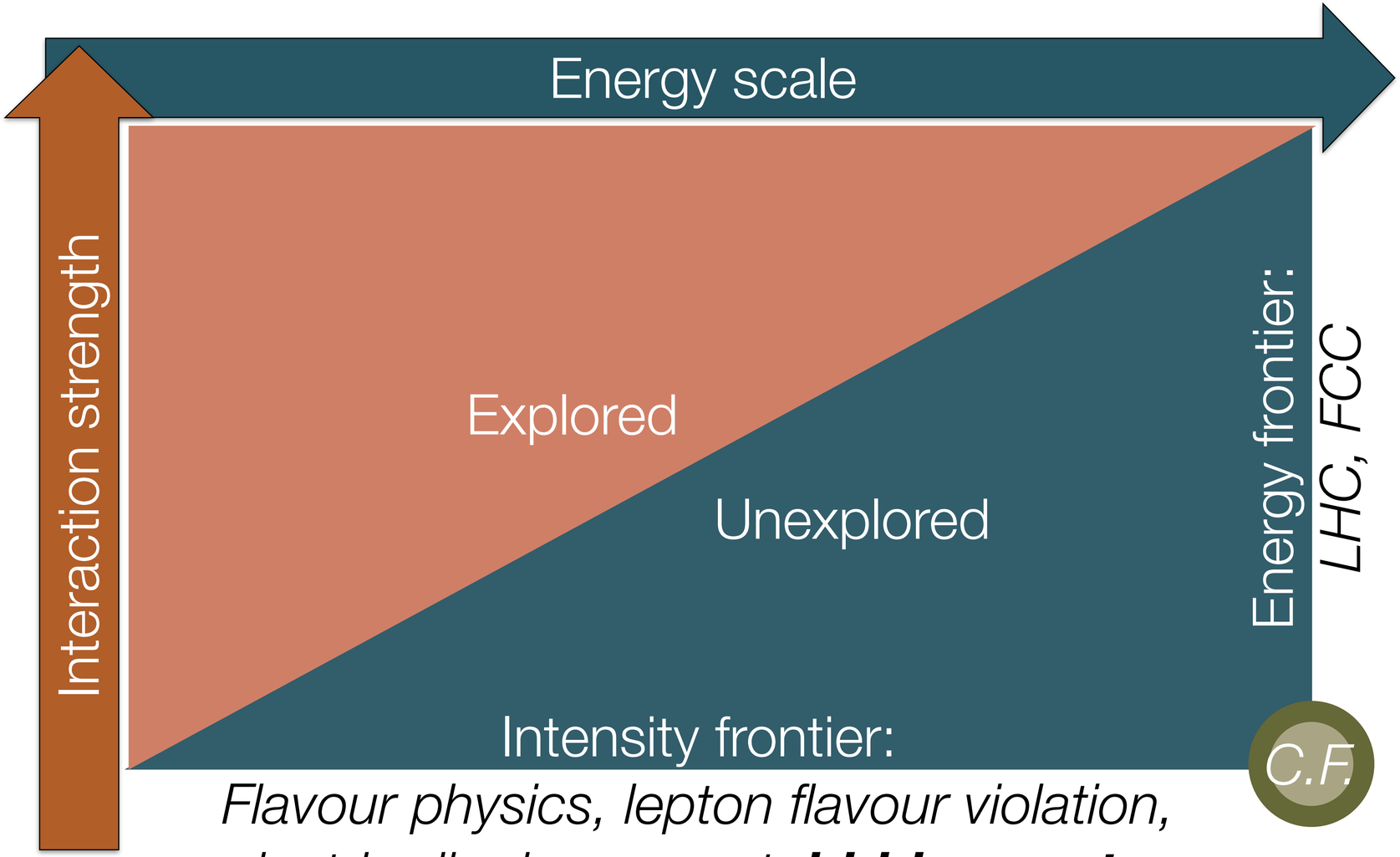
YETI2020 - Durham

Searching for Dark Photons with LHCb

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



Flavour physics, lepton flavour violation, electric dipole moment, ***hidden sector***

Landscape today

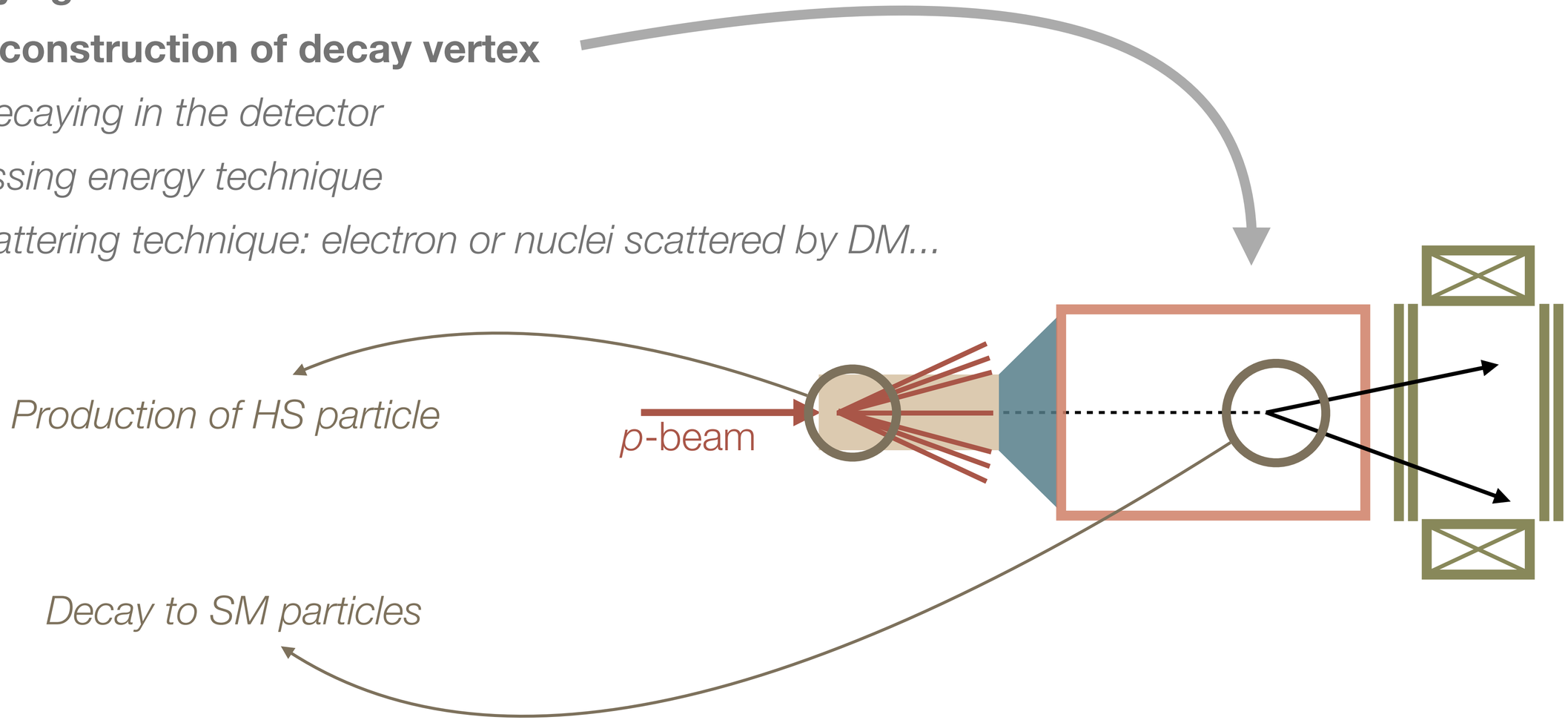
- The Intensity frontier is a **broad** and **diverse**, yet **connected**, set of science opportunities
  - Light Dark Matter (**LDM**)
    Portals to Hidden Sector (**HS**) (the photon, Higgs, and neutrino portals)
    Axion Like Particles (**ALP**)
    Heavy Neutral Leptons (**HNL**) (extension of SM)
- In this talk, I will concentrate on Hidden Sector particles, specifically **Dark Photons** 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: $\boldsymbol{L = L_{SM} + L_{mediator} + L_{HS}}$
  - 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 technique*
    - *Scattering technique: electron or nuclei scattered by DM...*
  - ***Decaying in the detector***
    - *Reconstruction of decay vertex*

Exploring the dark sector / 2

- **Decaying in the detector**
  - **Reconstruction of decay vertex**
- *Not decaying in the detector*
  - *Missing energy technique*
  - *Scattering technique: electron or nuclei scattered by DM...*



Exploring the dark sector / 3

- *Decaying in the detector*
  - *Reconstruction of decay vertex*
- **Not decaying in the detector**
  - **Missing energy technique**
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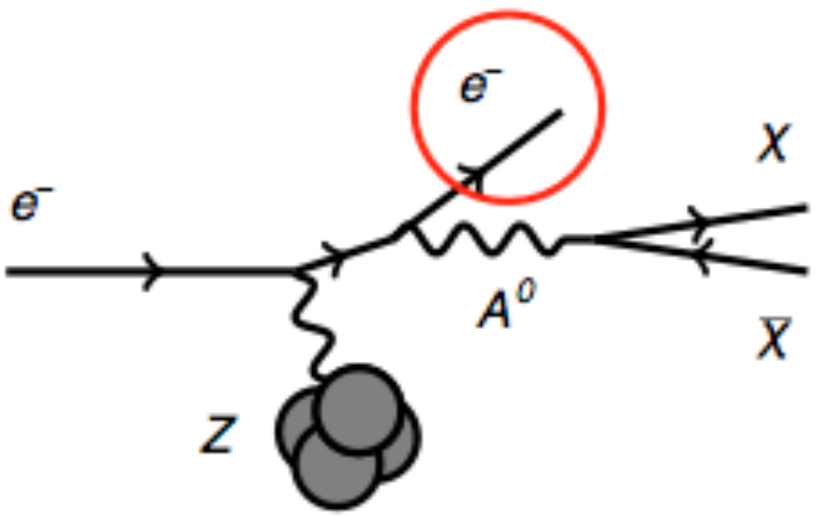
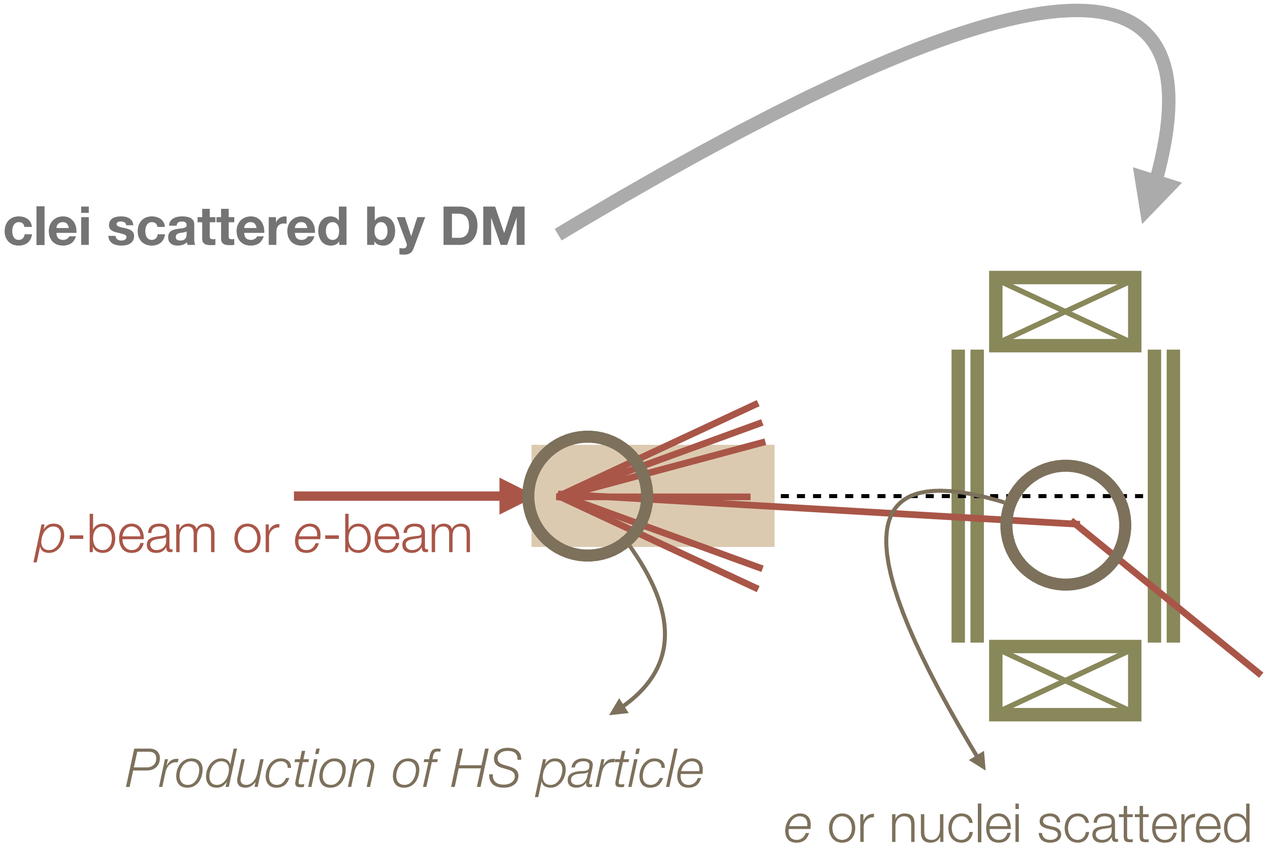
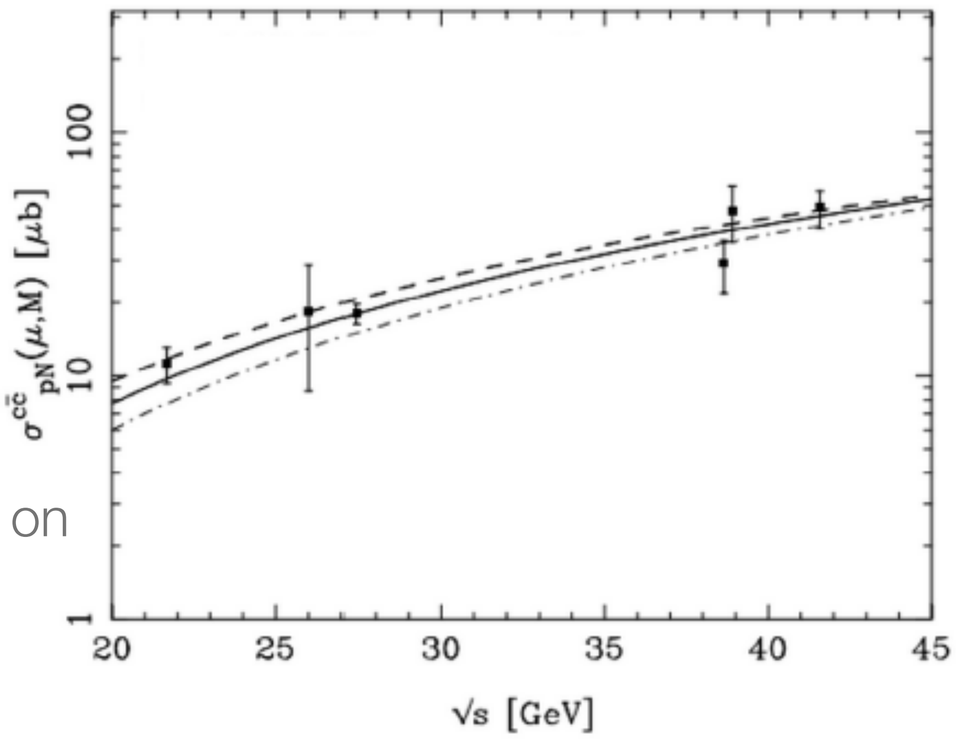




Decaying dark sector candidates / 1



- **Experimental requirements**:
  - Particle beam with maximal intensity
  - Search for HS particles in Heavy Flavour decays
    - Charm (and beauty) cross-sections strongly dependent on the beam energy.
    - At CERN SPS:
      $\sigma(pp \rightarrow ssbar\ X)/\sigma(pp \rightarrow X) \sim 0.15$
      $\sigma(pp \rightarrow ccbar\ X)/\sigma(pp \rightarrow X) \sim 2.0 \times 10^{-3}$
      $\sigma(pp \rightarrow bbbar\ X)/\sigma(pp \rightarrow X) \sim 1.6 \times 10^{-7}$
- HS produced in charm and beauty decays have **significant p_T**
- *Detector must be placed close to the target to maximise geometrical acceptance. Effective (and "short") muon shield is the key element to reduce muon-induced backgrounds*
- *Long decay volume and large geometrical acceptance of the spectrometer are essential to maximise detection efficiency...*

Decaying dark sector candidates / 2

- Detector must be placed **close to the target** to maximise geometrical acceptance. Effective (and “short”) **muon shield** is the **key element** to reduce muon-induced backgrounds
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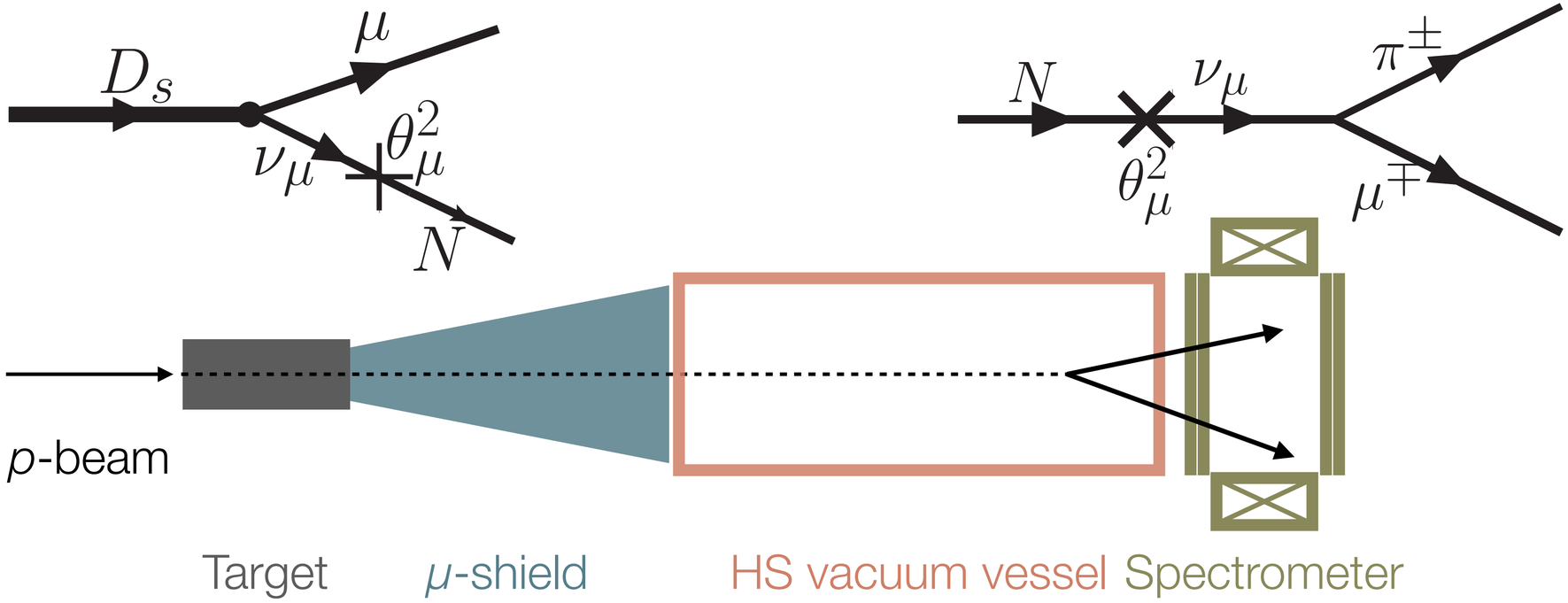
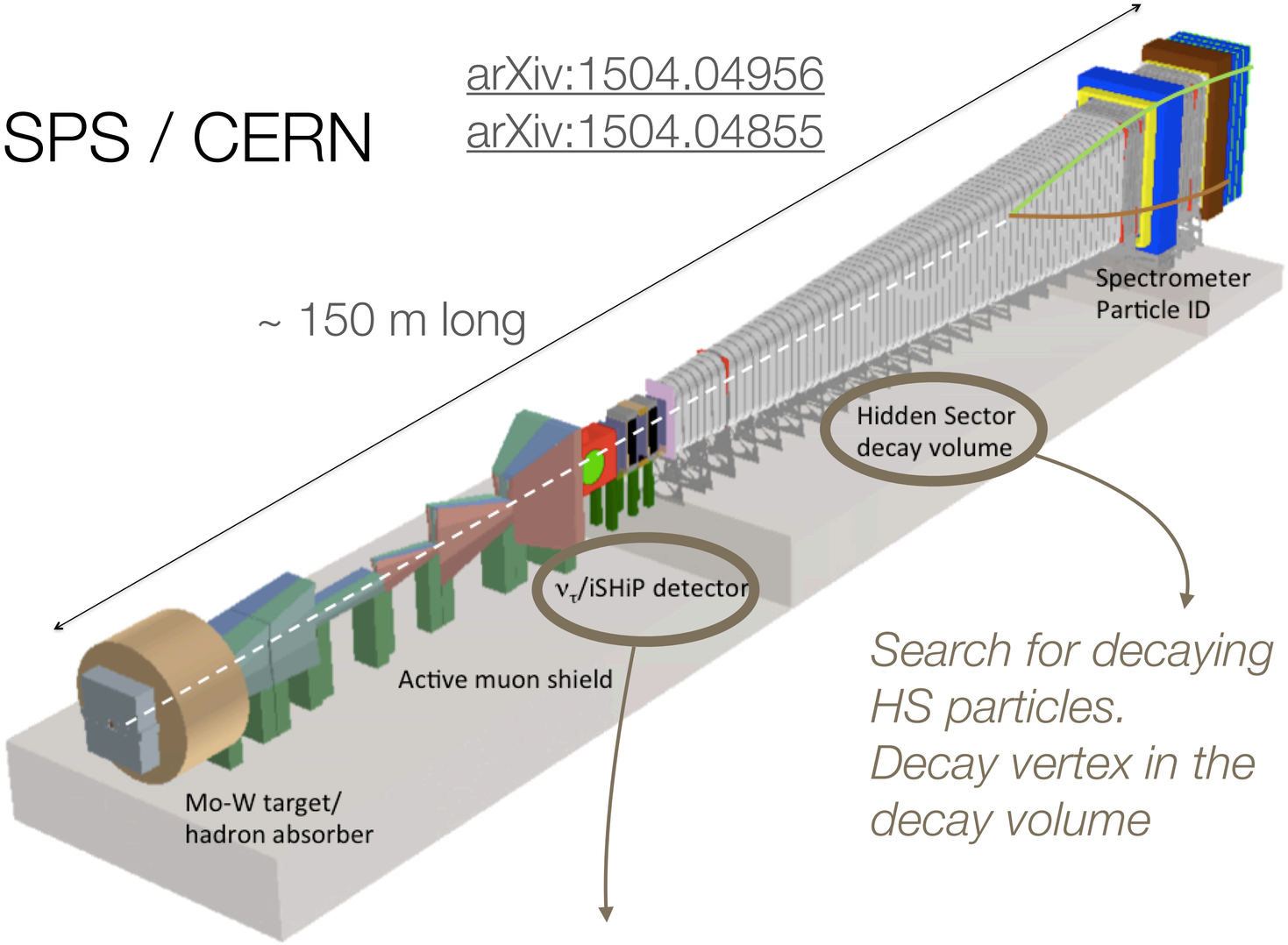


SHiP Beam Dump Facility at SPS / CERN

arXiv:1504.04956
arXiv:1504.04855

- Numbers:
  $>10^{18}$ D,
  $>10^{16}$ τ,
  $>10^{20}$ γ
  for **2×10^{20} pot (in 5 years)**
- "***Zero background***" experiment
  Heavy target
  Muon shield
  Surrounding Veto detectors
  Timing and PID detectors, etc.
- Multipurpose layout: near and far detector (**new**)

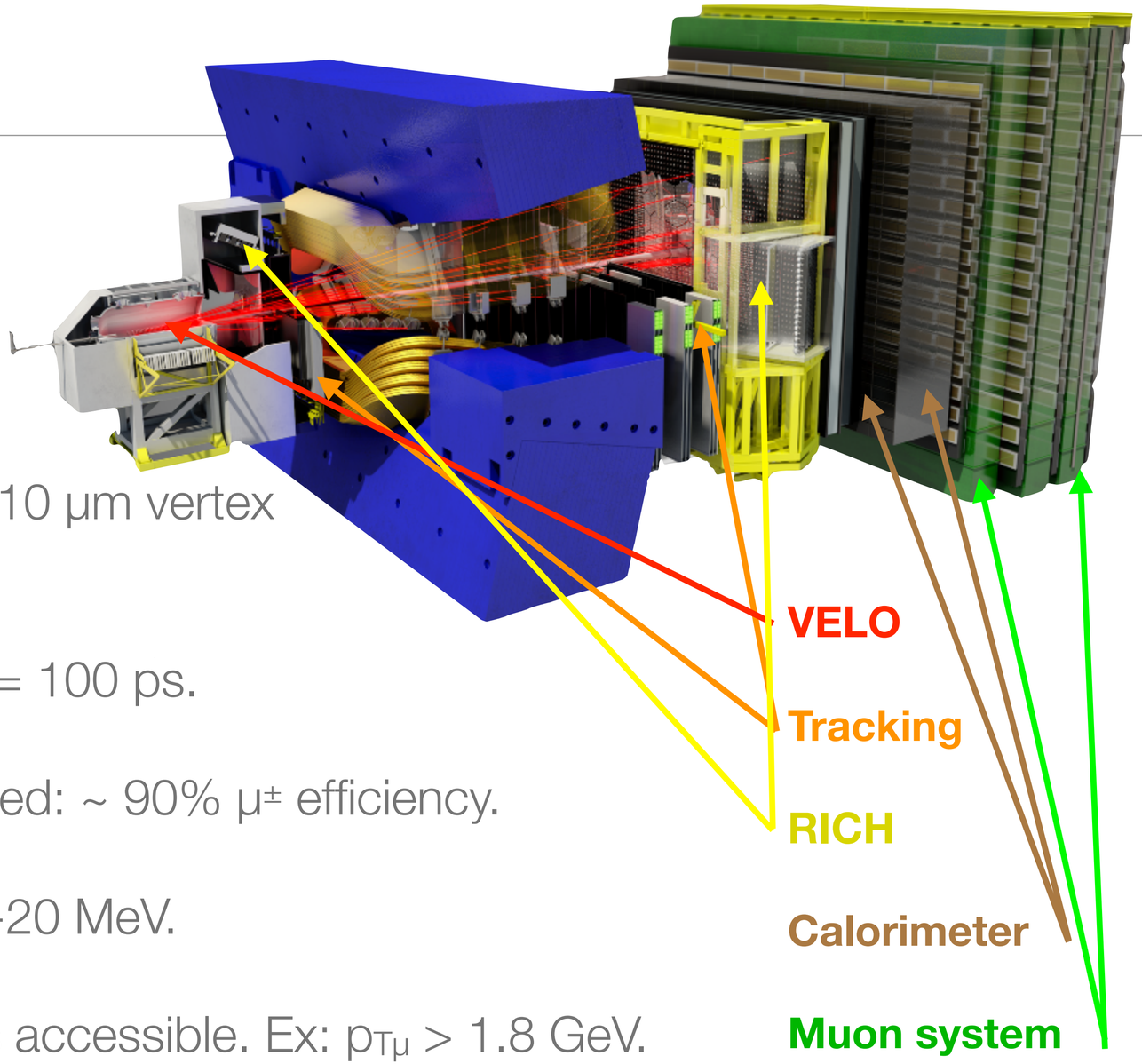


Search for decaying HS particles. Decay vertex in the decay volume

Search for HS (scattering on atoms) and ν physics. Specific event topology in emulsion. Background reducible to a manageable level

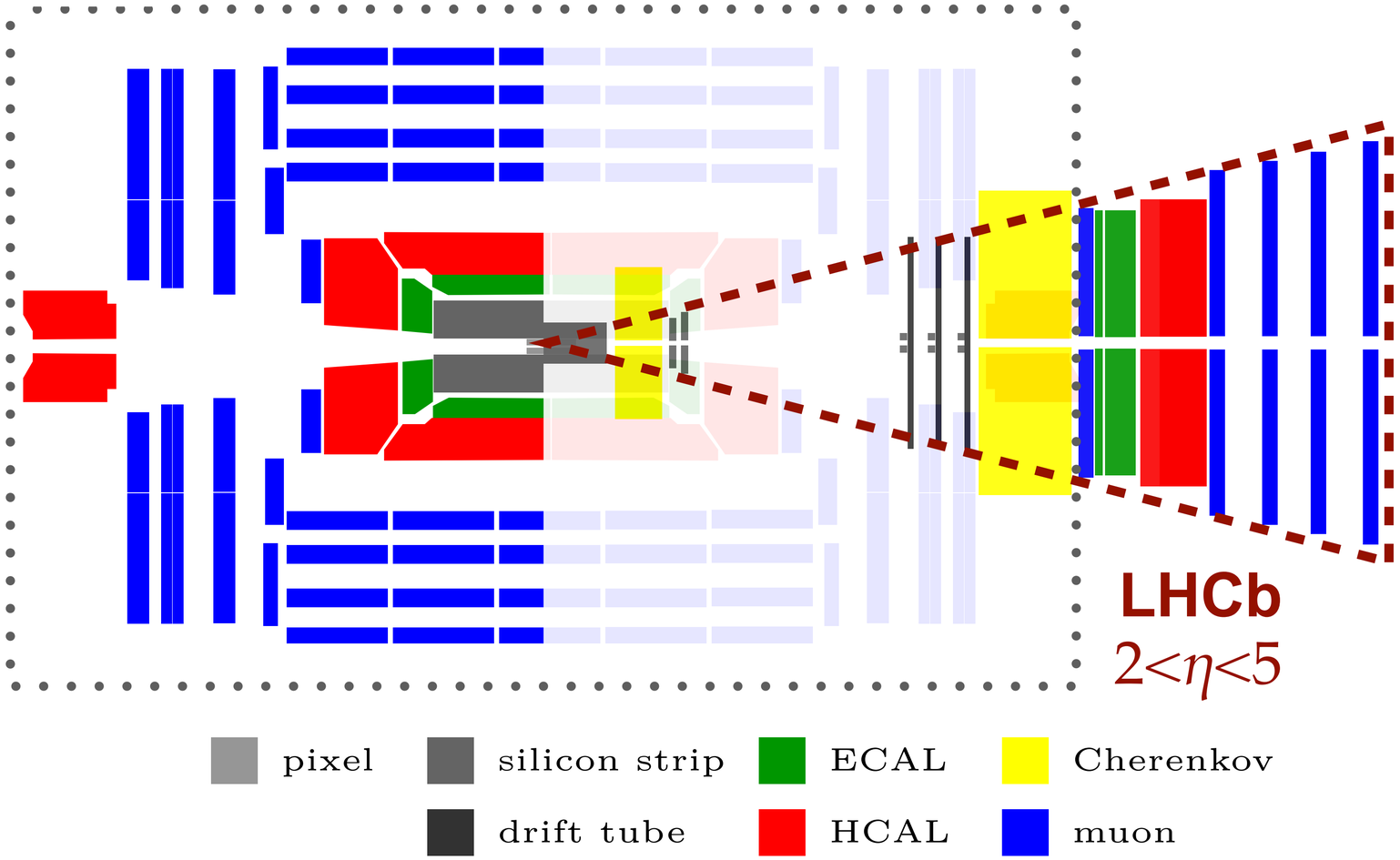
The LHCb detector / 1

- **LHCb** is a dedicated flavour experiment in the **forward region** at the LHC ($1.9 < \eta < 4.9$) (~1°-15°)
- **Precise vertex reconstruction** < 10 μm vertex resolution in transverse plane.
- Lifetime resolution of ~ 0.2 ps for τ = 100 ps.
- **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: $p_{T\mu} > 1.8$ GeV.



The LHCb detector / 1bis

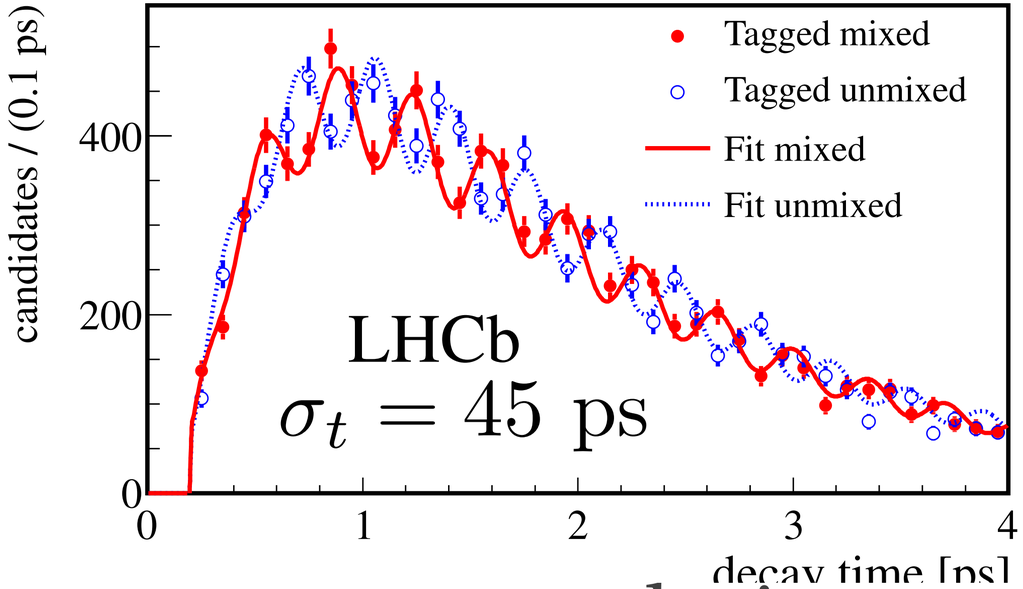
Int.J.Mod.Phys. A 30, 1530022 (2015)



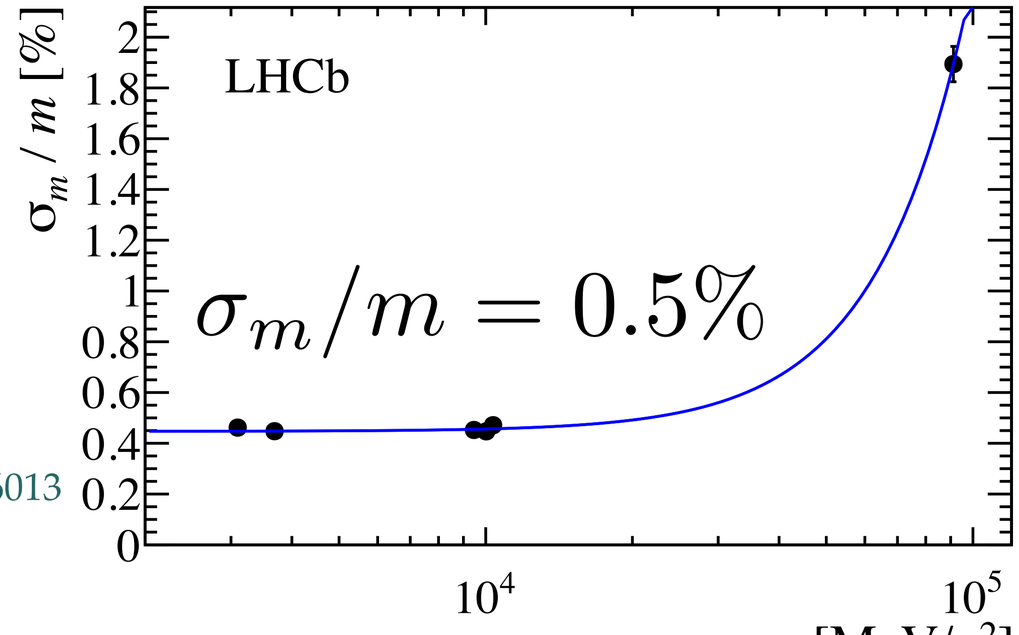
The LHCb detector / 2

- **Capable of soft trigger:**
- In hardware: $p_{T\mu} > 1.8$ GeV and for electrons and hadrons: $p_T > 3\text{-}4$ GeV
- Real time analysis is possible with off-line quality alignment
- Turbo stream only keeps interesting part of the event

vertex reconstruction



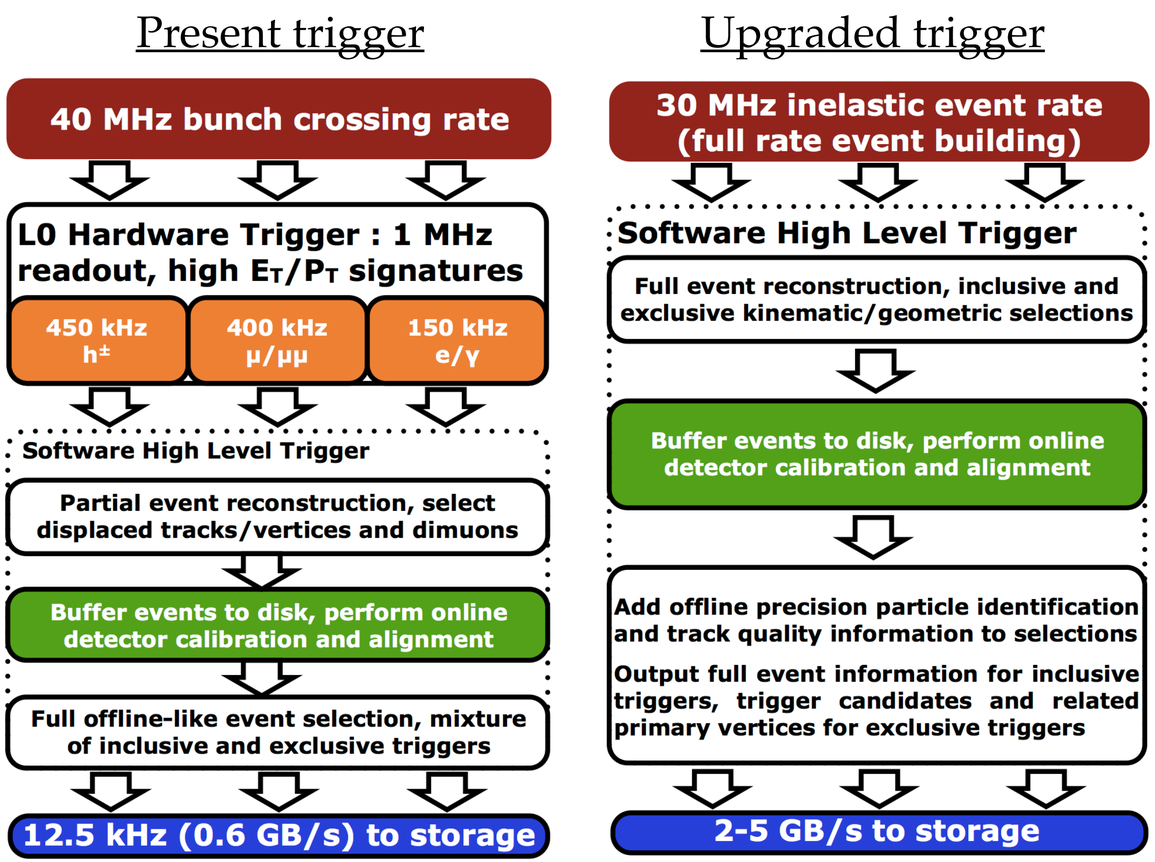
mass resolution



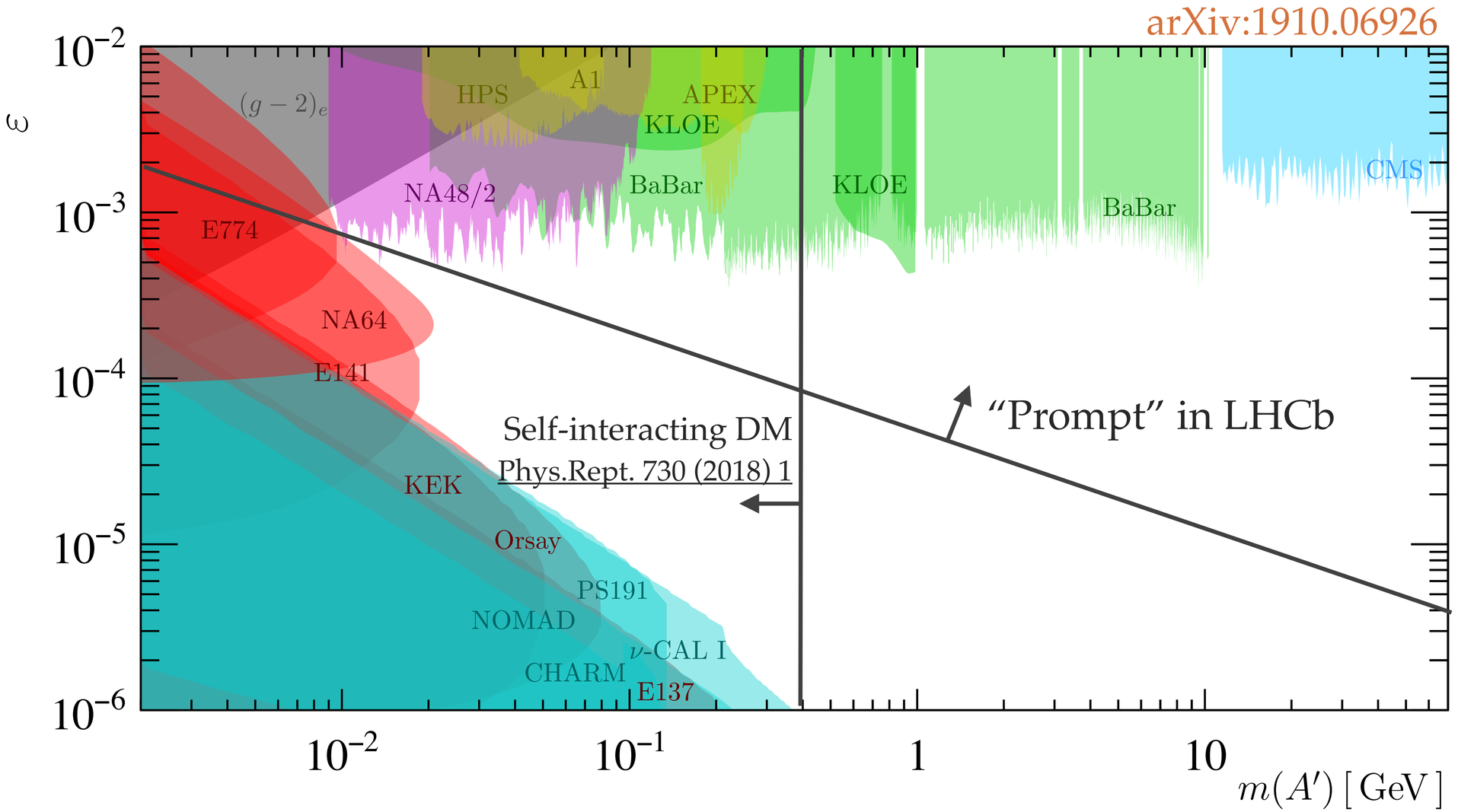
LHCb, JINST 10 (2015) P06013

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



The state of the art

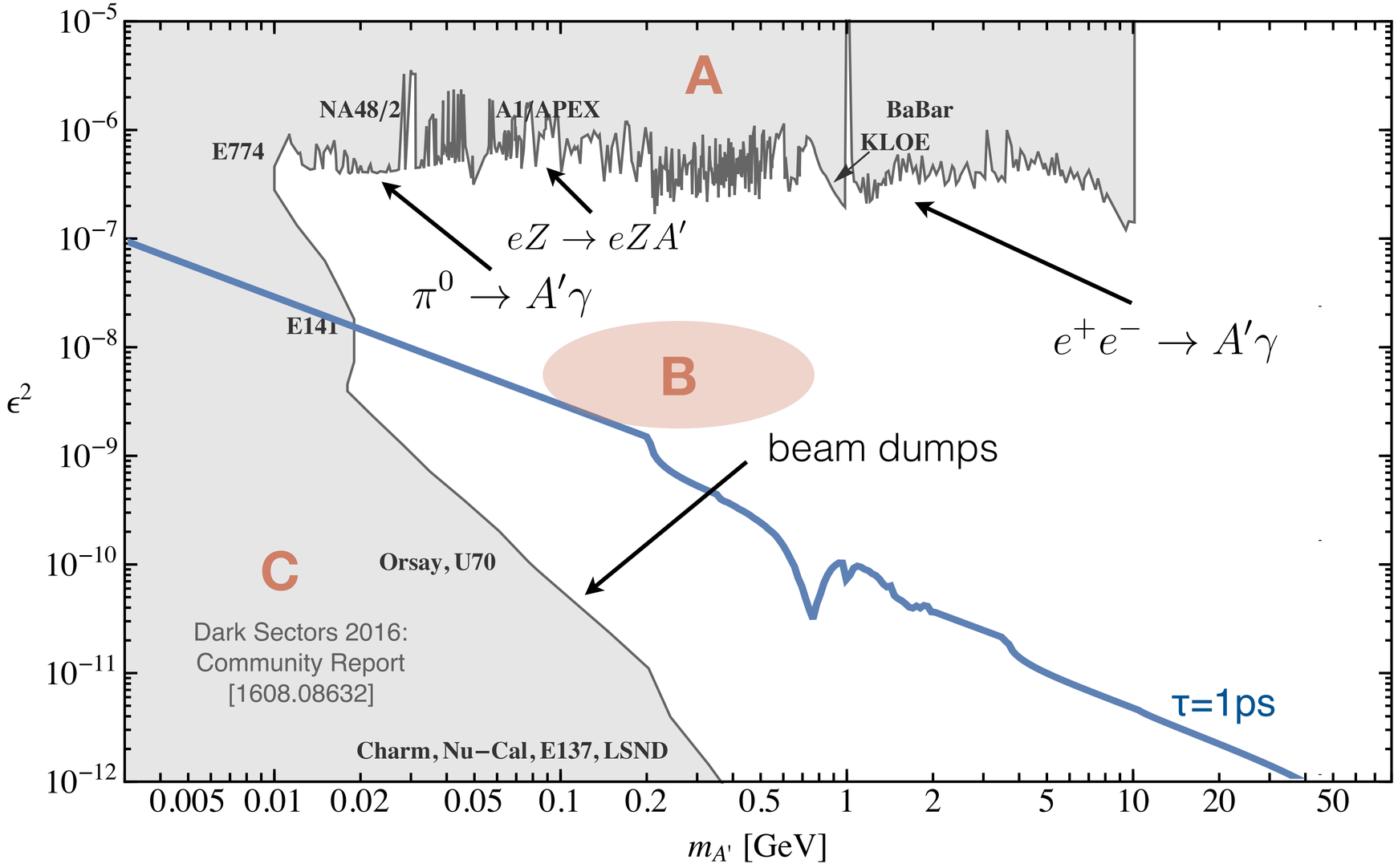


Visible dark photons

Courtesy of Mike Williams

Dark Sectors 2016: Community Report [1608.08632]

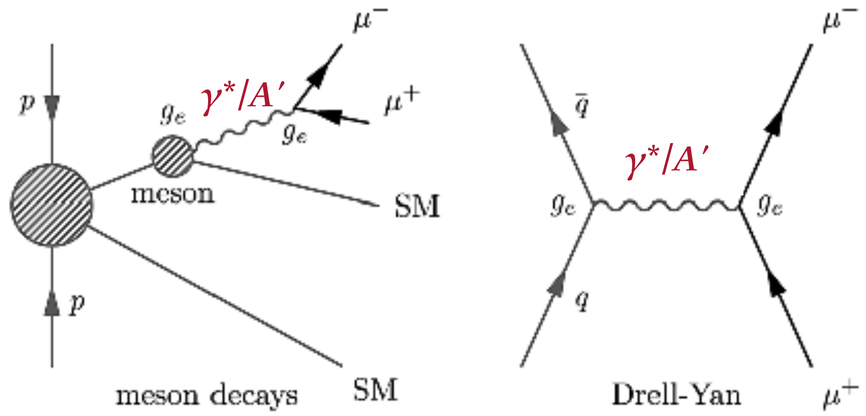
- **A**: Bump hunts, visible or invisible
- **B**: Displaced vertex searches, short decay lengths
- **C**: Displaced vertex searches, long decay lengths



Searching for Dark Photons / 1

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

- Search for dark photons decaying into **a pair of muons**
- Used **5.5 fb^{-1}** of Run 2 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 γ^* → $\mu^+\mu^-$
  - 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



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

off-shell photon

phase-space

A′ / γ^* eff ratio, ϵ=1 for prompt

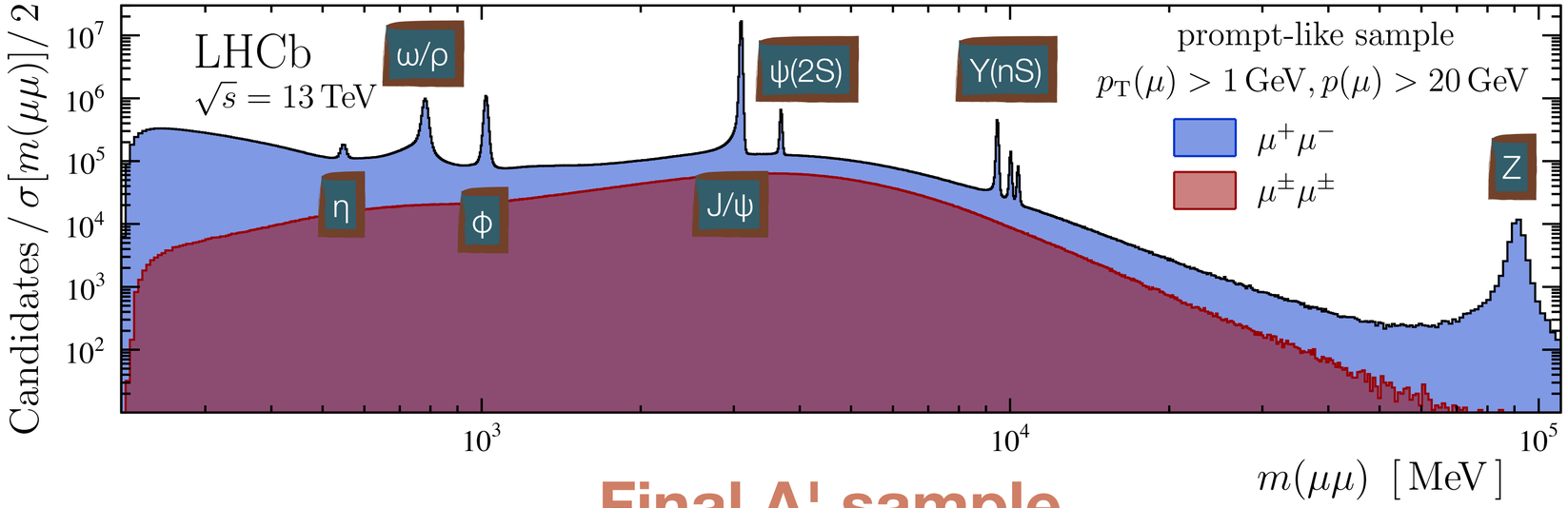
Need to separate from background

Searching for Dark Photons / 2

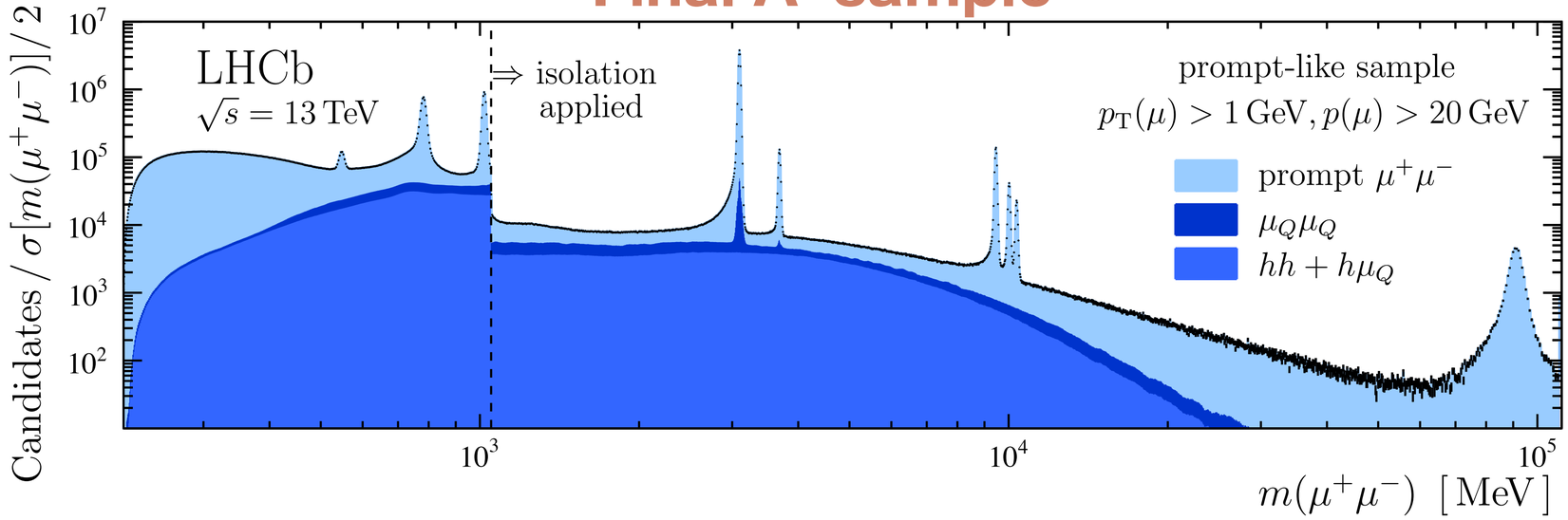
Phys. Rev. Lett. 120, 061801 (2018)
new arXiv:1910.06926

- 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

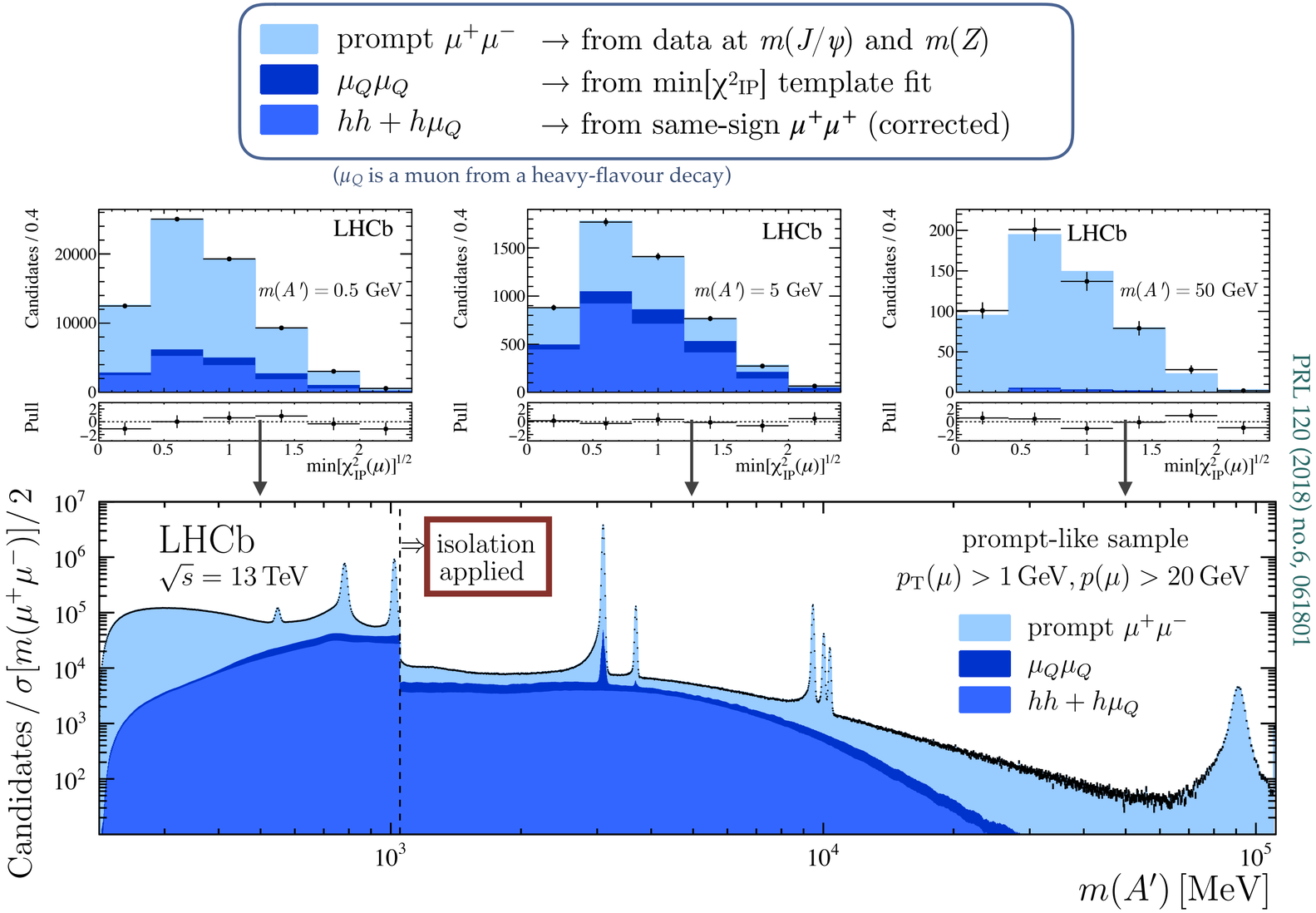


Final A' sample



Searching for Dark Photons / 3

Phys. Rev. Lett. 120, 061801 (2018)
new arXiv:1910.06926

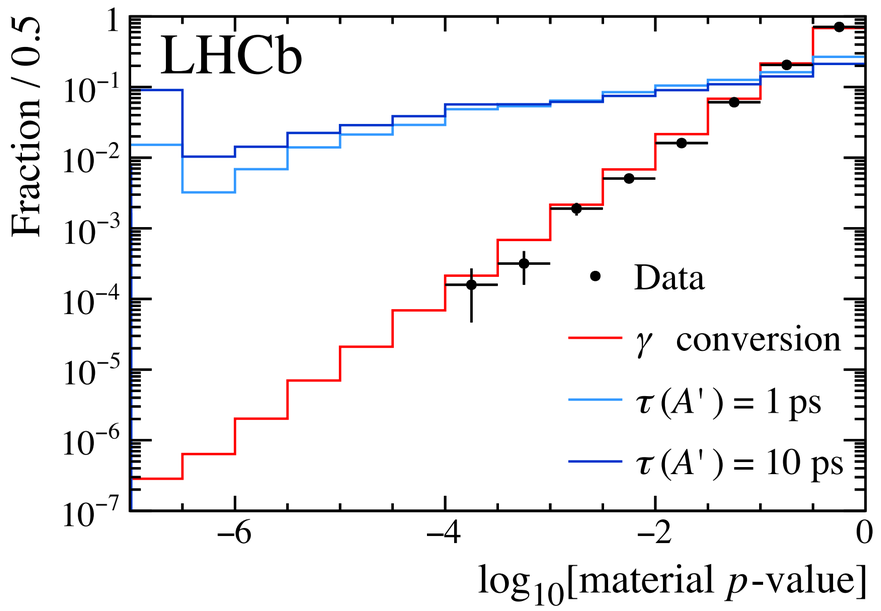


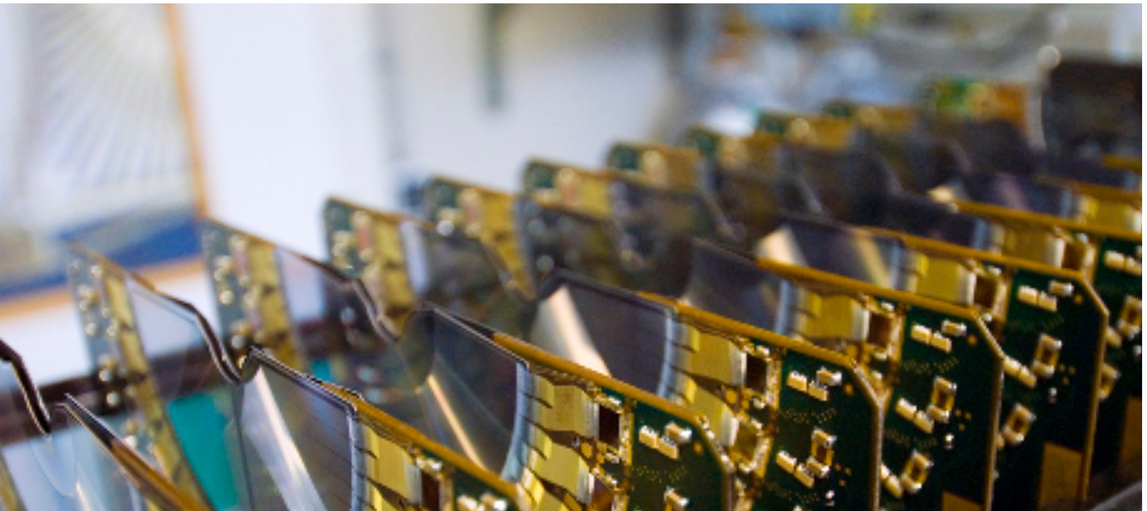
PRL 120 (2018) no.6, 061801

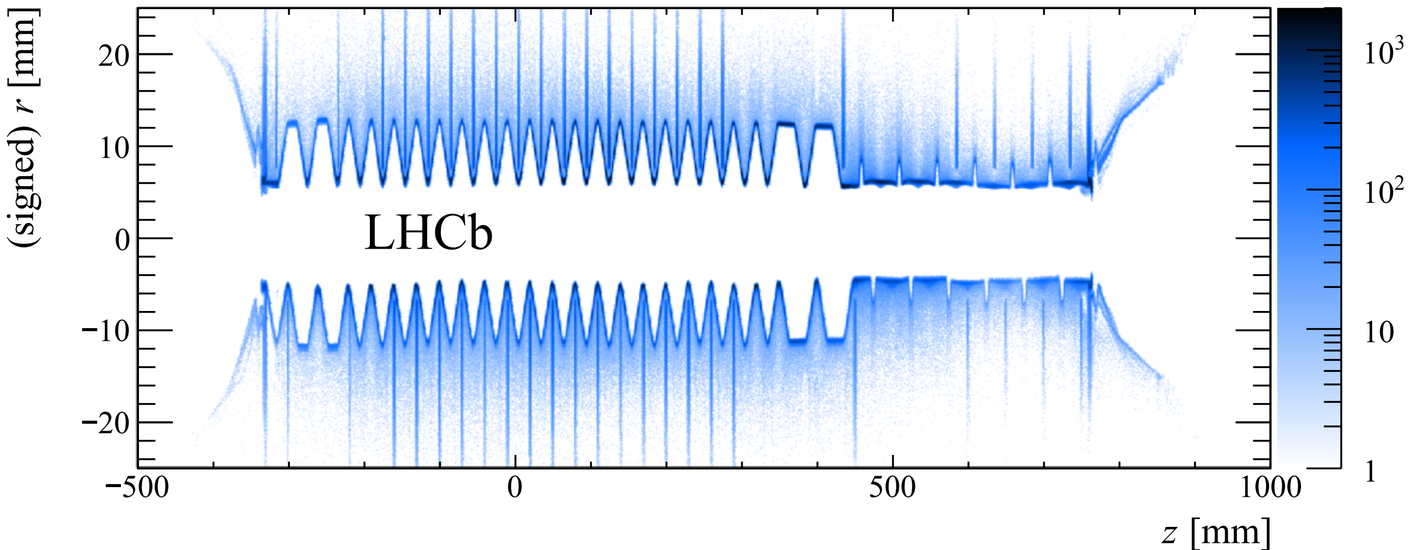
Searching for Dark Photons / 3

arXiv:[1803.07466]

- 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



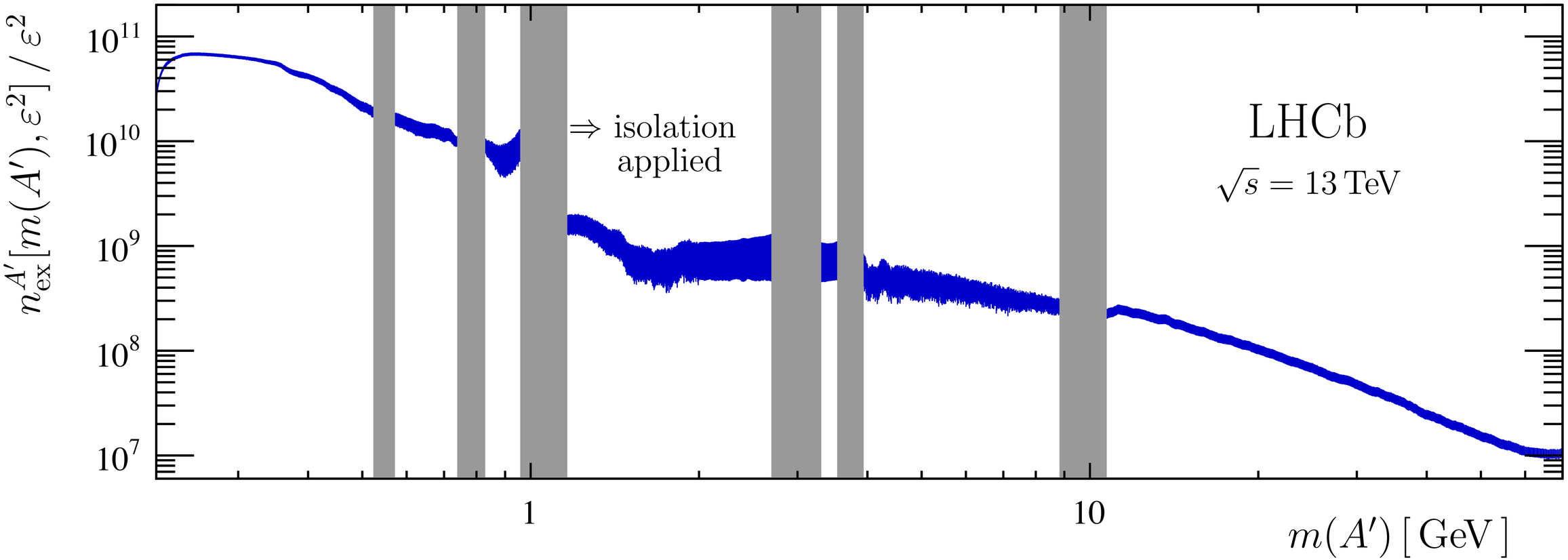




Search for Dark Photons / Prompt / 1

arXiv:1910.06926

- **O(10^7-10^{11}) x ε^2** dark photons are expected
- **Peak hunt** is performed on top of large combinatorial background
- **QCD resonances are vetoed**



Search for Dark Photons / Prompt / 2

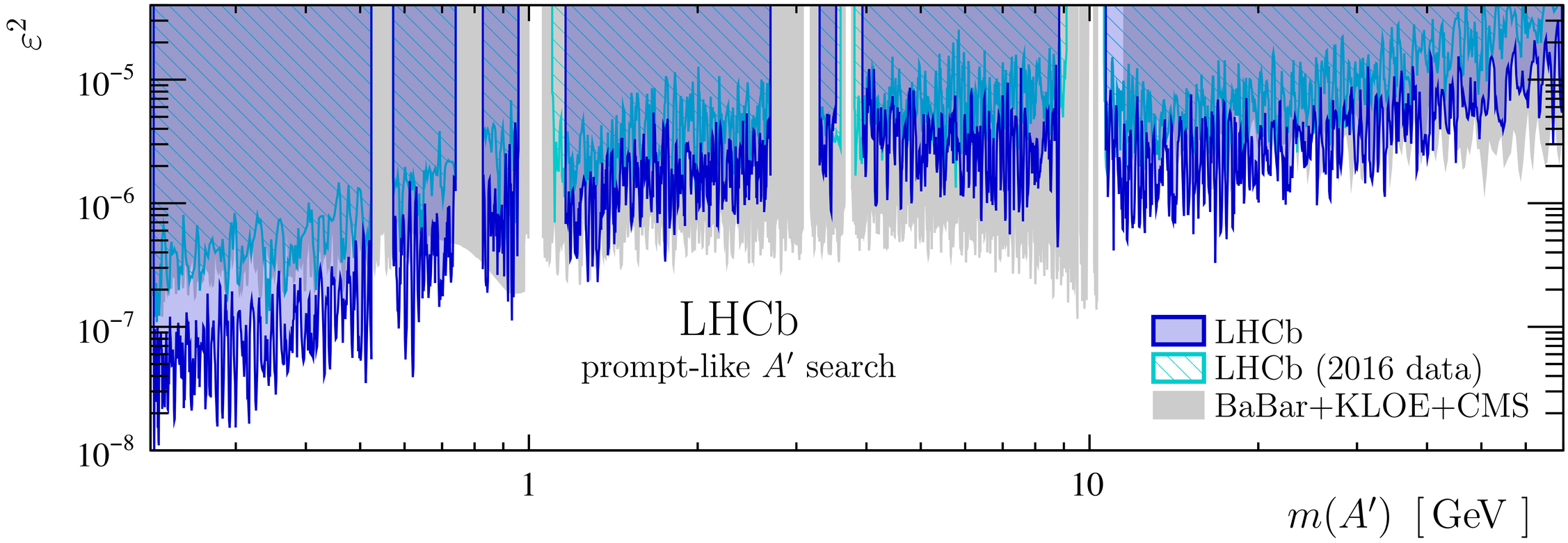
2017 JINST 12 P09034

- A search for **unknown particles** using a scan of an invariant mass spectrum
- If background-only probability density function (**PDF**) has enough complexity then signal-strength estimator **S** will likely be unbiased but i**ncreasing the background-model complexity increases the variance on S**, which degrades the sensitivity of the search
- If underlying PDFs are not well known, **simulation studies are not possible**
- Use a **data-driven method** to choose how much complexity is required in the background model
- **Transform** the fit interval onto [–1, 1] centred on the test mass and **choose** an appropriate wide model, i.e. choose a wide model that is capable of describing the data well enough in the absence of a signal contribution to provide an unbiased S and a valid CI and p-value
- Model selection is then performed using the **Akaike Information Criterion-based approach**, where all odd modes are included in every model considered and all even modes are arbitrated on

Search for Dark Photons / Prompt / 3

arXiv:1910.06926

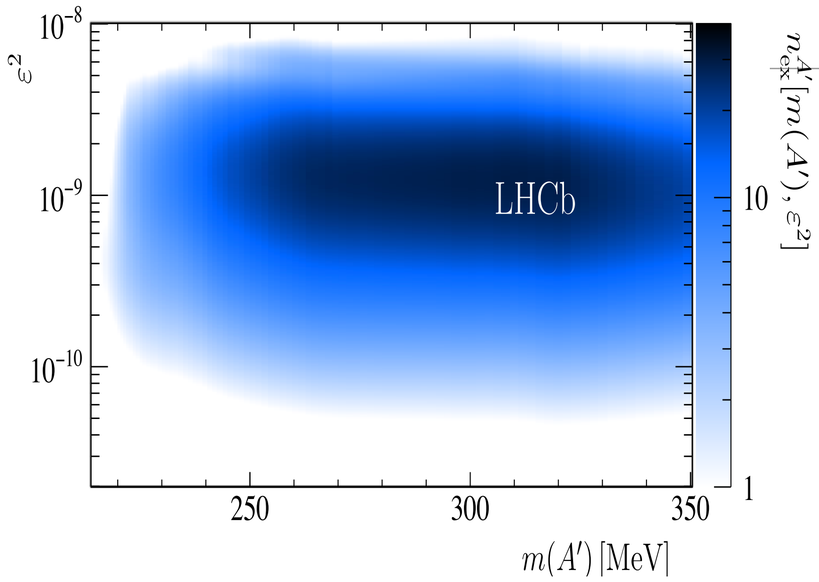
- **Factor 5** better sensitivity than 2016 for lower masses
- **Factor 2** better sensitivity than 2016 for higher masses



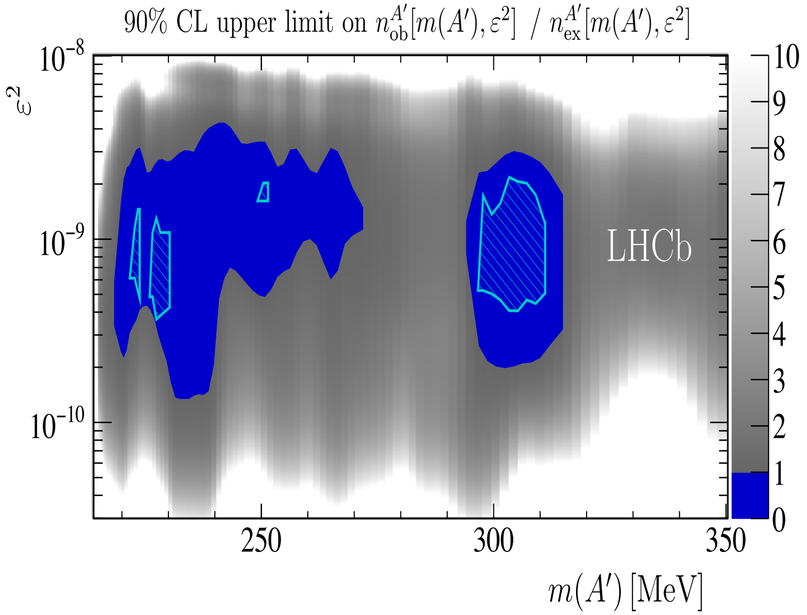
Search for Dark Photons / Displaced

arXiv:1910.06926

- **Looser requirements** on muon transverse momentum
- **Background** mainly from material interaction 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**



A'→μ+μ− yield

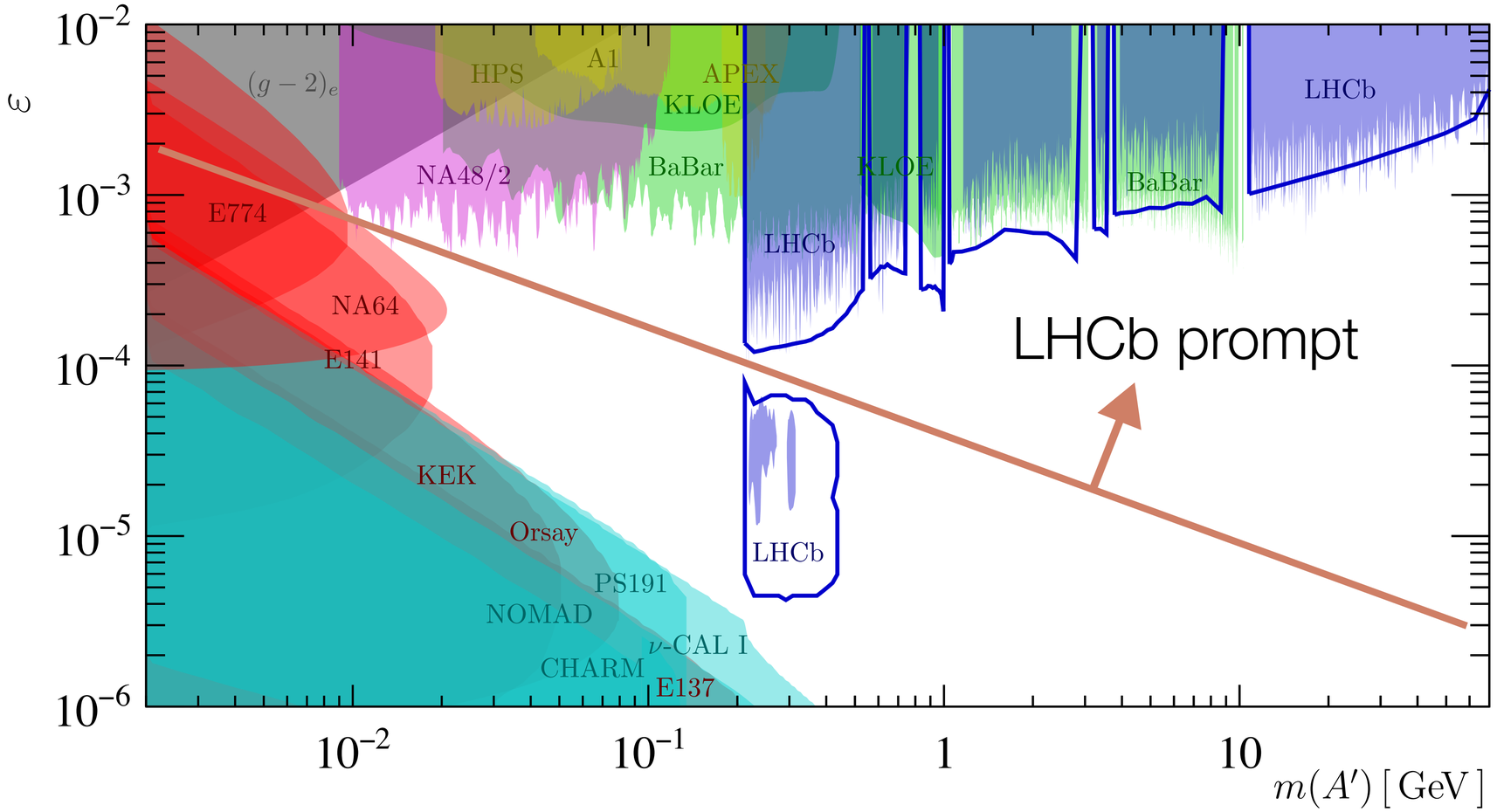


90% CL upper l.

Search for Dark Photons / Results

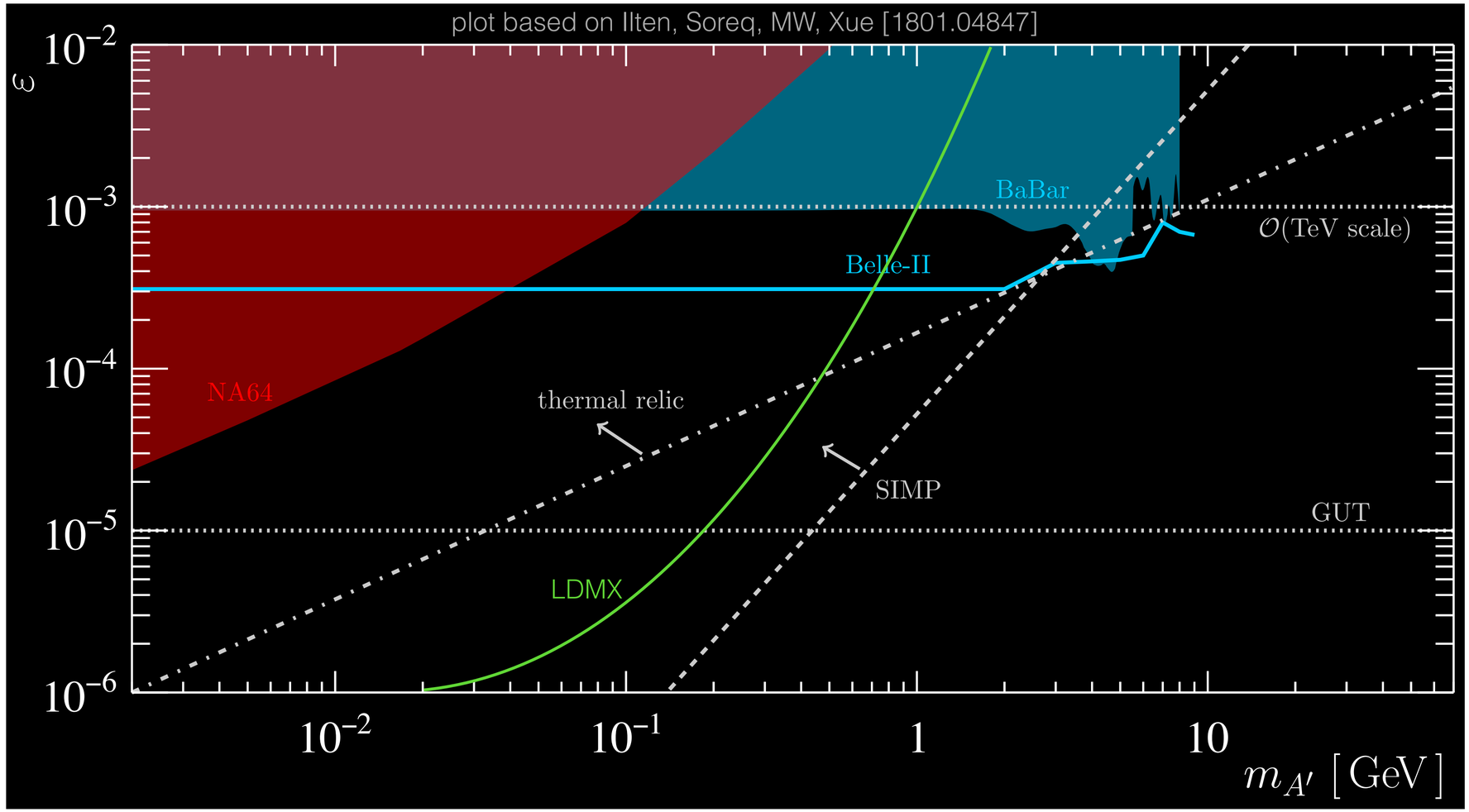
arXiv:1910.06926

- The Run 2 dimuon results are **consistent** with (better than) predictions for prompt (long-lived) dark photons
- We implemented huge improvements in the 2017 triggers for low masses, so plan **quick turn around for Run 3** dimuon search (solid line)
- **Electrons are the next thing** in these type of searches at LHCb



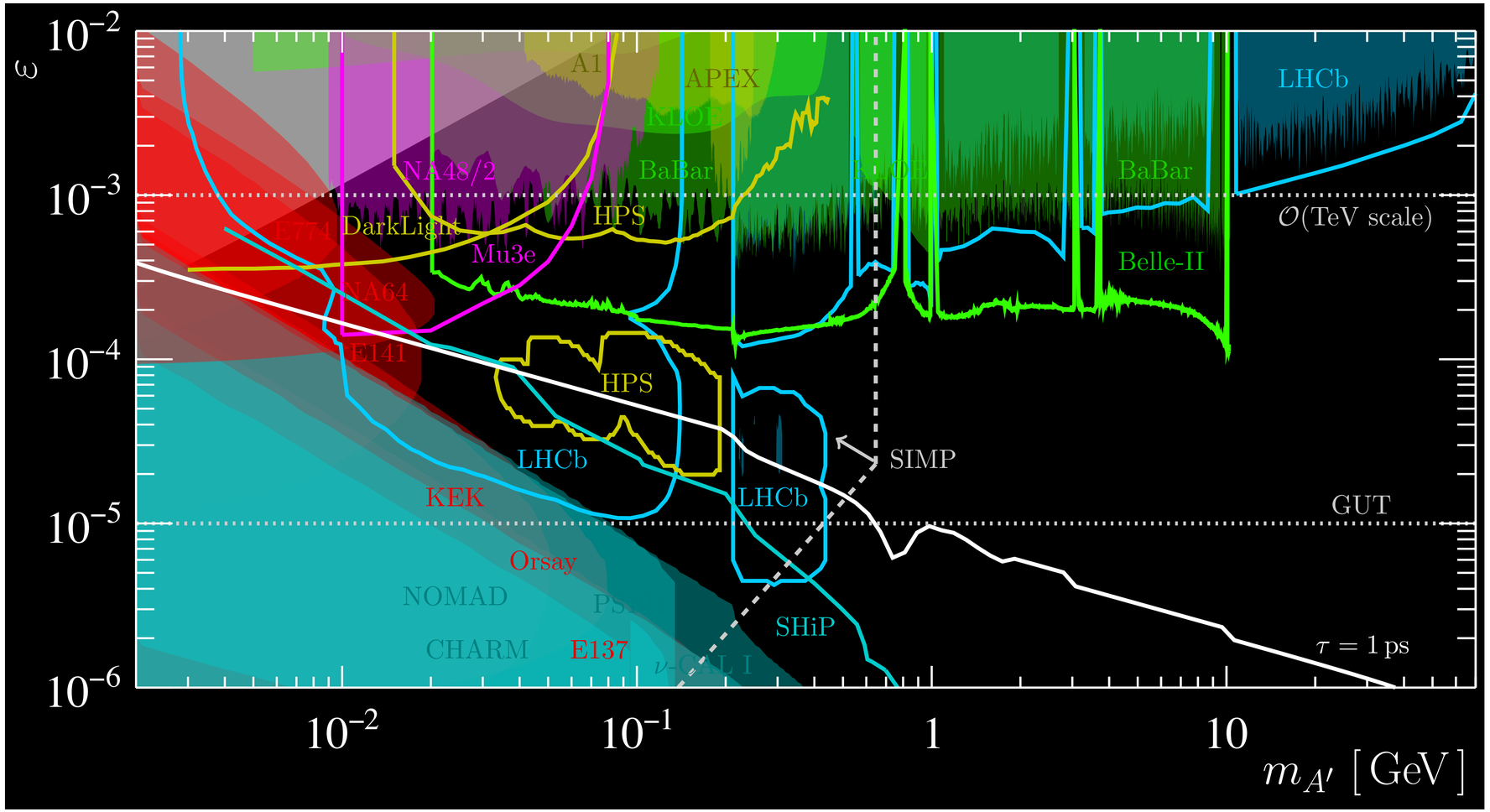
Invisible A' decays [Stolen from M. Williams IPA2018]

- If $m_{A'}$ is greater than $2xm_{DM}$, then **A' will predominantly decay into DM** final states
- Well defined thermal-relic targets: the DM annihilation cross section depends on the strength of the kinetic mixing
- **Belle II** and **à la LDMX** will expand and cover most thermal-relic target space and strongly interacting massive particle mixing space



Visible A' decays [Stolen from M. Williams IPA2018]

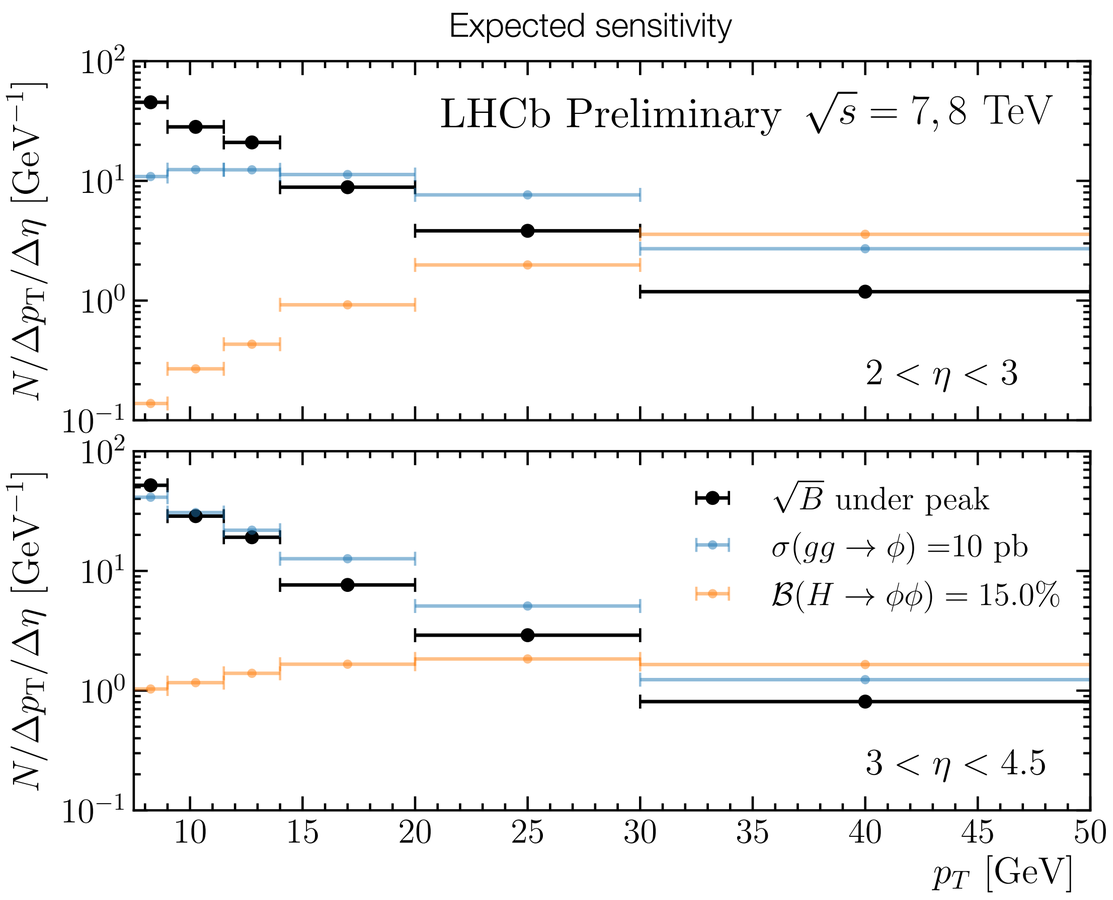
- If $m_{A'}$ is smaller than $2xm_{DM}$, then **A' will predominantly decay into SM** final states
- Target in ε is well defined but thermal-relic targets unknown: DM is secluded for visible A'
- Exploit LHCb trigger less readout system in Run 3 with great **τ resolution**
- Majority of mixing space covered in the next 5 years



Searching in the Y mass region / 1

arXiv:[1805.09820]

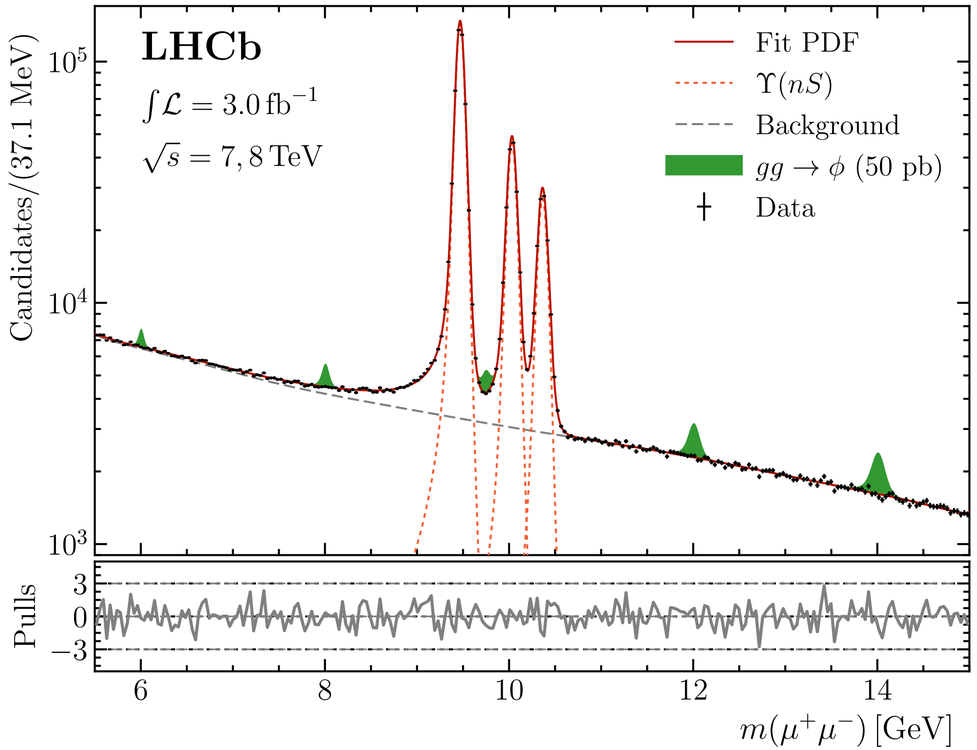
- Other light spin-0 particles in which LHCb can do well are light bosons from pp; **only Run 1**
- Spin-0 boson, ϕ, using Run 1 prompt $\phi \rightarrow \mu^+\mu^-$ decays, have been searched for
- Use **dimuon** final states:
  - Access to different mass window w.r.t γγ or ττ searches in 4π experiments
- Done in **bins of kinematics** ([pT,η]) to maximise sensitivity
- Precise modelling of Y(nS) tails to extend search range as much as possible
- **Mass independent** efficiency (uBDT)

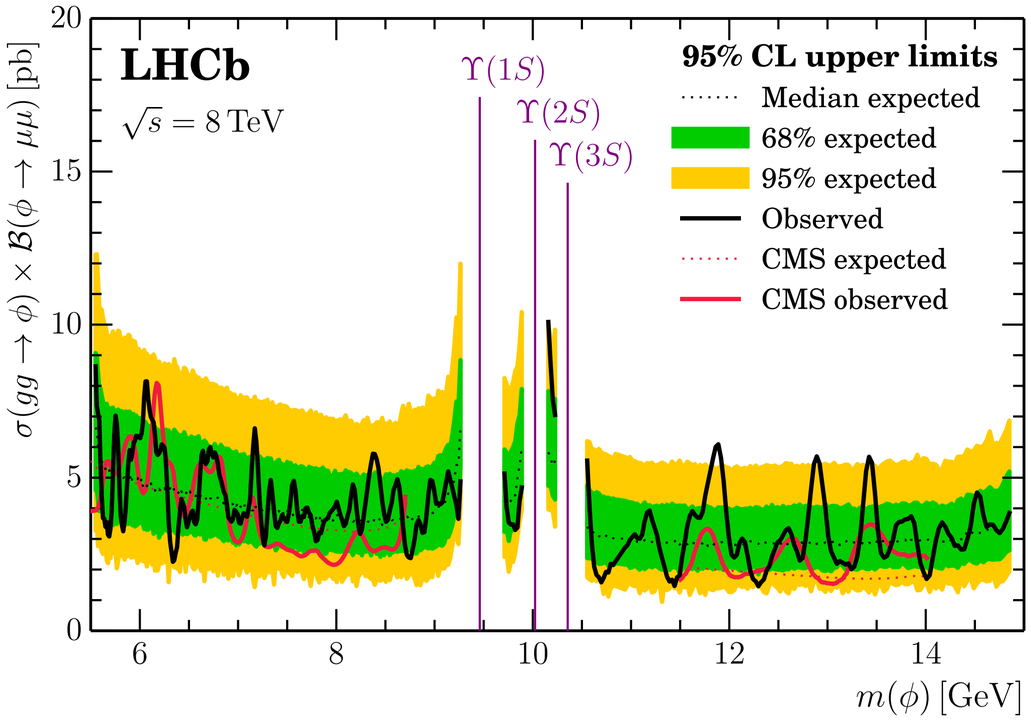


Searching in the Y mass region / 2

arXiv:[1805.09820]

- Search for dimuon resonance in $m_{\mu\mu}$ from 5.5 to 15 GeV (also between Y(nS) peaks)
- No signal: limits on σ•BR set on (pseudo)scalars as proposed by **Haisch** & **Kamenik** [1601.05110]
- First limits in 8.7-11.5 GeV region - elsewhere competitive with CMS





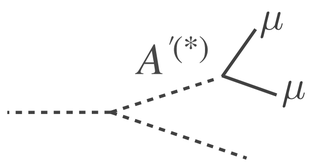
Future / 1 [Stolen from Martino Borsato slides from LLP Ghent 2019]

Future Prospects

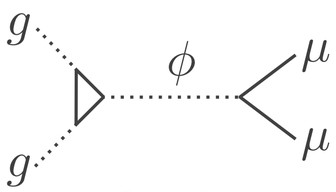
More $\ell^+\ell^-$ from Run 2

- Non-minimal A′ search (no data-driven normalisation)
- No muon tracks isolation (e.g. dark showers)
  A.Pierce et al. PRD97 (2018) no.9, 095033
- Dimuon with associated b-jet (e.g. CMS excess?)
  CMS: JHEP 11 (2018) 161
- Non-standard topology (e.g. non-pointing $\mu\mu$)
- Four-muons searches (e.g. dark Higgs)
- Inclusive dielectron search (below $2\,m_\mu$)

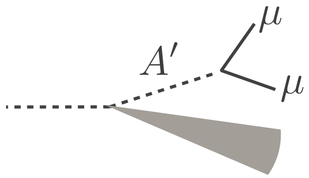
Non-minimal



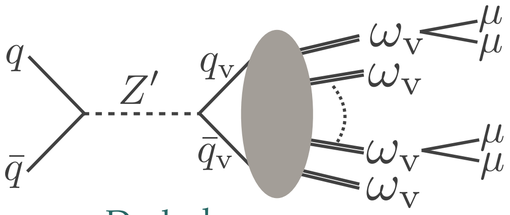
Non-pointing



Spin-0



With b-jet



Dark showers

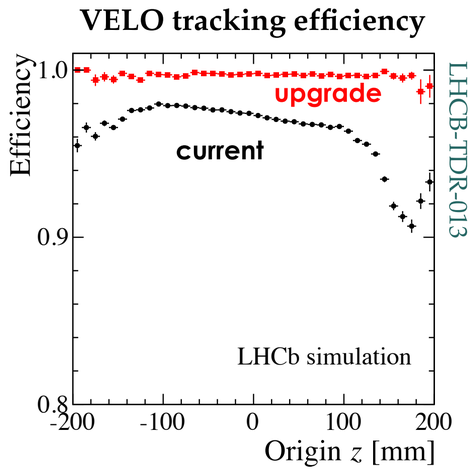
Future / 2

Future Prospects

The LHCb upgrades

	Current	Upgrade-Ia	Upgrade-Ib	Upgrade-II
$\mathcal{L}/(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	4×10^{32}	2×10^{33}	2×10^{33}	2×10^{34}
$\int \mathcal{L}$	$8\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$\sqrt{s}$	7, 8, 13 TeV	14 TeV	14 TeV	14 TeV
μ	~ 1	~ 5	~ 5	~ 50

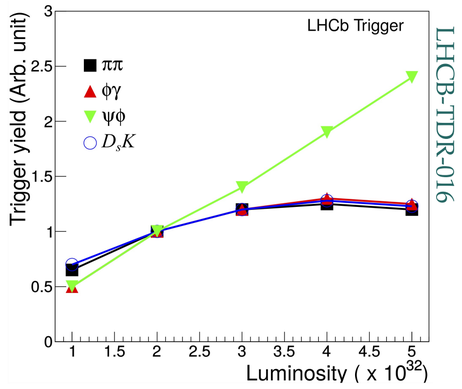
CERN-LHCC-2018-026



- Upgrade Ia LHCb detector:
  - Upgraded **VELO** with pixels and live readout
    - Lower fake rate and faster pattern recognition
    - Less material interaction (factor 3 better)
    - Better IP resolution (factor 2 better at p_T~0.5 GeV)

    LHCB-TDR-013
  - Upgraded Trigger all in software
    - Reading out full detector in real time (~30 MHz)
    - Lower p_T thresholds, displaced vertices at first level
    - Turbo stream with offline-quality calibration

    LHCB-TDR-016



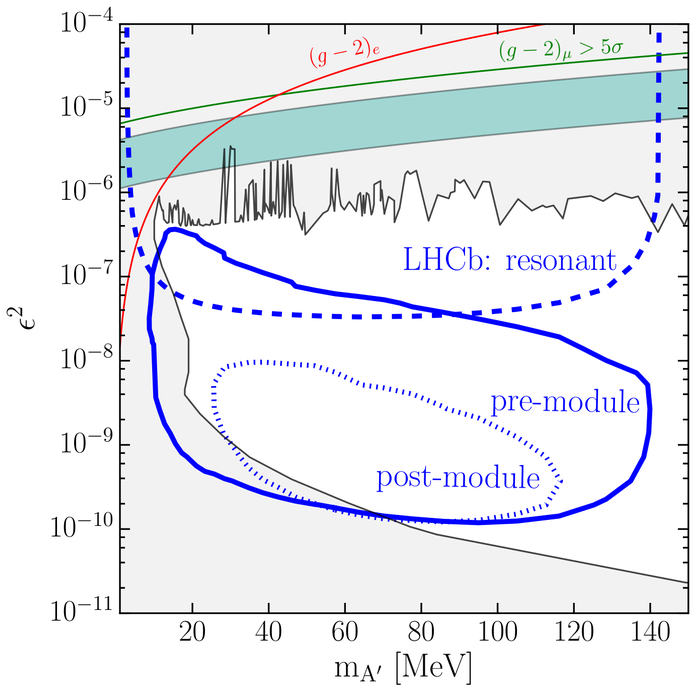
Future / 3

Future Prospects

Dark Photons below $2m_\mu$

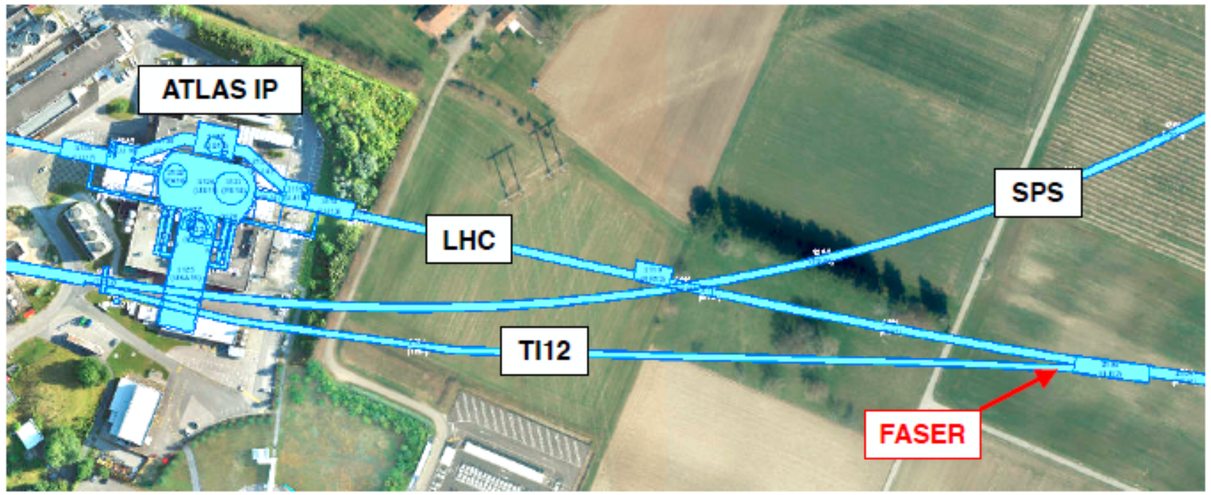
Ilten, Thaler, Williams, Xue PRD 92 no.11, 115017 (2015)

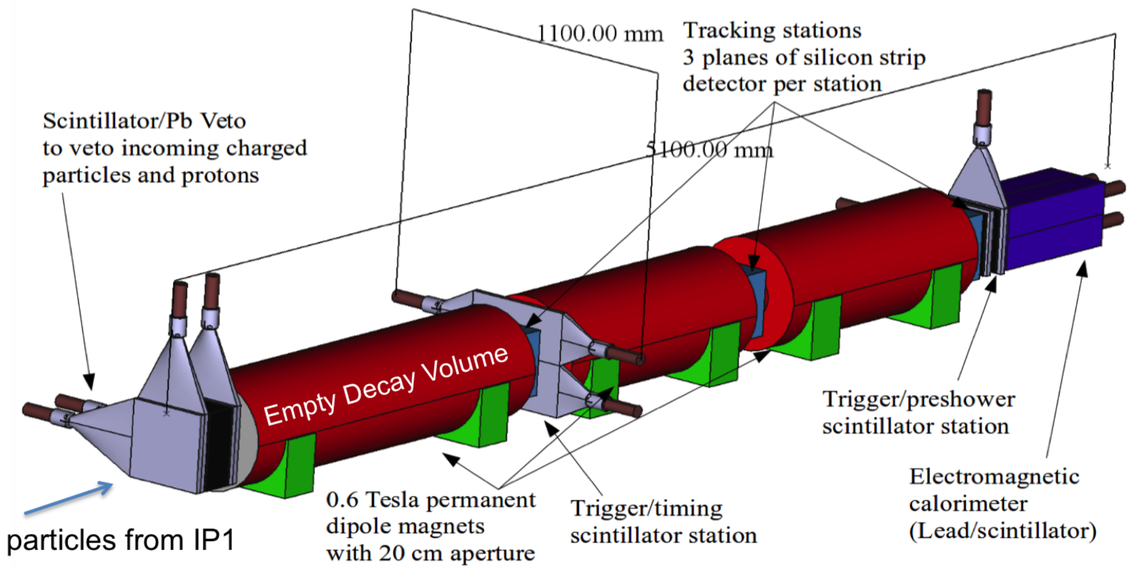
- Can cover region below $2m_\mu$ using charm decays $D^{*0} \to D^0 A'(ee)$
  - Requires upgraded trigger to select efficiently soft final state
  - Get **300×10⁹** $D^{*0} \to D^0\gamma$ **per fb⁻¹**
  - Can use $D^{(*)}$ mass constraint to correct bremsstrahlung losses
  - At these p electrons emit light in RICH while pions don't → excellent PID
  - Both displaced and prompt searches



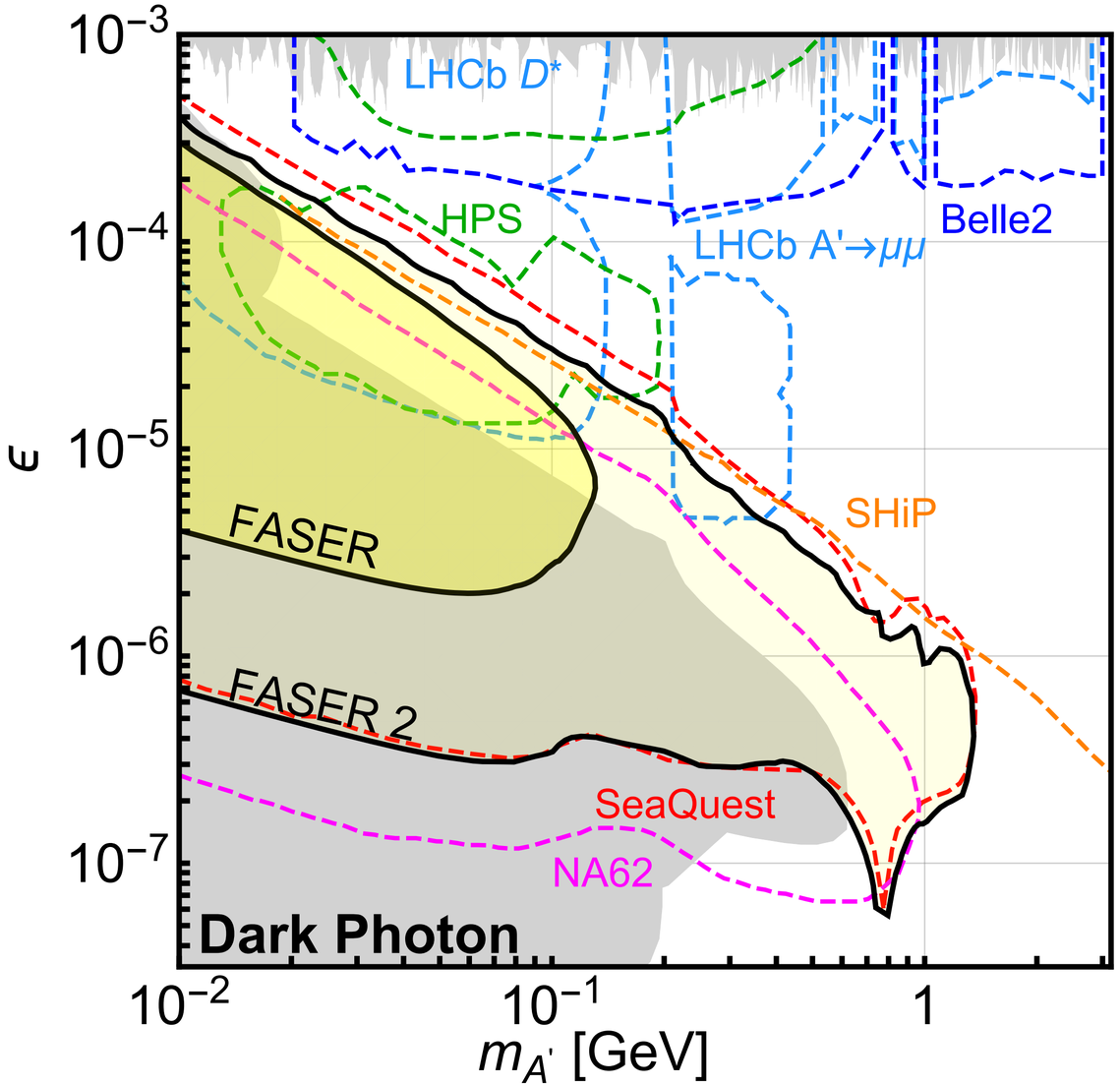
Faser / 1

- Huge forward π rate (~ 10^{15}) in FASER acceptance
- Large suppression (ε^2) in π → A' X but substantial rates of A' in acceptance
- Multi-TeV LLP produced at ATLAS IP; 480 m to FASER, including 100 m of concrete
- Decay within 1.5 m decay volume to charged particle pair, e.g. $\mathbf{e^+e^-}$
- Oppositely charged tracks separated by spectrometer B field
- Silicon strip tracker (from ATLAS) to measure charged track trajectory
- EM calorimeter (from LHCb) to measure energy, e vs. μ ID





Faser / 2



- FASER probes new parameter space with just 1 fb−1 starting in 2021
  - FASER 2 larger volume (R = 1 m, L = 5 m) and HL-LHC Lumi

Conclusions

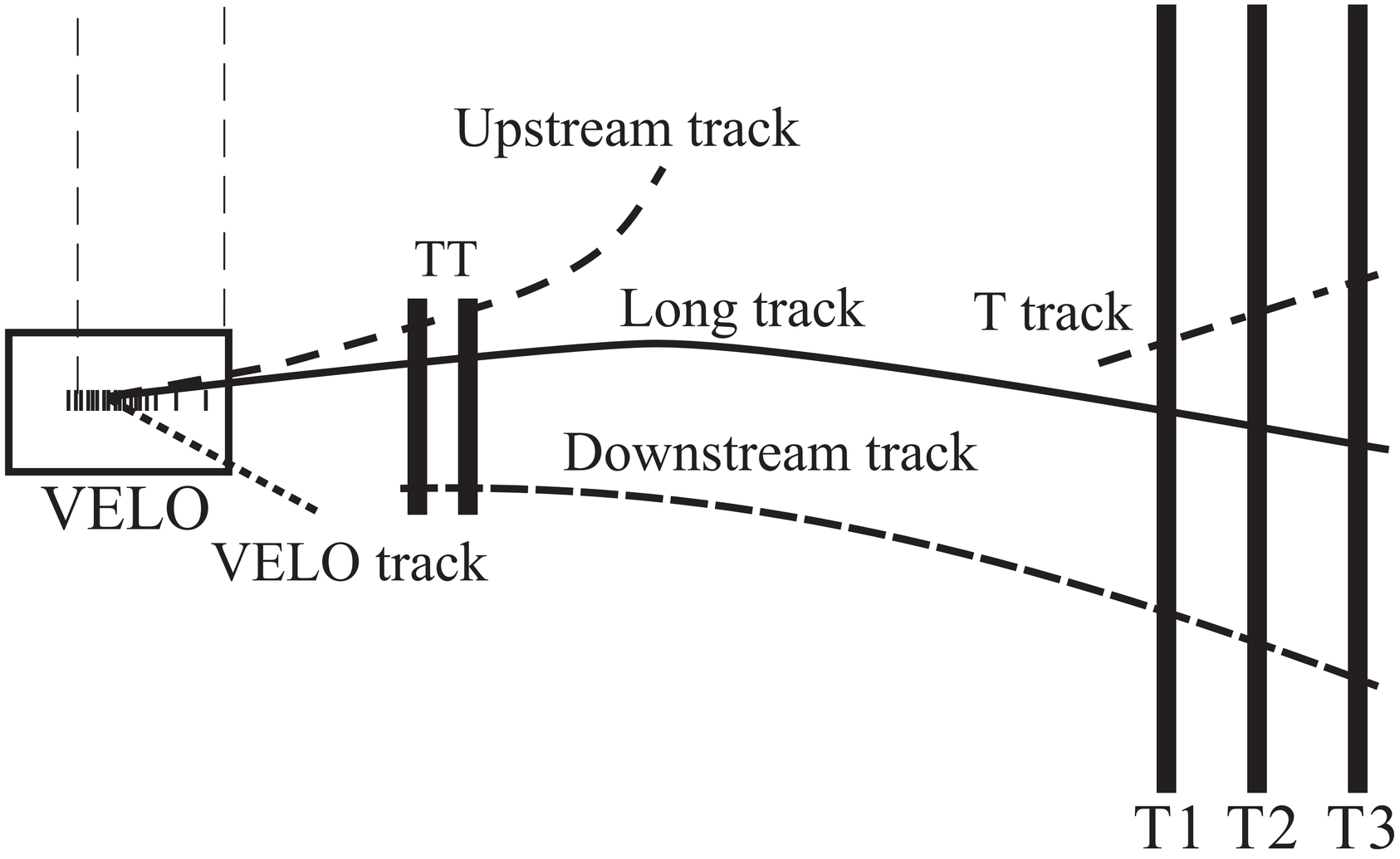
- LHCb has an **extensive program** of searches even beyond flavour physics
  - Searches for **dimuon resonances** in very broad parameter space (this talk)
  - Searches for **on-shell** new physics from heavy flavour decays
  - Searches for **long-lived** particles with low mass and short lifetime
- Bright future ahead:
  - 6 fb^{-1} in Run 2 (with larger cross-sections) expect huge improvement in Run 3
  - A lot of potential in the upgraded trigger (also 5x 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 fb^{-1}			LHCb Upgrade Phase II (proposed)		L = 2e34; 300 fb^{-1} (proposed)	

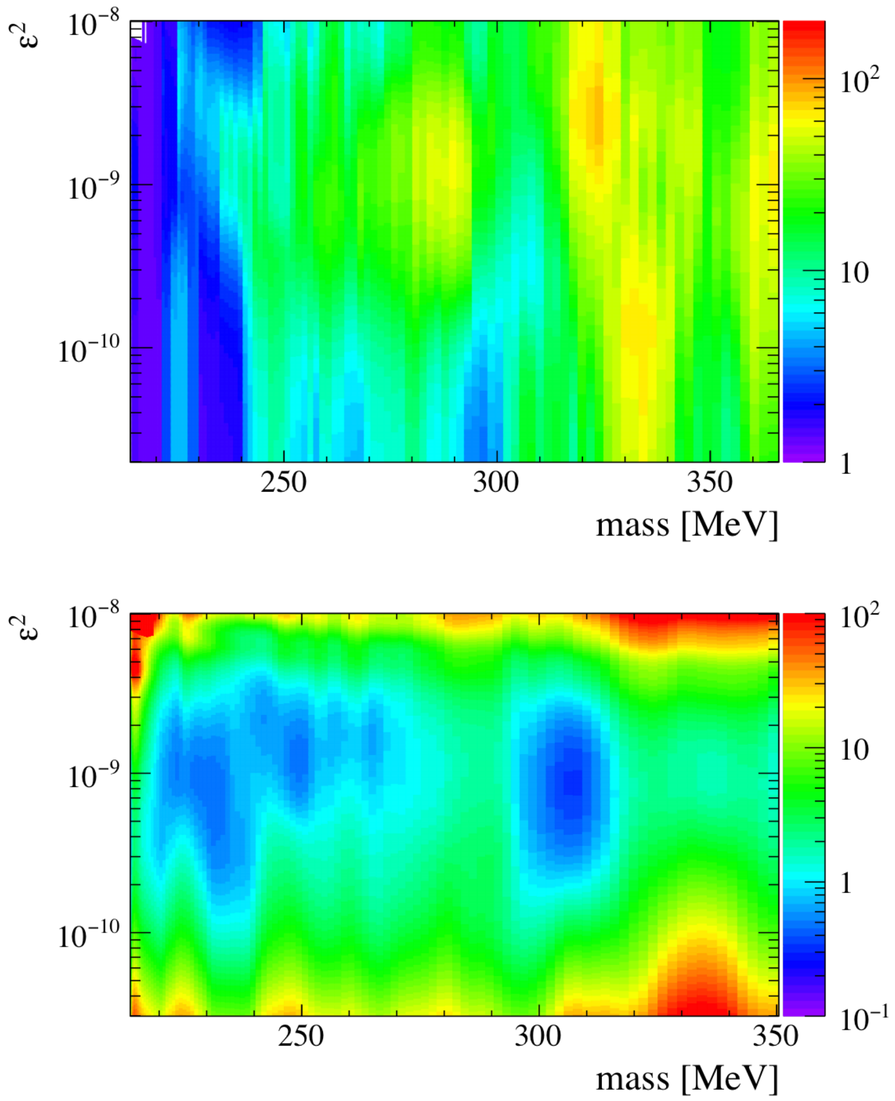
Thanks

Federico Leo Redi

LCHb track types



Exclusion plots for displaced region



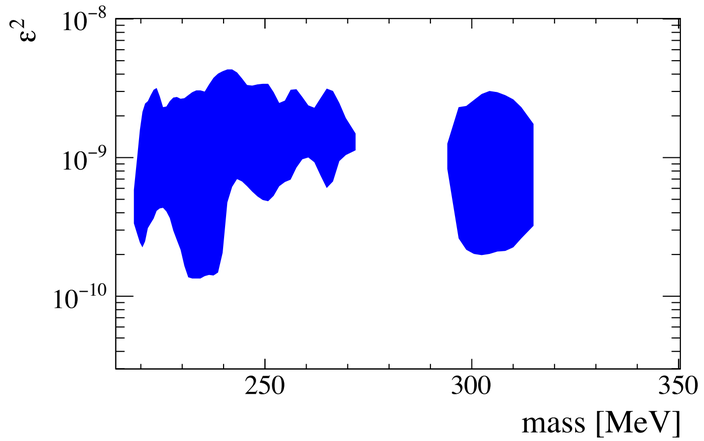


Figure 15: Exclusion limits at 90% confidence level from the displaced search. The top plot shows the upper limits on the reconstructed yields. The middle plot shows the ratio of the upper limit on the yield to the expected yield for each signal hypothesis. Values less than one are excluded (roughly cyan to blue are excluded). The bottom plot shows the excluded regions.