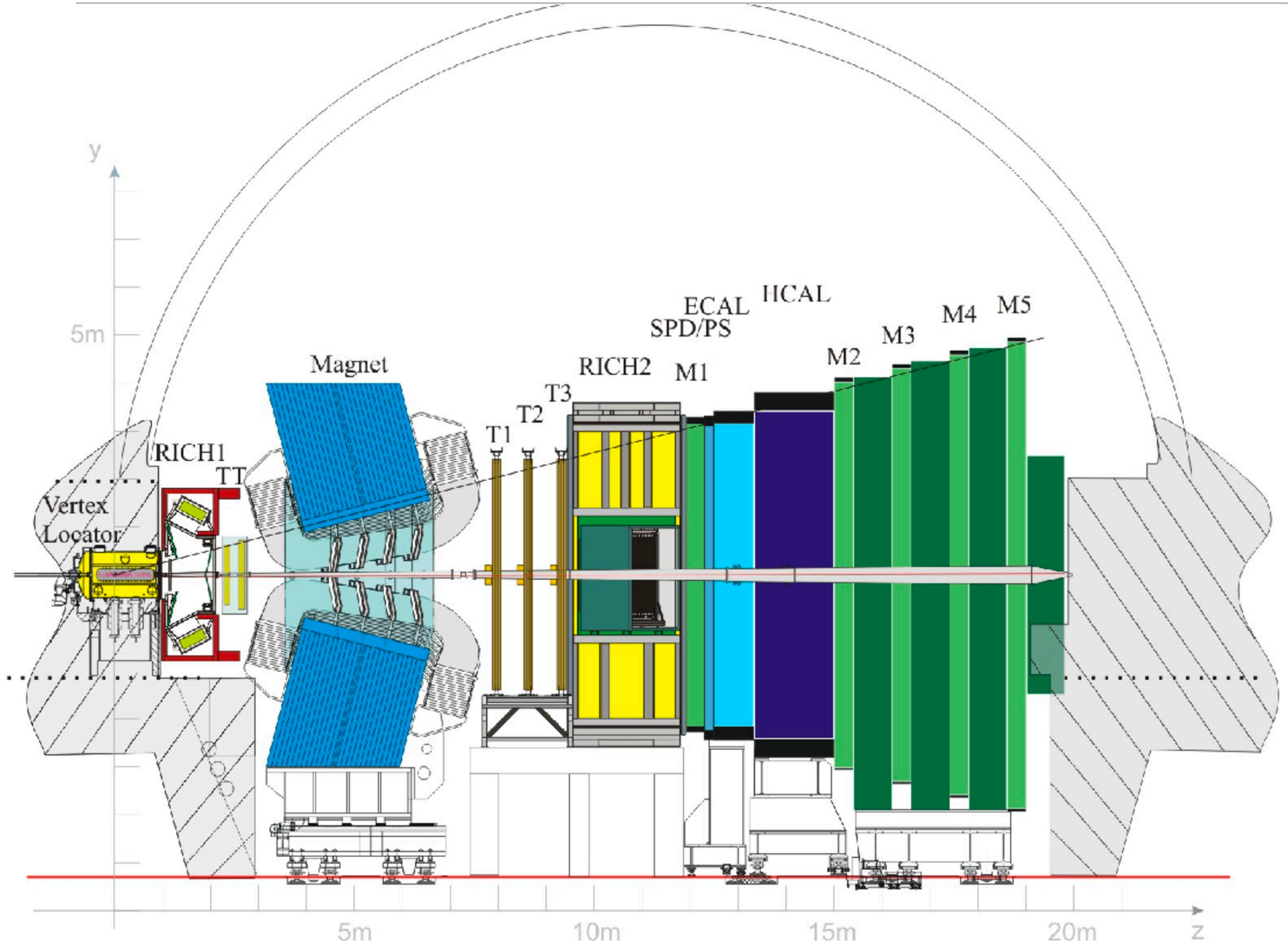
Searches for Dark Photons at LHCb

Adrián Casais Vidal (MIT) - on behalf of the **LHCb** collaboration

15th May, 2024. **Roadmap of Dark matter models for Run 3 -** CERN (Geneva)

The LHCb experiment



LHCb is a spectrometer in the forward region

- Excellent vertex resolution
  - IP resolution $\mathcal{O}(10\ \mu\mathrm{m})$
- $\mathcal{O}(1\%)$ momentum resolution
- Excellent configuration for low masses searches in pp collisions

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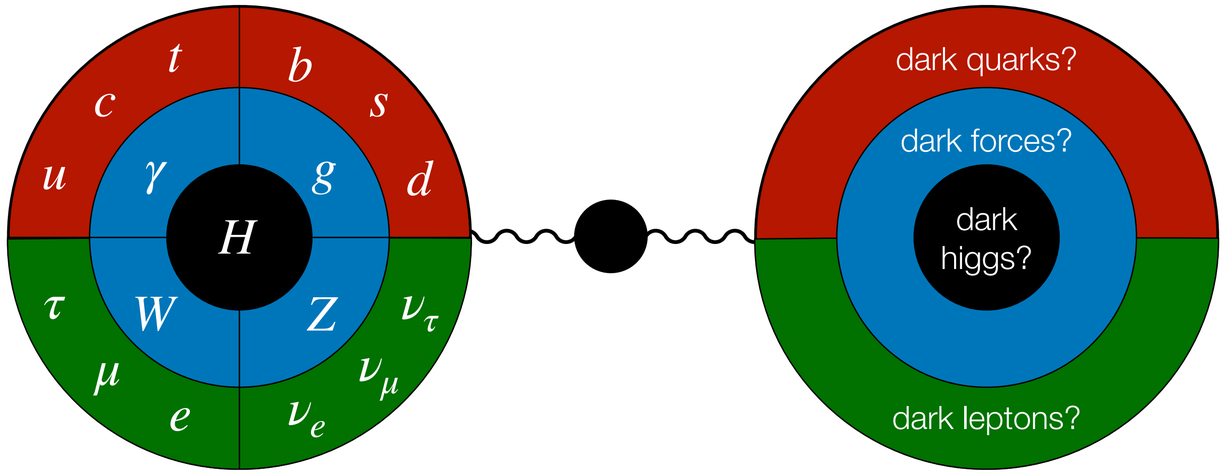
Dark sectors

- Different Dark Sectors could communicate to SM through portals
- Portals generated by **Quantum Mechanics** between sectors that don't interact **classically**
- Examples of portals:
  - Vector portal (A'): $-\frac{\epsilon}{2\theta_W}F'_{\mu\nu}B^{\mu\nu}$
  - Scalar portal (H): $(\mu S + \lambda S^2)H^\dagger H$
  - Axion portal (a): $\frac{a}{f_a}F_{\mu\nu}\bar{F}^{\mu\nu}$
  - Neutrino portal (N) : $y_N LHN$



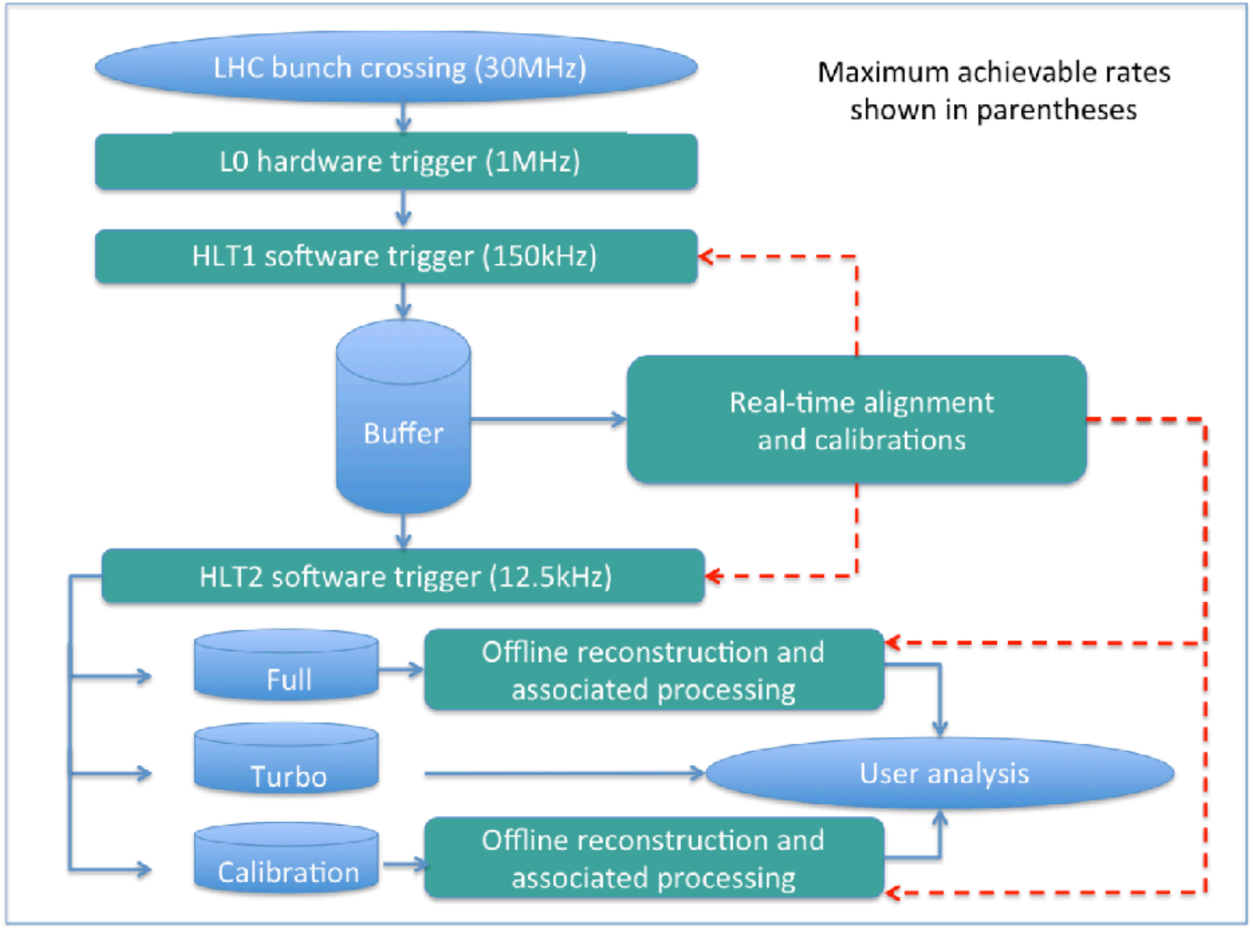
[Diagrams thanks to Mike Williams]

Dark Photons [PRL (2020) 124 041801]

- Search for dark photons decaying into a pair of muons
- Used 5.6 fb^{-1} of the full Run 2 LHCb dataset (13 TeV)
- Prompt-like search (up to 70 GeV) → displaced search (214-350 MeV)
  - A' is long lived if the mixing factor (ε) is small
- Kinetic mixing of the dark photon (A') with **off-shell photon** (γ^*) by factor ε:
  - A' inherits the production mode mechanisms from γ^*
  - $A' \to \mu^+\mu^-$ can be normalised to $\gamma^* \to \mu^+\mu^-$
  - $$n_{\text{ex}}^{A'}[m(A'), \varepsilon^2] = \varepsilon^2 \frac{n_{\text{obs}}^{\gamma^*}[m(A')]}{2\Delta m} \mathcal{F}[m(A')] \epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$$
    - Normalize with respect to the expected number of A' events taken directly from data

Searches for Dark Photons [JINST 14 (2019) 04, P04006]

- Large dimuon yield
- Prompt Dark Photons were selected using the TURBO stream
  - Save all particles selected online
  - Discard low level information
- Technique introduced in [1604.05596]



Searches for Dark Photons [PRL (2020) 124 041801]

- **Event selection:**
  - Hardware trigger stage:
    - $p_T(\mu) > 1.8$ GeV || $p_T(\mu_1)p_T(\mu_2) > 1.5$ (GeV)^2
  - Software trigger stage:
    - MuonID criteria
    - Good quality vertex
  - Offline:
    - Dimuon isolation strategy

- Long-lived (prompt) search:
  - $p_T(\mu)$ > 0.5 (1.0) GeV
  - $p(\mu)$ > 10 (20) GeV
  - Inconsistency (consistency) with origin at the PV

- **Prompt search misRECO backgrounds:**
  - Double mis ID (hh) : μ as prompt hadron, most likely a pion
  - misID (h) + misRECO (μ_Q): μ from b(c)-hadron decay and reconstructed as prompt
  - Double misRECO $(\mu_Q\mu_Q)$

- **Displaced search backgrounds:**
  - Photon conversions to $\mu^+\mu^-$ in the VELO (matter veto strategy in the back-up)
  - b-hadron decays with two muons produced in the decay chain
  - Low mass tail from $K_s^0 \to \pi^+\pi^-$ where both pions misidentified as muons

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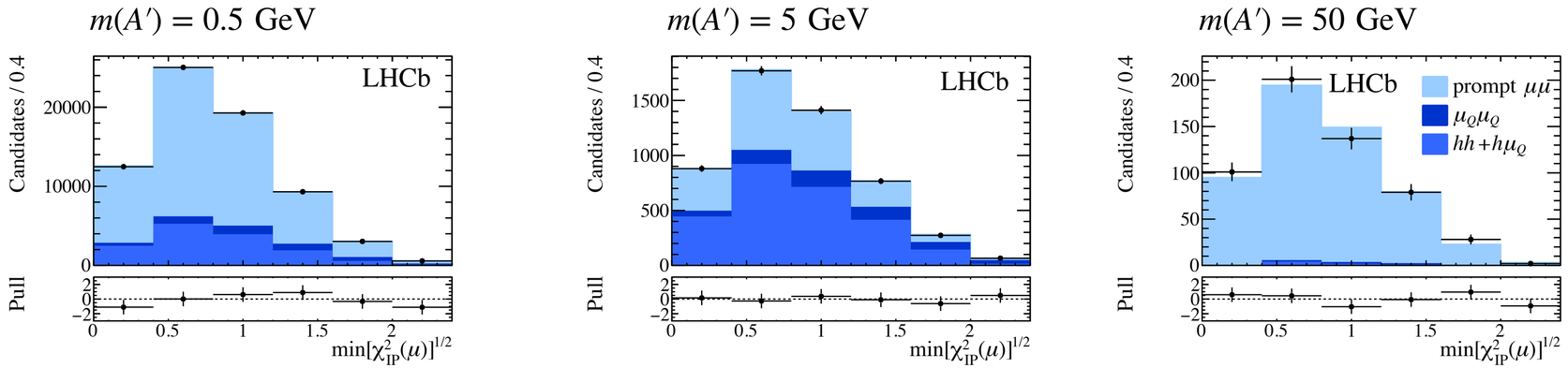
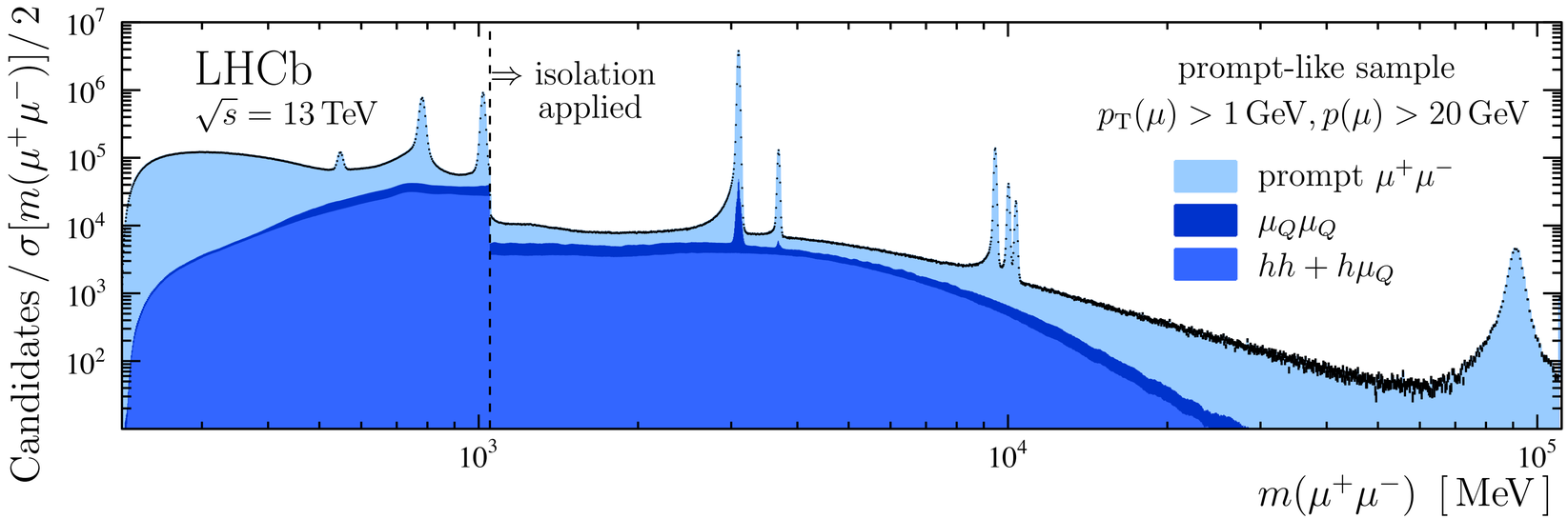
Dark Photons: prompt search [PRL (2020) 124 041801]

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

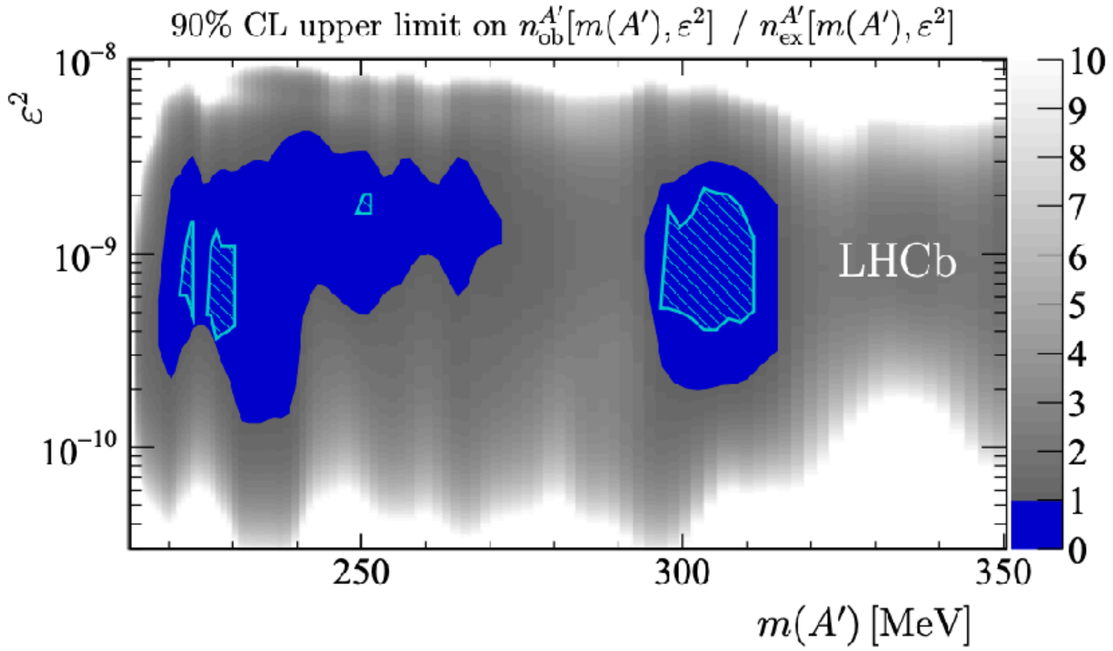
prompt $\mu^+\mu^-$ → from data at $m(J/\psi)$ and $m(Z)$
$\mu_Q\mu_Q$ → from simulation (validated)
$hh + h\mu_Q$ → from same-sign dimuons (corrected)

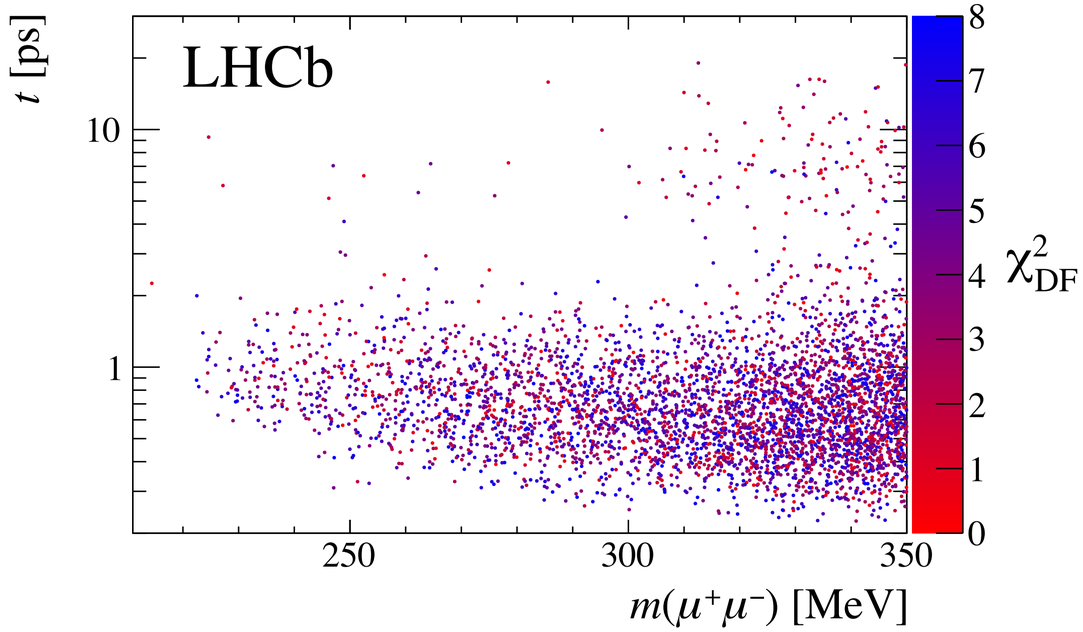




Dark Photons: displaced search [PRL (2020) 124 041801]

- Looser requirements on muon transverse momentum.
- Material background is mainly from photon conversions
- Isolation decision tree from $B_s^0 \to \mu^+\mu^-$ 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 .

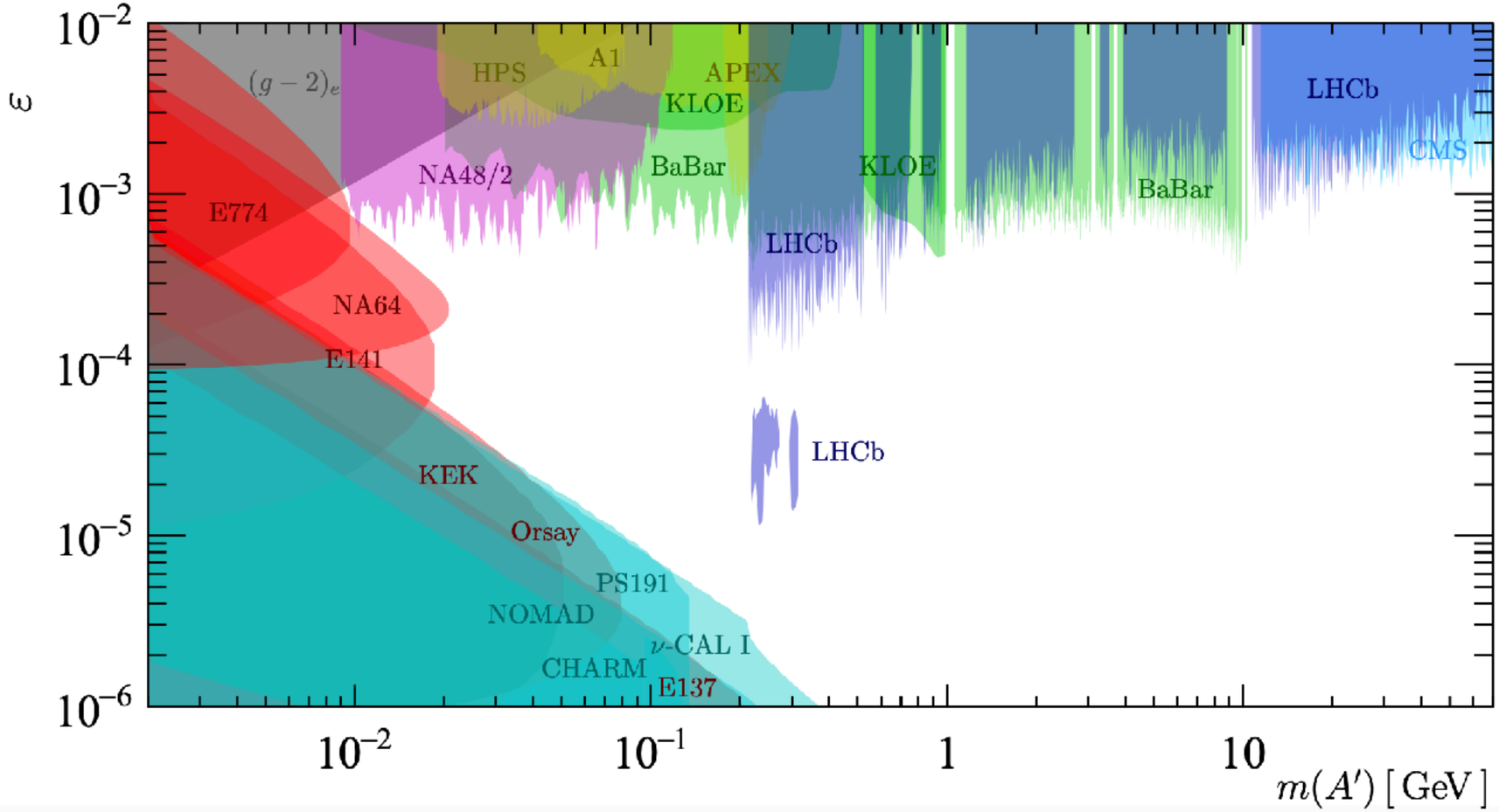




- **No significant excess found** - small parameter space region excluded:
- First limit ever **not from beam dump**.

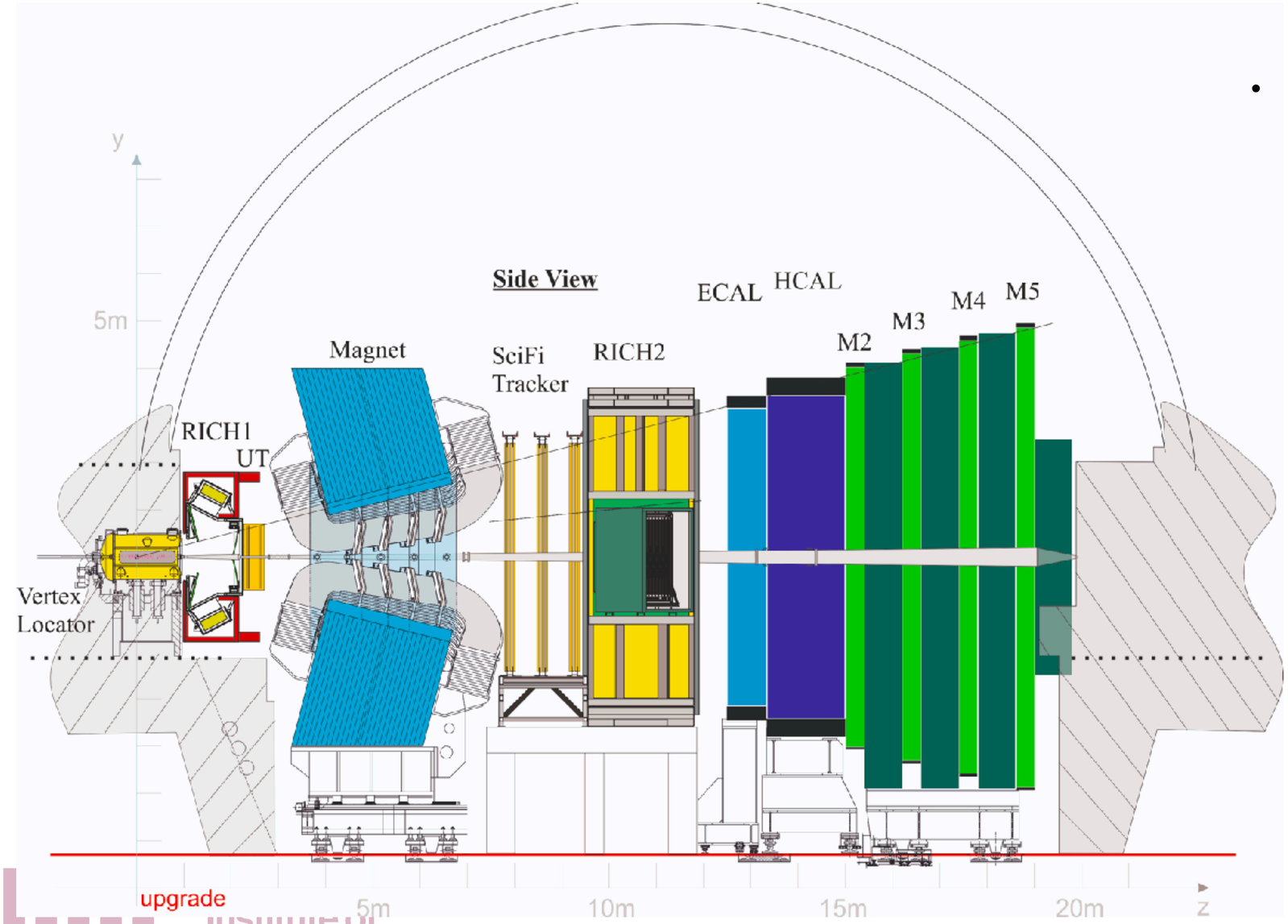
Dark Photons: results [PRL (2020) 124 041801]

- Results obtained with 5.6 fb^{-1} at 13 TeV
  - Prompt search in large range: $2m(\mu) < m(\mu\mu) < m(Z)$
  - Displaced search in sensitive region $214 < m(\mu\mu) < 350$ MeV



The upgraded LHCb detector

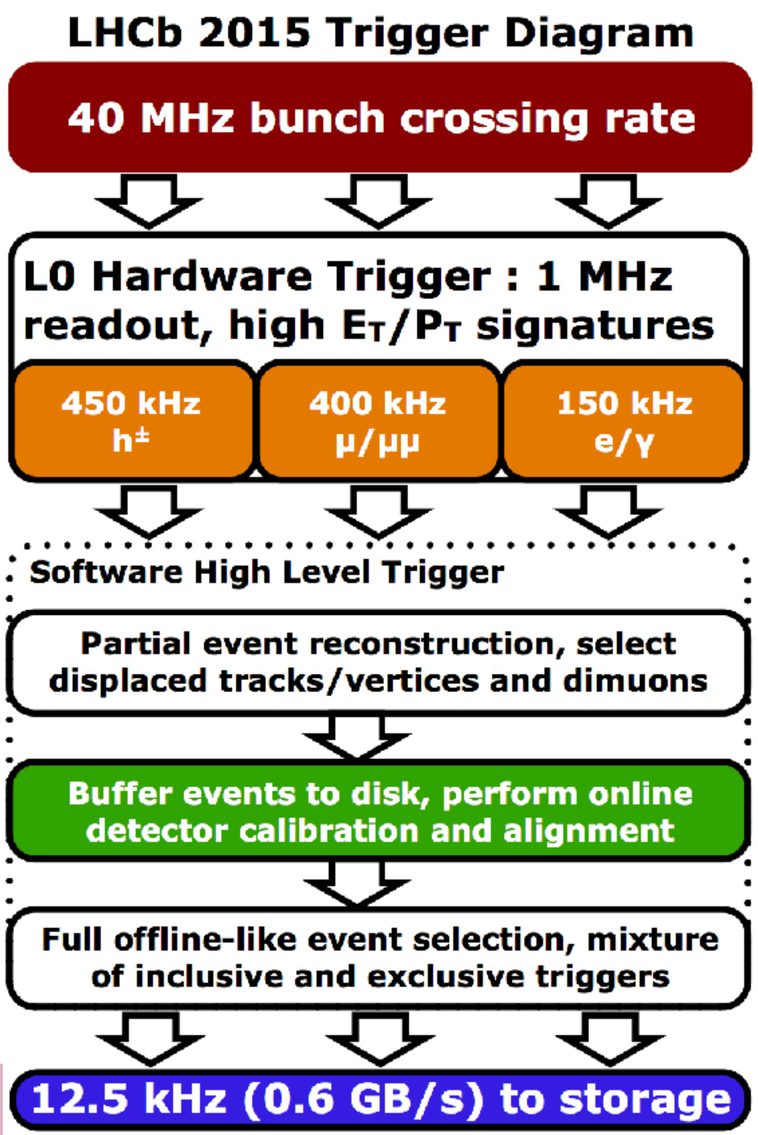
[2305.10515]

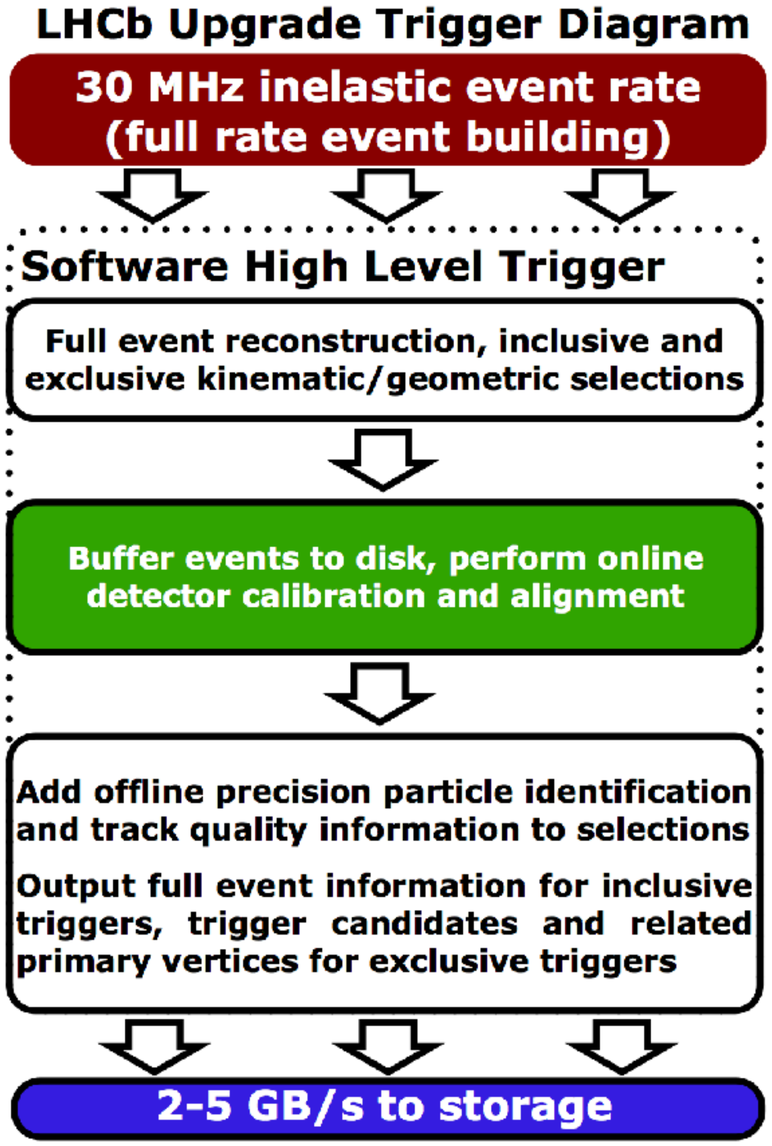


- The experiment was upgraded after the end of Run 2 in 2018
  - General:
    - Adapt the detector for higher occupancy and readout capacity
  - Replace detectors:
    - VELO
    - Tracking:
      - UT: replaces TT
      - SciFi: replaces T-stations
      - First MUON station is removed

The upgraded dataflow

[LHCb-FIGURE-2020-016]

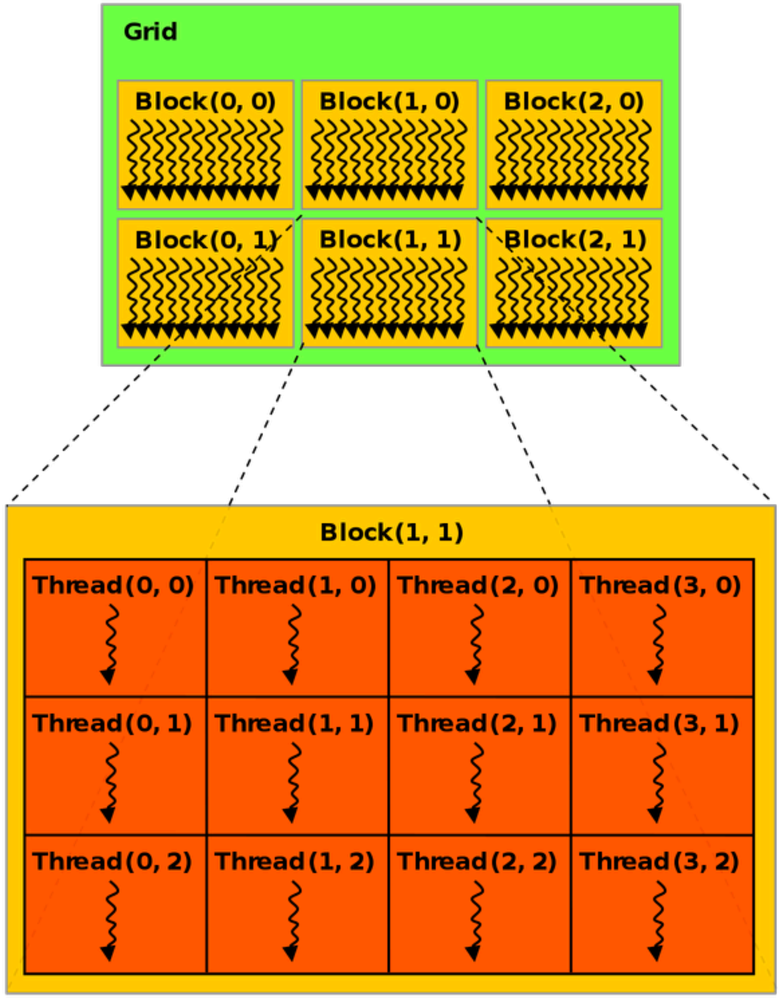




- Removal of L0 hardware trigger
- Triggerless readout
  - Software HLT1: GPU
  - Reconstruction of all charged particles
  - More flexible than L0
- HLT2: CPU
  - Semi-online
  - Data buffered
- Alignment and calibration online
    - Inject back in HLT1/2

Allen: a GPU High Level Trigger for LHCb [Comput.Softw.Big Sci. 4 (2020) 1, 7]

- GPU: a LOT of threads $> \mathcal{O}(1000)$
  - Grouped in **blocks of threads**
- Parallelisation:
  - Grid $\longleftrightarrow$ Set of events
  - Event $\longleftrightarrow$ Block
  - Track $\longleftrightarrow$ Thread
- No dynamic allocation:
  - Count first write later
  - The size of the arrays are set before running each kernel
- Single precision **floats**



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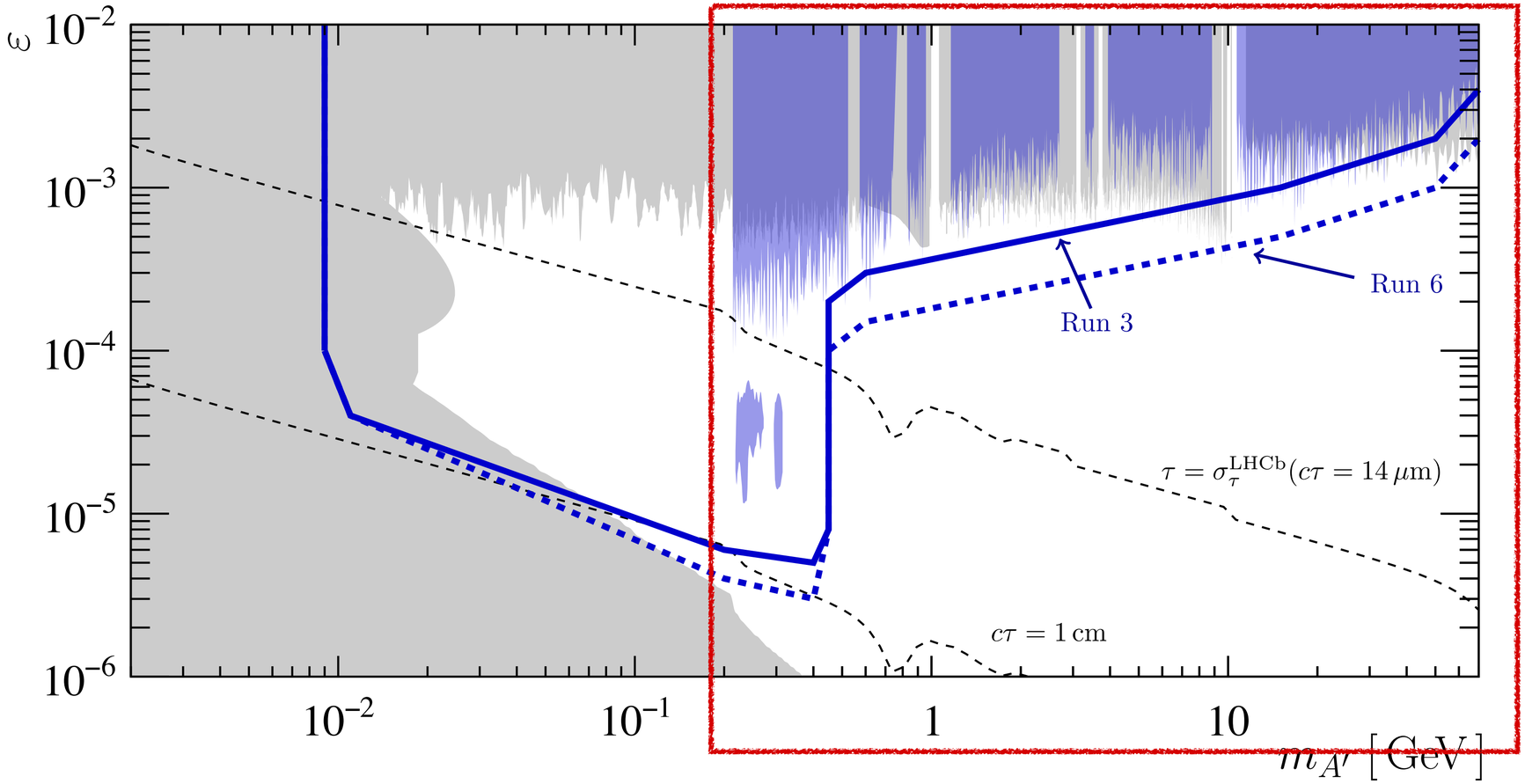
Dark Photons: Run 3

[2203.07048]

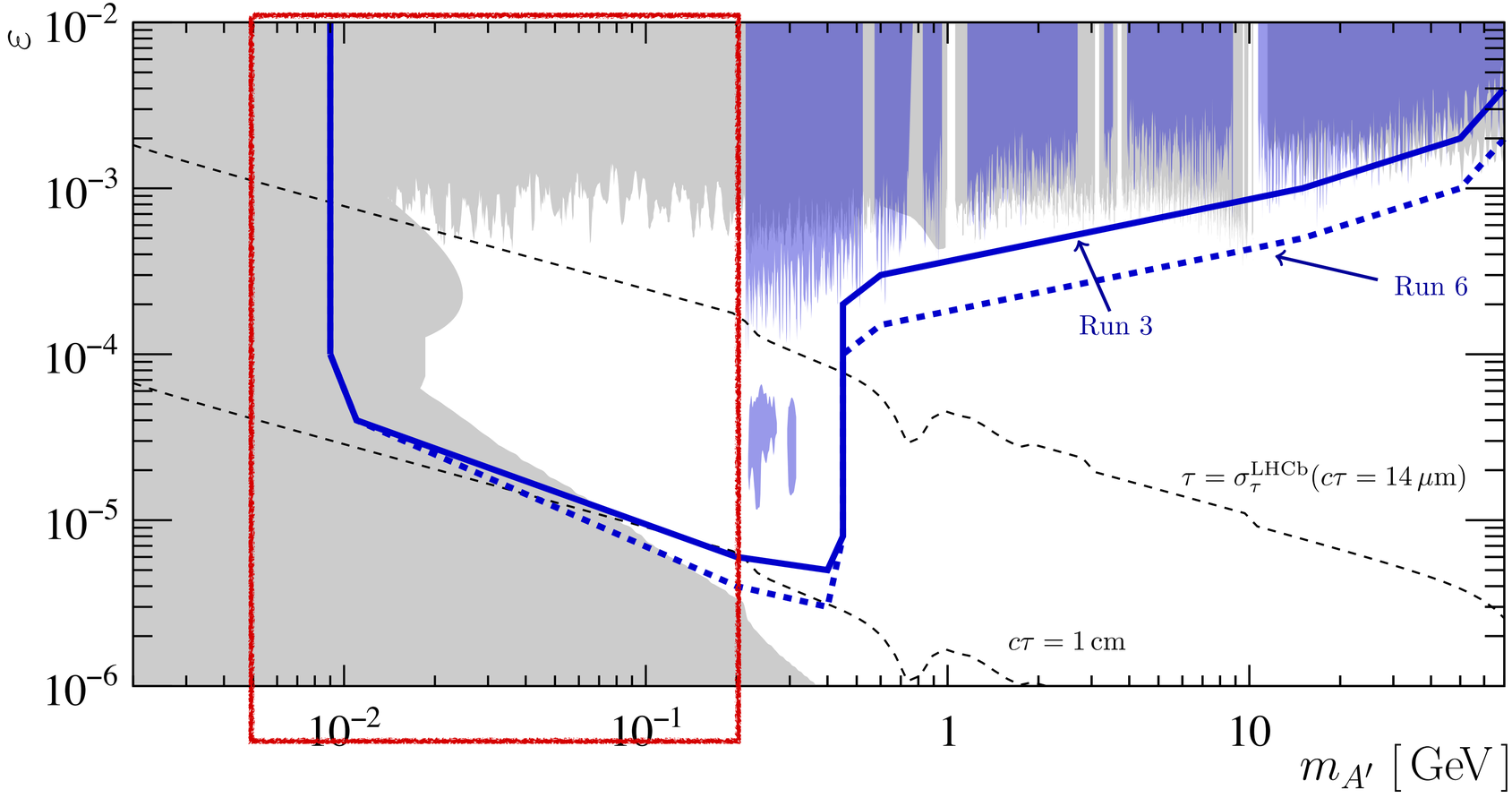
- Better reach for the dimuon search: expected to improve LHCb Run 2 result
  - During Run3 we can take all the Run2 data in ∼ a couple of months



Dark Photons: Run 3

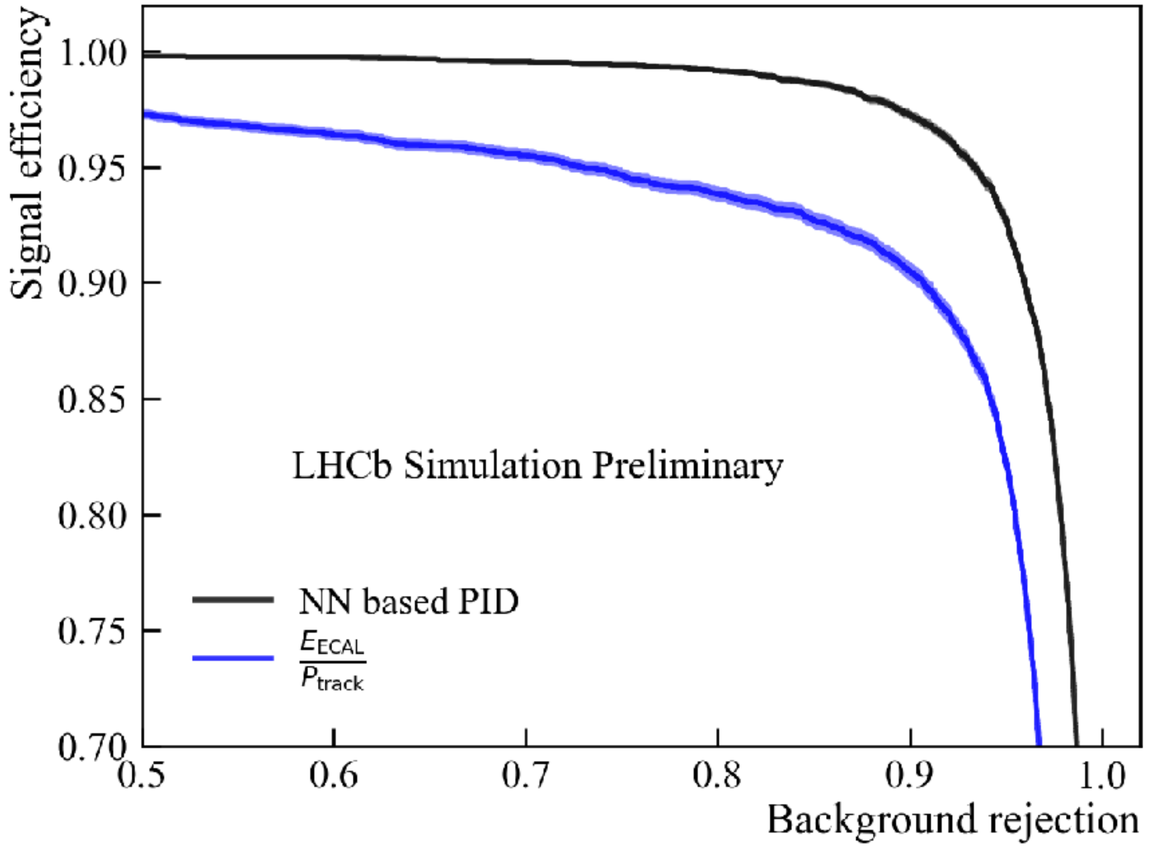
[2203.07048]

- Serious sensitivity below the 2μ threshold: dielectron channel
  - Exploit the largely produced $\pi^0 \to e^+e^-\gamma$ to easily normalise



Dark Photons: Run 3, electron PID

- Dedicated electron ID using Lipschitz constrained Neural Network
- Reconstruction of electron features at HLT1
  - $\frac{E_{\mathrm{ECAL}}}{P_{\mathrm{track}}}$
  - Electron cluster dispersion
  - Electron cluster barycentre
- 50% improvement wrt baseline EoP based selection
- “Hyper-turbo” selection:
  - Prompt dielectrons are saved to histograms right before the event is triggered
  - Fully reconstructed events are prescaled
  - Necessary to cope with the large amount of background



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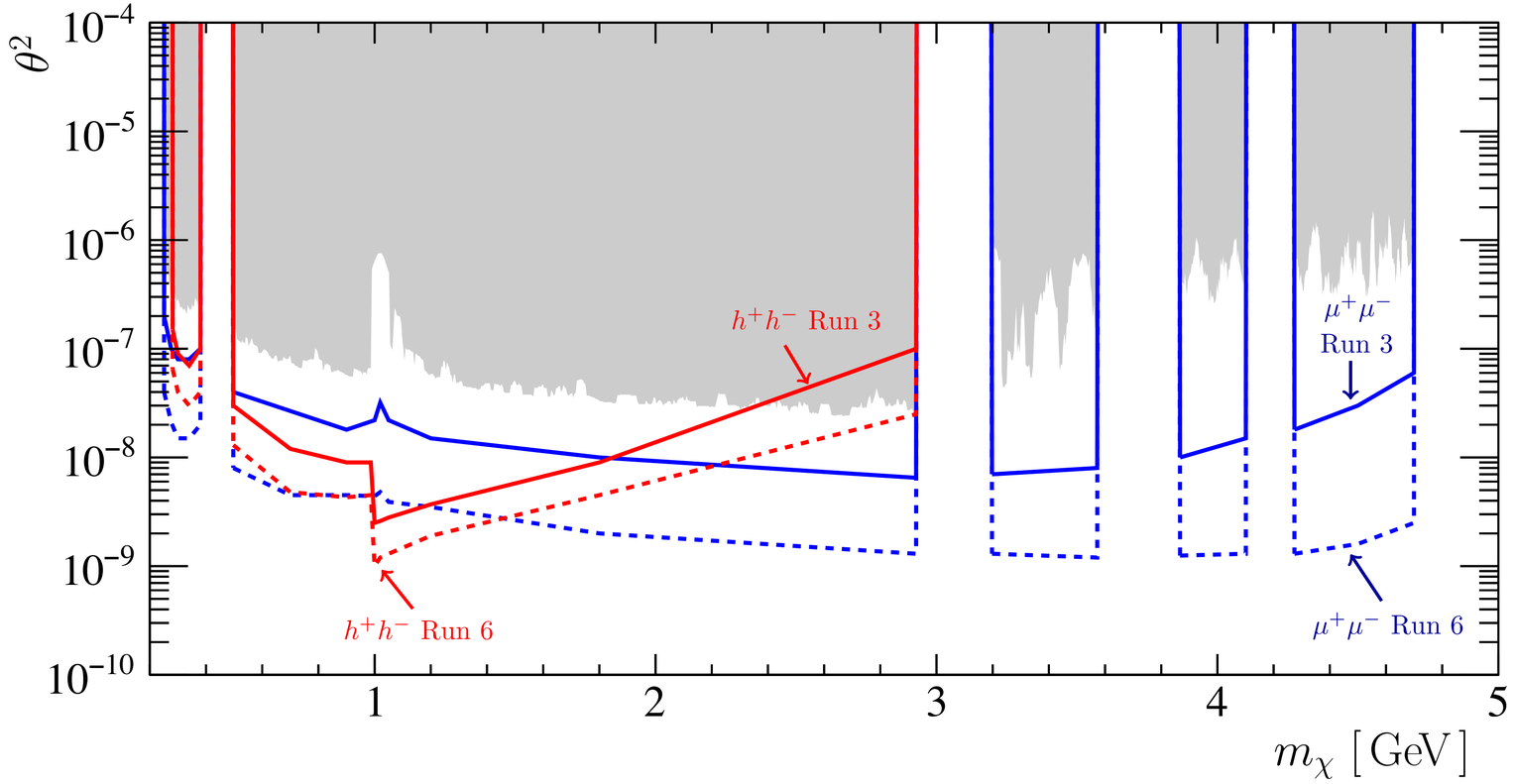
Coming up next: Higgs portal [PRD 83 (2011) 054005,PRD 96 (2017) 7, 075033, 2203.07048]



- Dark scalar coupling to the Higgs via mixing angle: θ
- $B^0 \to K^*\chi$ decays
  - Penguin decay enhancement thanks to the **top** quark mass
- Best limits placed by LHCb using Run 1 data
- Upgrading with **Run 2 data** now

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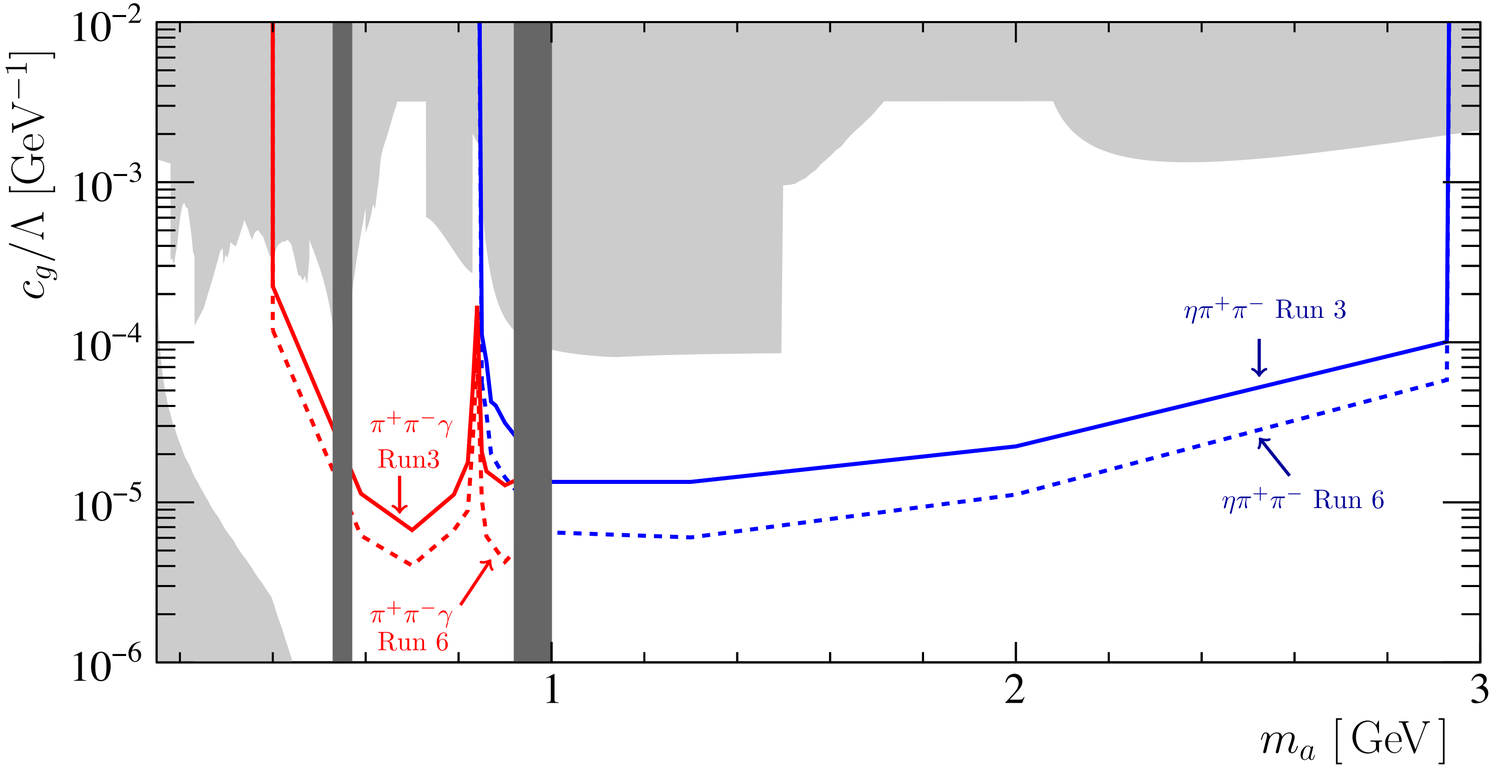
ALPs coupled to gluons

[PRL (2019) 123 031803, 2203.07048]



- Similar to HP:
  - Enhancement for $B \to K^{(*)}a$ decays
- Gluon coupling dominates in [1,3] GeV region
- ALP to hadron decays
  - $a \to \eta\pi^+\pi^-$
  - $a \to \pi^+\pi^-\gamma$
  - $a \to \pi^+\pi^-\pi^0$
- Current limits:
  - BaBar recast of η and η' spectra
- We are also updating with **Run 2** data now

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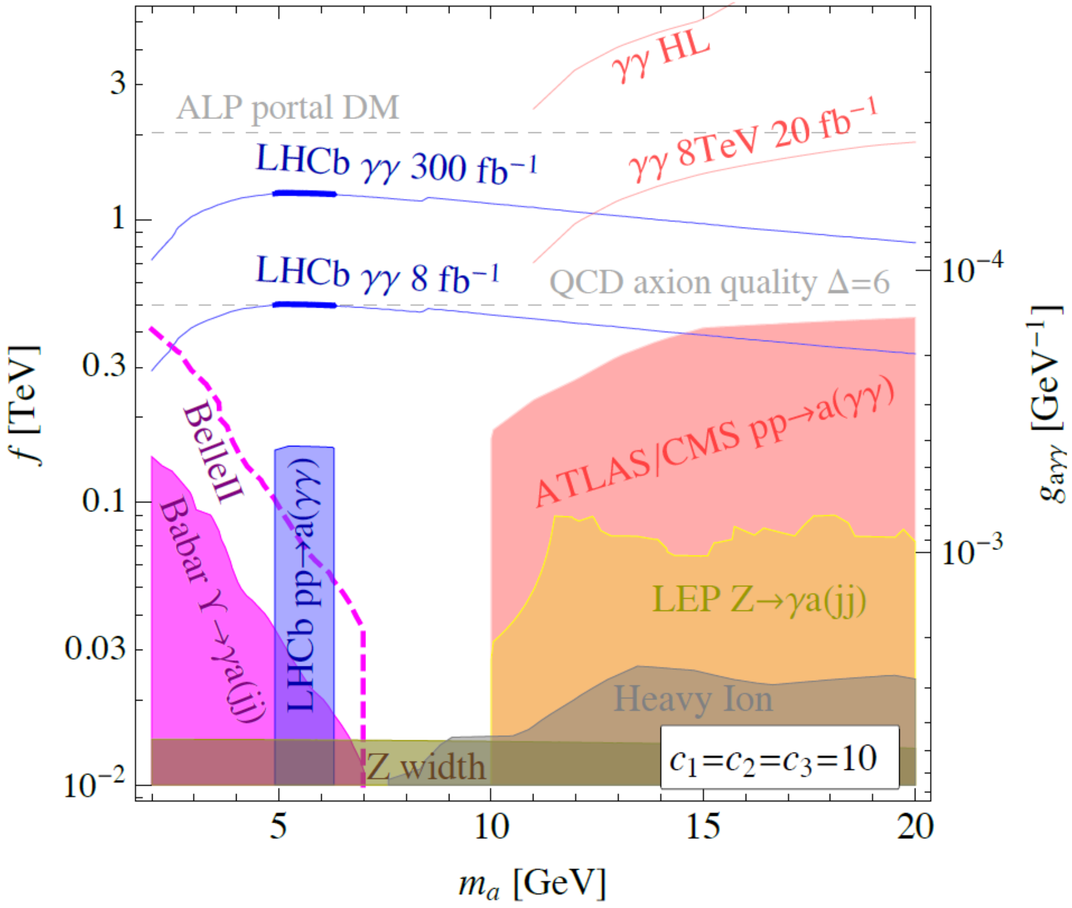
ALP $\rightarrow \gamma\gamma$

[JHEP 1901 (2019) 113]

- ALPs produced by gluon fusion decaying to $\gamma\gamma$
- Light ALPs not reachable for ATLAS and CMS
- Current **best limits** in mass gap done with **80 pb^{-1}** of **public LHCb data**
- First LHCb analysis using only unconverted photons
  - Trigger mass range extended in 2018
  - Result expected to come out later this year
    - Stay tuned!

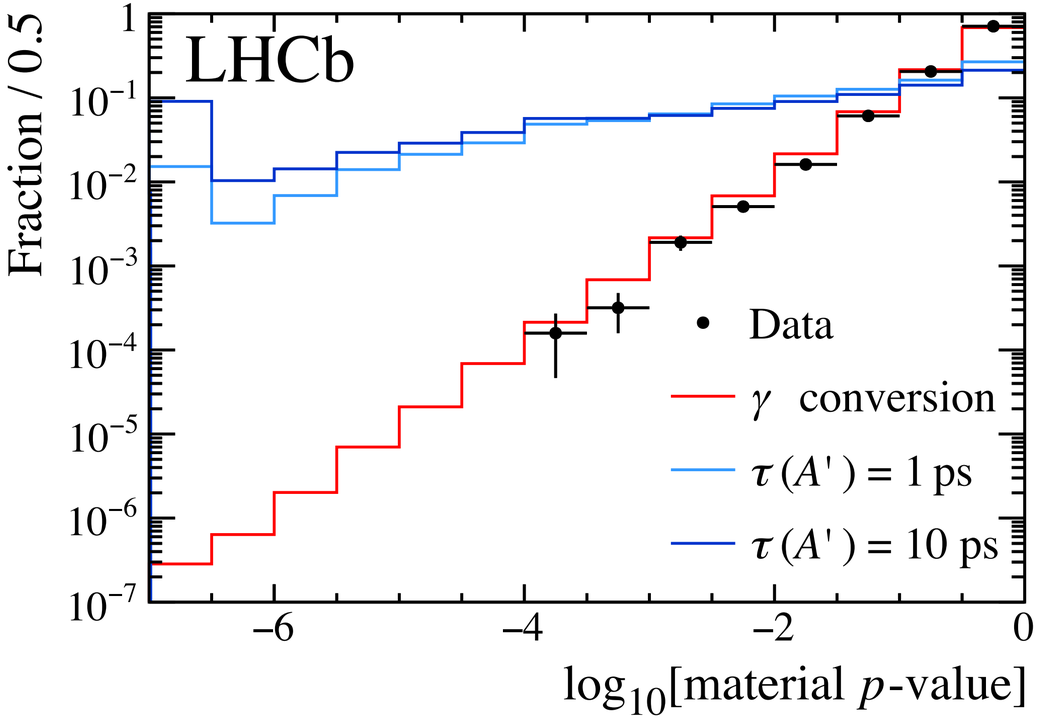


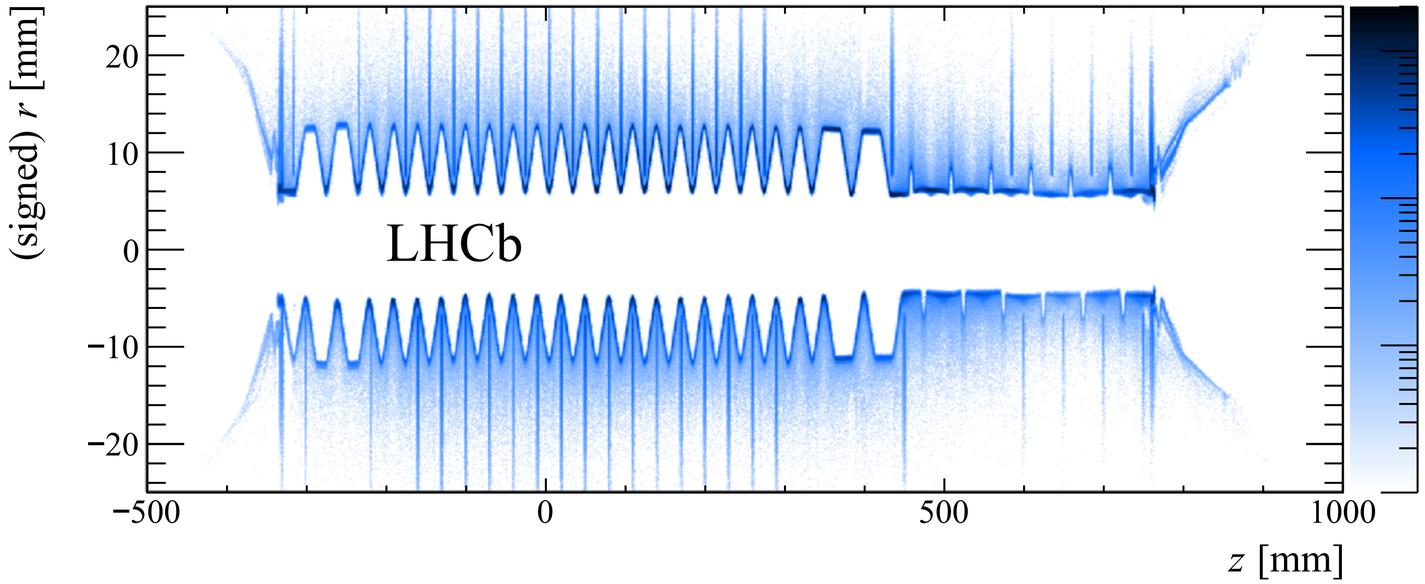
Take home

- LHCb has shown world leading $A' \to \mu^+\mu^-$ results using Run 2 [2016,2018] data:
  - Prompt decays with $m(A') \in [2m(\mu),\ 1\ \mathrm{GeV}]$ and $[1\ \mathrm{GeV},\ 10\ \mathrm{GeV}]$
  - Displaced decays with $m(A') \in [2m(\mu),\ 350\ \mathrm{MeV}]$
- Very relevant updates are expected for Run3:
  - More integrated lumi for $A' \to \mu^+\mu^-$
    - Tight muon ID at first trigger level allows to soften kinematic cuts
  - $A' \to e^+e^-$ for the first time at LHCb thanks to GPU trigger
    - Dedicated electronID at first trigger level
    - Copious $\pi^0 \to e^+e^-\gamma$ production
    - Store histograms before triggering allows to keep all candidates
- Stay tuned for new results coming from ALP and Dark Scalar soon!

BACKUP

Material interaction backgrounds [JINST 13, P06008 (2018)]





- Method to identify particles created in secondary vertices in interaction with VELO
- Three dimensional map produced from data sample of secondary hadronic interactions

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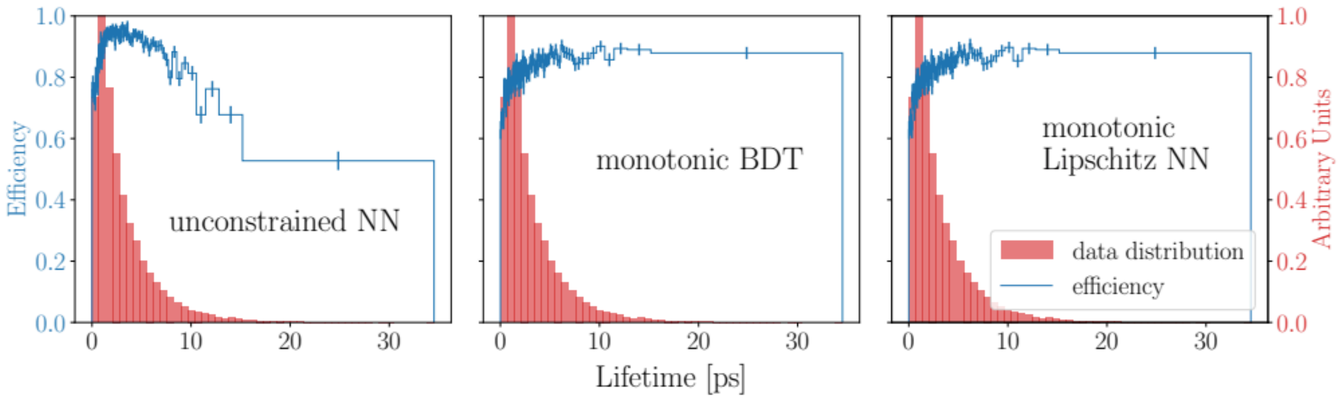
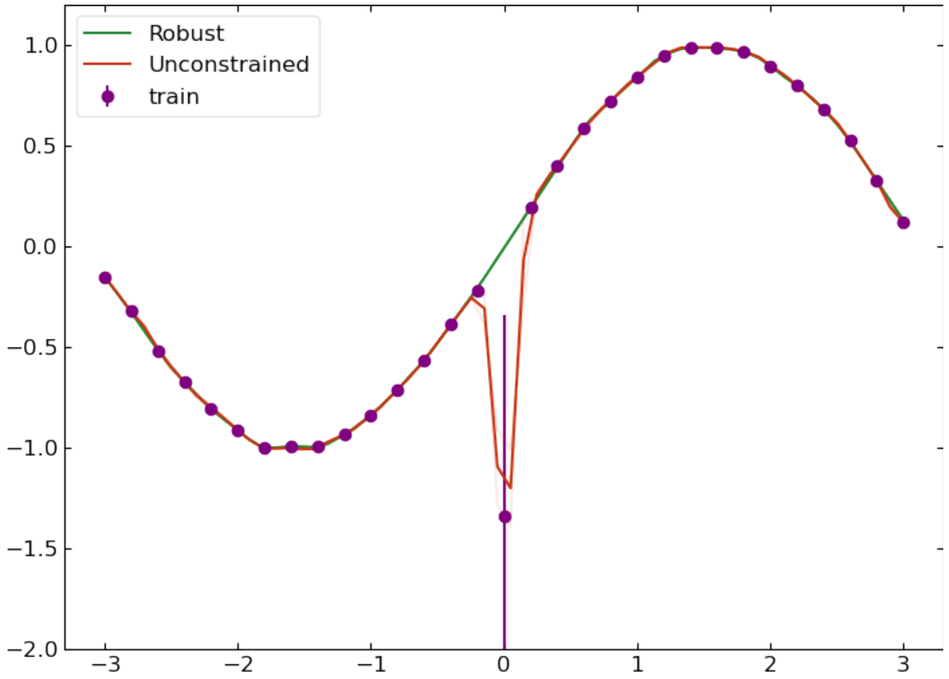
Lipschitz constrained NN [2204.10156]

- Robustness
  - Strict bound on the slope of the function
  - Natural way of rejecting noisy outliers
- Monotonicity:
  - Trigger:
    - Especially interesting for p_T and displacement



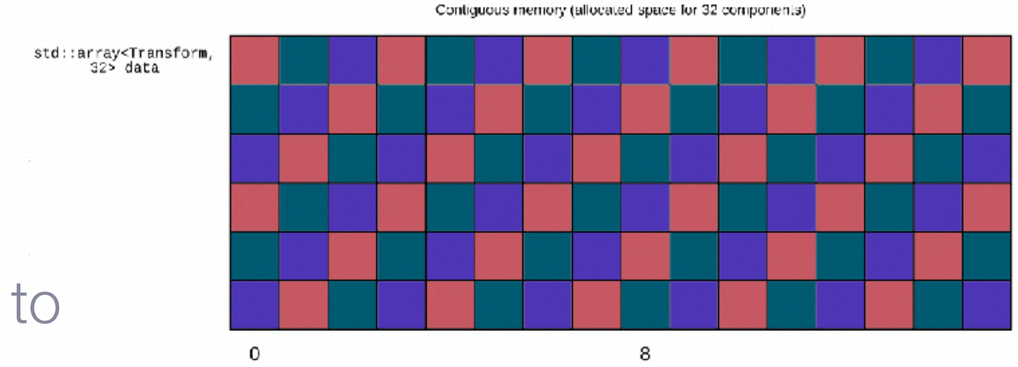


Allen: a GPU High Level Trigger for LHCb [Comput.Softw.Big Sci. 4 (2020) 1, 7]

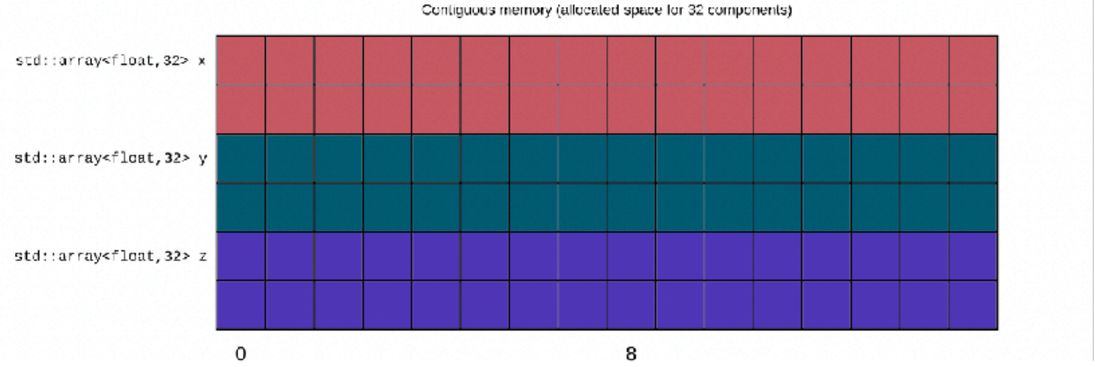
```
1  struct point3D {
2      float x;
3      float y;
4      float z;
5  };
6  struct point3D points[N];
7  float get_point_x(int i) { return points[i].x; }
```

```
1  struct pointlist3D {
2      float x[N];
3      float y[N];
4      float z[N];
5  };
6  struct pointlist3D points;
7  float get_point_x(int i) { return points.x[i]; }
```

AOS layout



SOA layout



Thanks to Renato Quagliani for the diagrams

- Contiguous memory access: structure of arrays (SoA)
  - Structure of "BIG" arrays that hold information of a bunch of events
- Adequate when a lot of memory is being written/read at the same time
- Block Index + Thread Index → Position in the array

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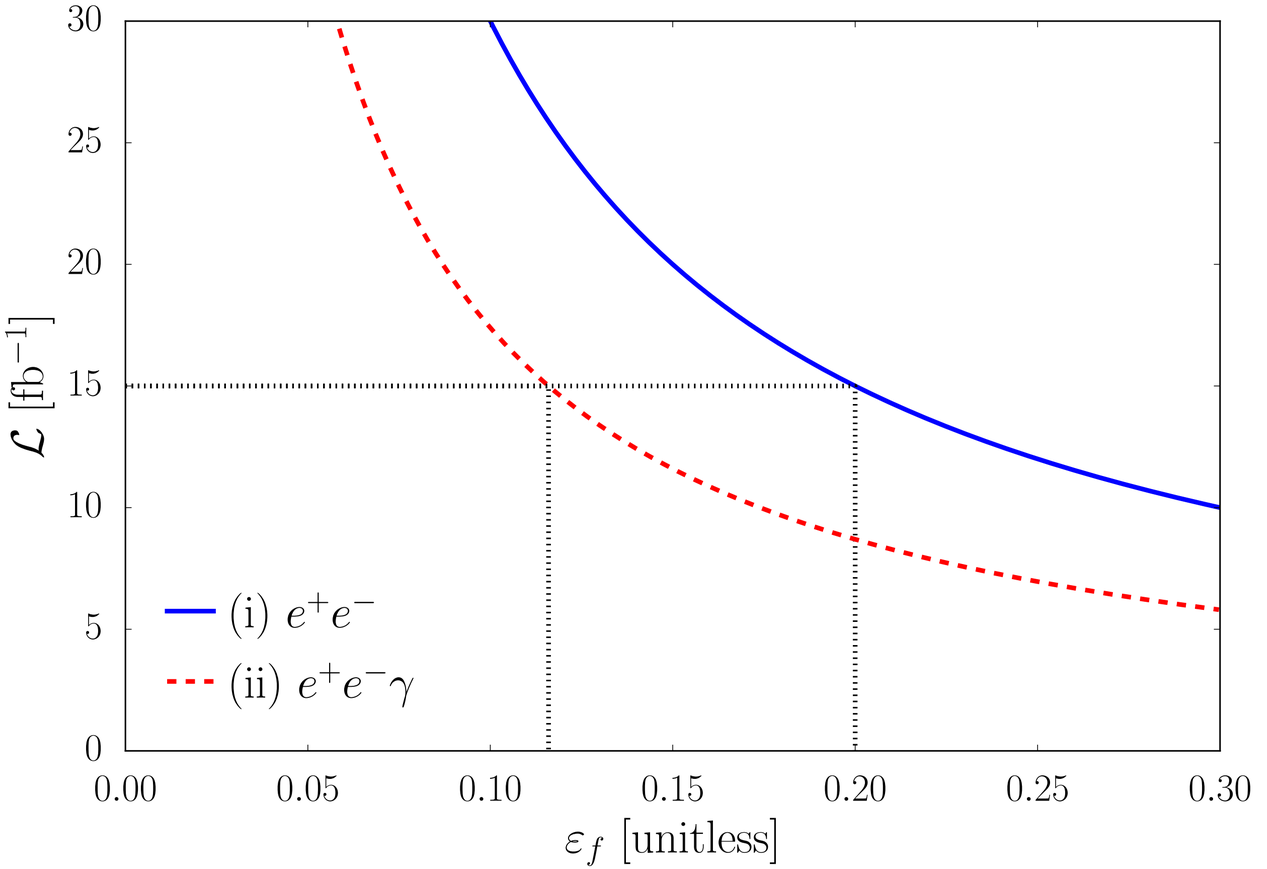
True muonium

[*Phys.Rev.D* 100 (2019) 5, 053003]

- Standard Model bound state
- Never observed
- Same final state as a $A' \to e^+e^-$
- Discovery potential using the full Run 3



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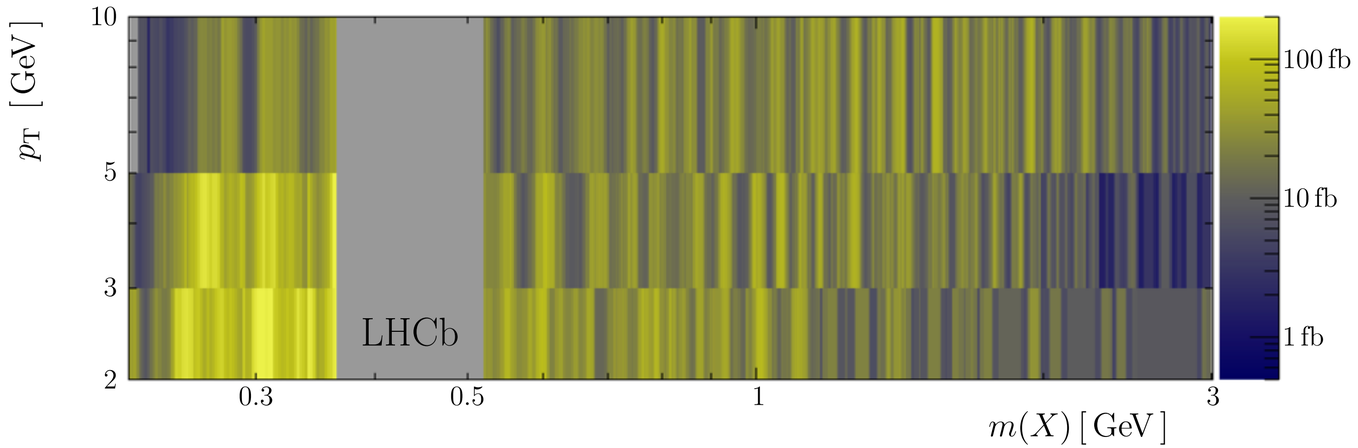
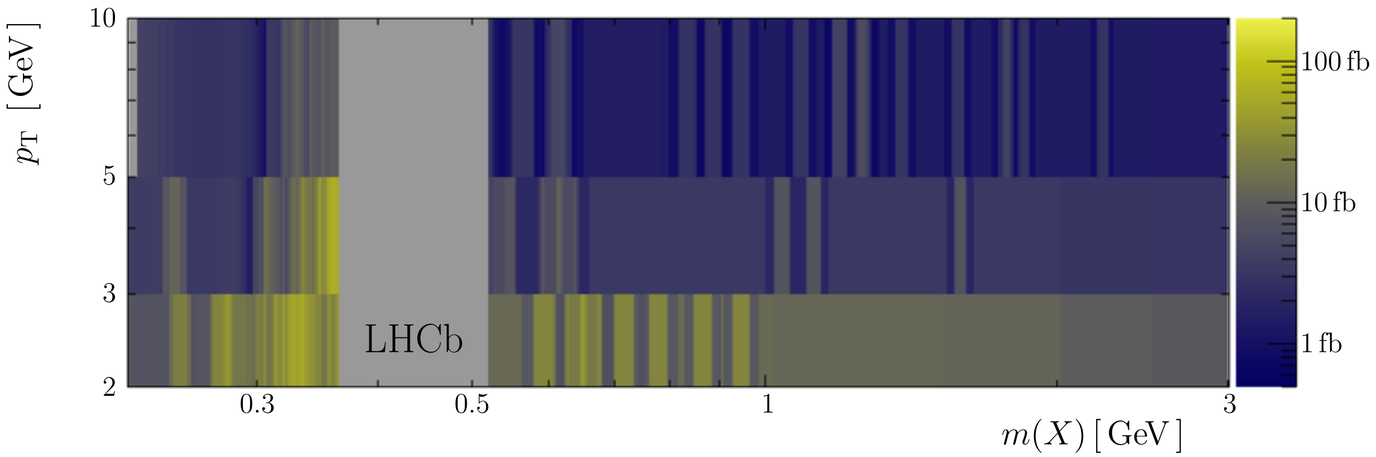
Dimuon resonances

[JHEP 10 (2020) 156]



- Inclusive displaced $\mu^+\mu^-$



- Inclusive prompt $\mu^+\mu^-$

- Inclusive search in the prompt and dimuon spectrum:
  - Easy recast of excluded cross-section