

DARK SECTOR PROBES FROM THE LHCb EXPERIMENT

33RD RENCONTRES DE BLOIS - DARK UNIVERSE(S)

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on behalf of the **LHCb** collaboration

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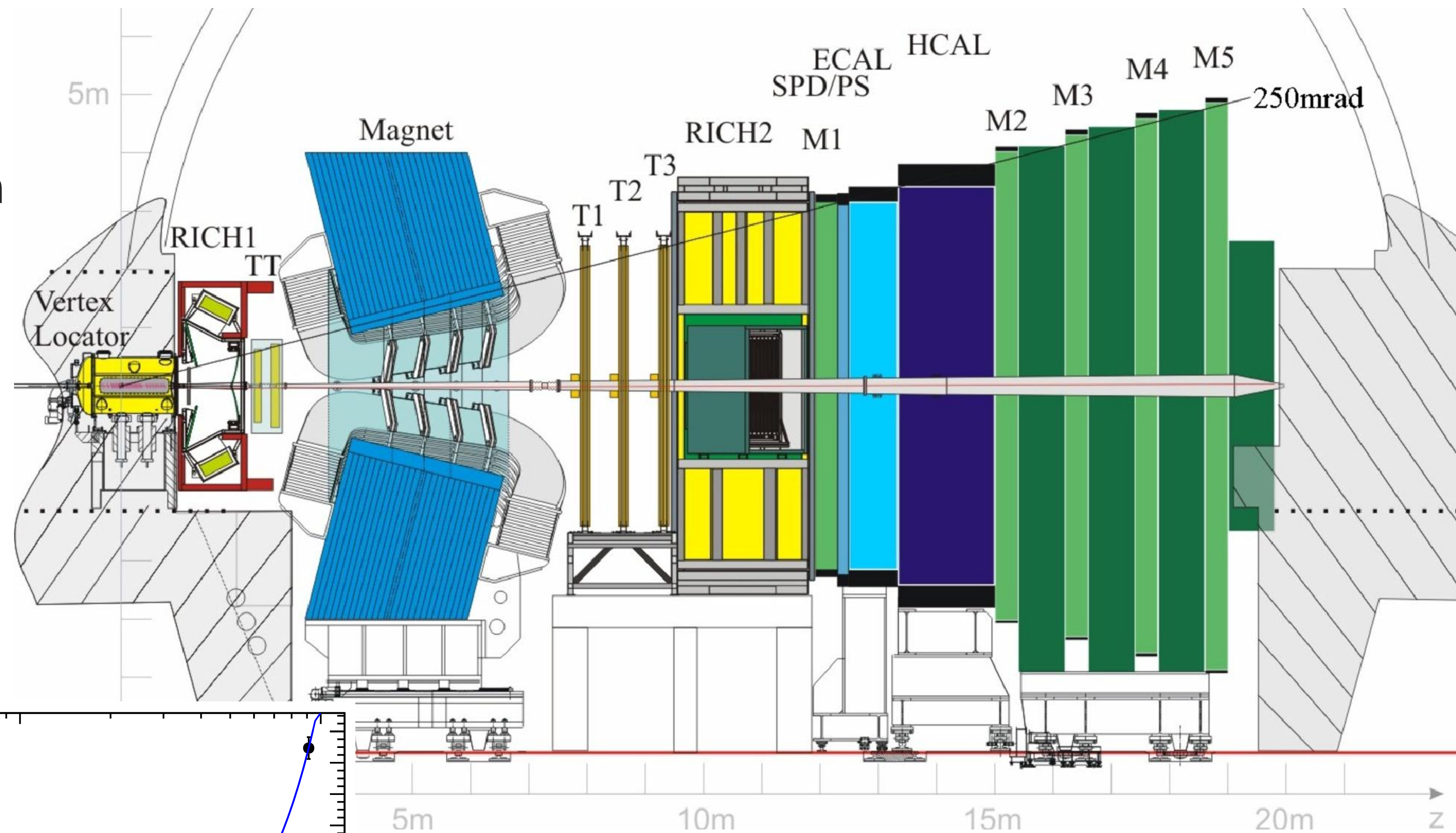
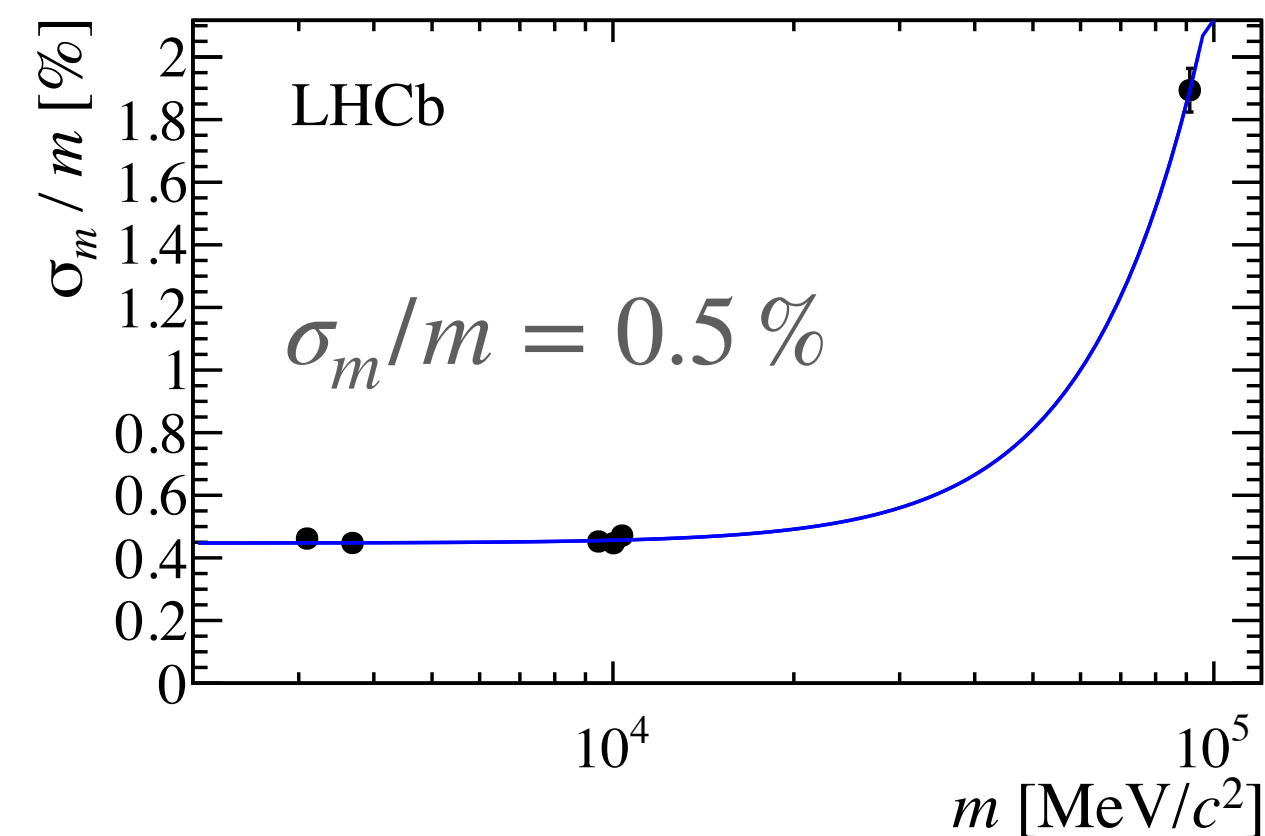
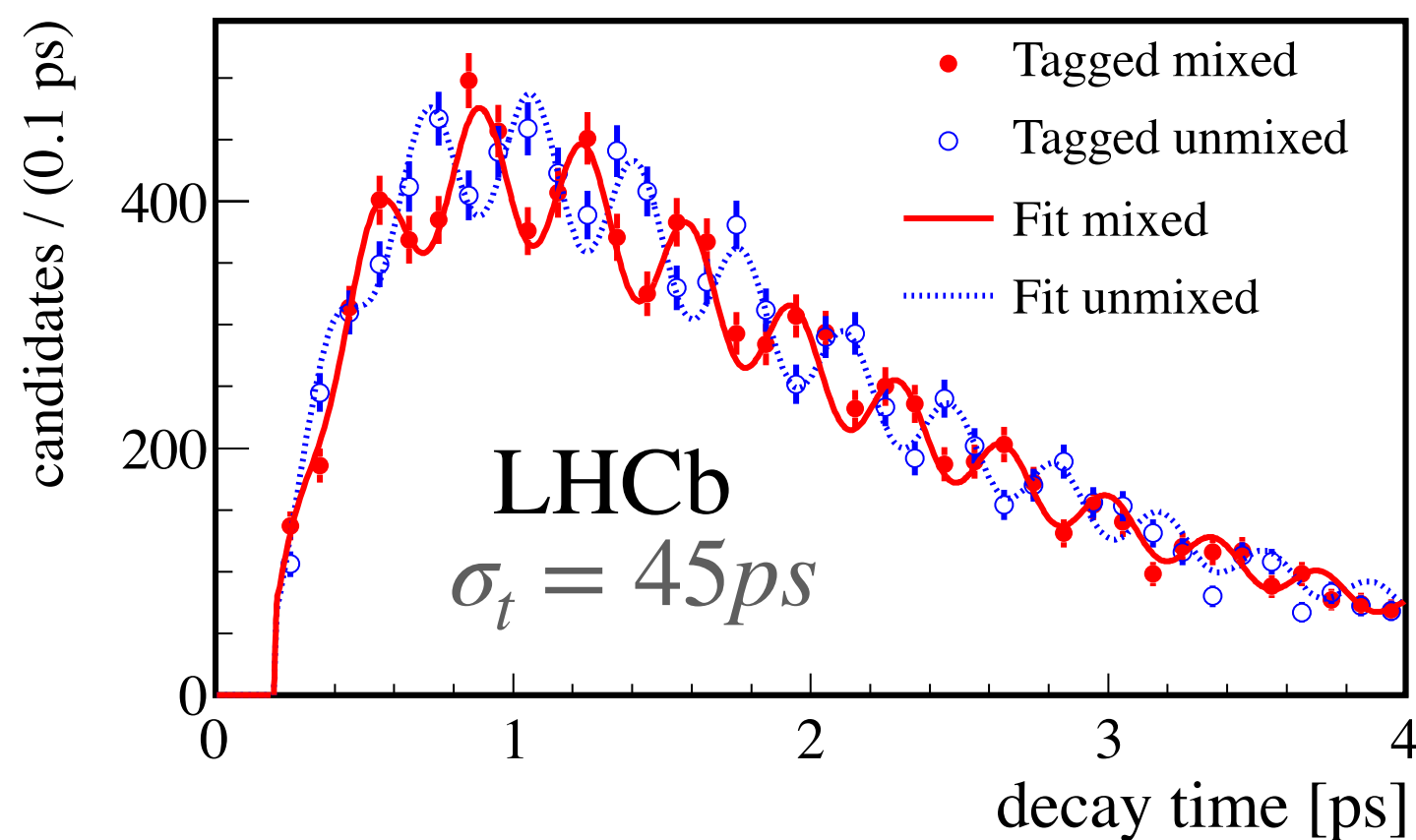
25/05/2022



EPFL

The LHCb detector [Int.J.Mod.Phys. A 30, 1530022 \(2015\)](#)

- **LHCb** is a dedicated flavour experiment in the forward region at LHC ($1.9 < \eta < 4.9$) or ($\sim 1^\circ - 15^\circ$)
- Excellent vertex, mass and lifetime resolution
- Unique particle ID
- Lower luminosity:
 - $\sim 1/8$ of ATLAS/CMS in Run 1
 - $\sim 1/20$ in Run 2
- Decay time for $B_s^0 \rightarrow D_s^- \pi^+$

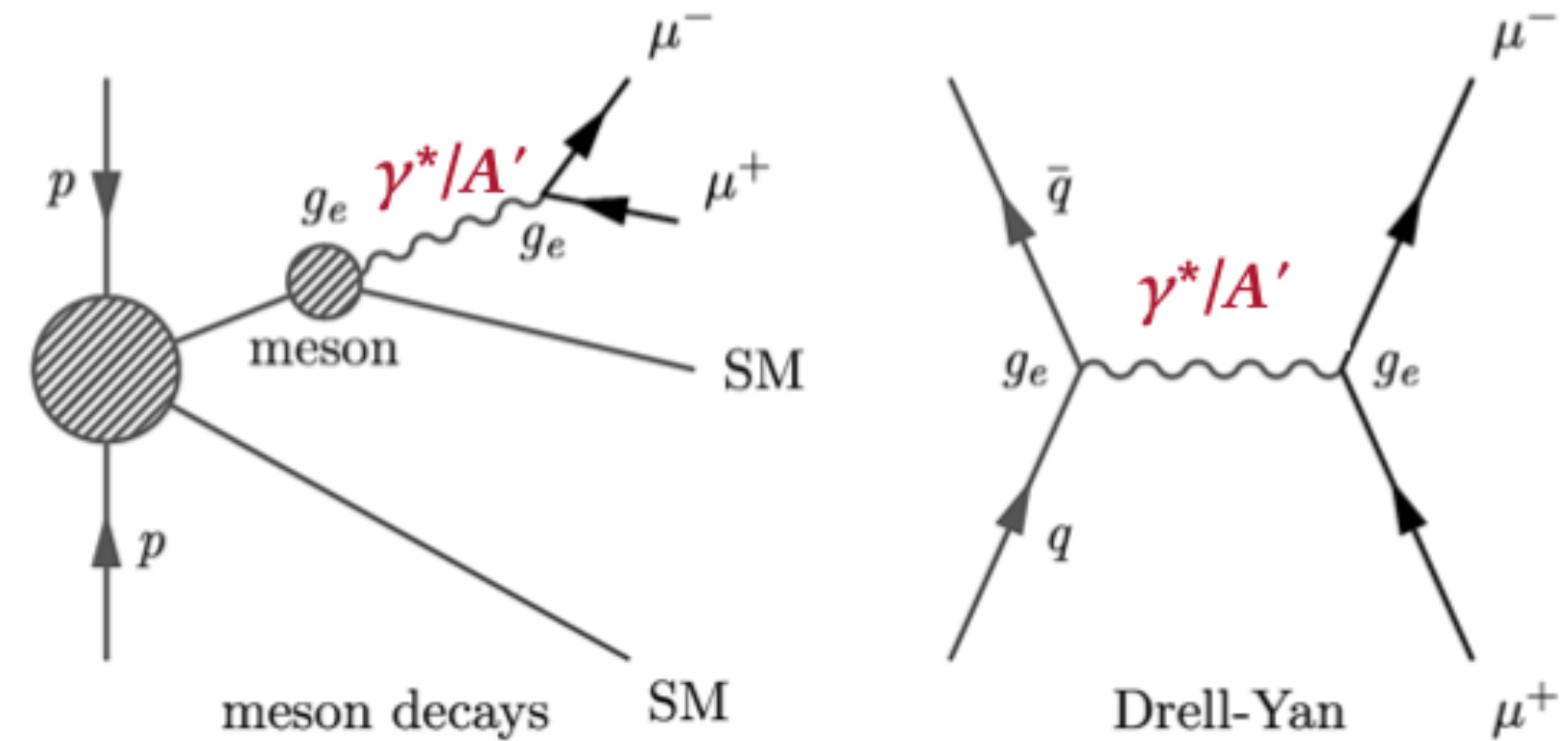


Dark sector searches at LHCb

- LHCb advantages:
 - **Light masses:** triggers with low p_T thresholds
 - **Low lifetimes:** VELO performance and large boosts in forward acceptance
- Signatures and models:
 - **Low-mass dimuons:** dark photons and non-minimal models
 - **Long-lived particles:** decaying (semi-)leptonically and hadronically
 - **B-meson decays:** hidden-sector bosons, HNLs

Dark Photon [PRL\(2020\) 124 041801](#)

- Kinetic mixing of the dark photon A' with off-shell photon γ^*
 - Proportional to ϵ^2
 - A' inherits production mode mechanisms from γ^*
 - $A' \rightarrow \mu^+ \mu^-$ can be normalised to $\gamma^* \rightarrow \mu^+ \mu^-$
- Separate γ^* signal from background and measure its fraction
- **Prompt-like** search (up to $70 \text{ GeV}/c^2$)
 - No need for efficiencies from simulation
→ fully data-driven search!
- **Displaced-like** search ($214 - 350 \text{ MeV}/c^2$)
- First search is published with 2016 dataset **PRL 120 (2018) no.6, 061801**
- Now with full Run 2 dataset + improved trigger efficiency



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

off-shell photon

phase-space

A'/γ^* eff ratio,
 $\epsilon=1$ for prompt

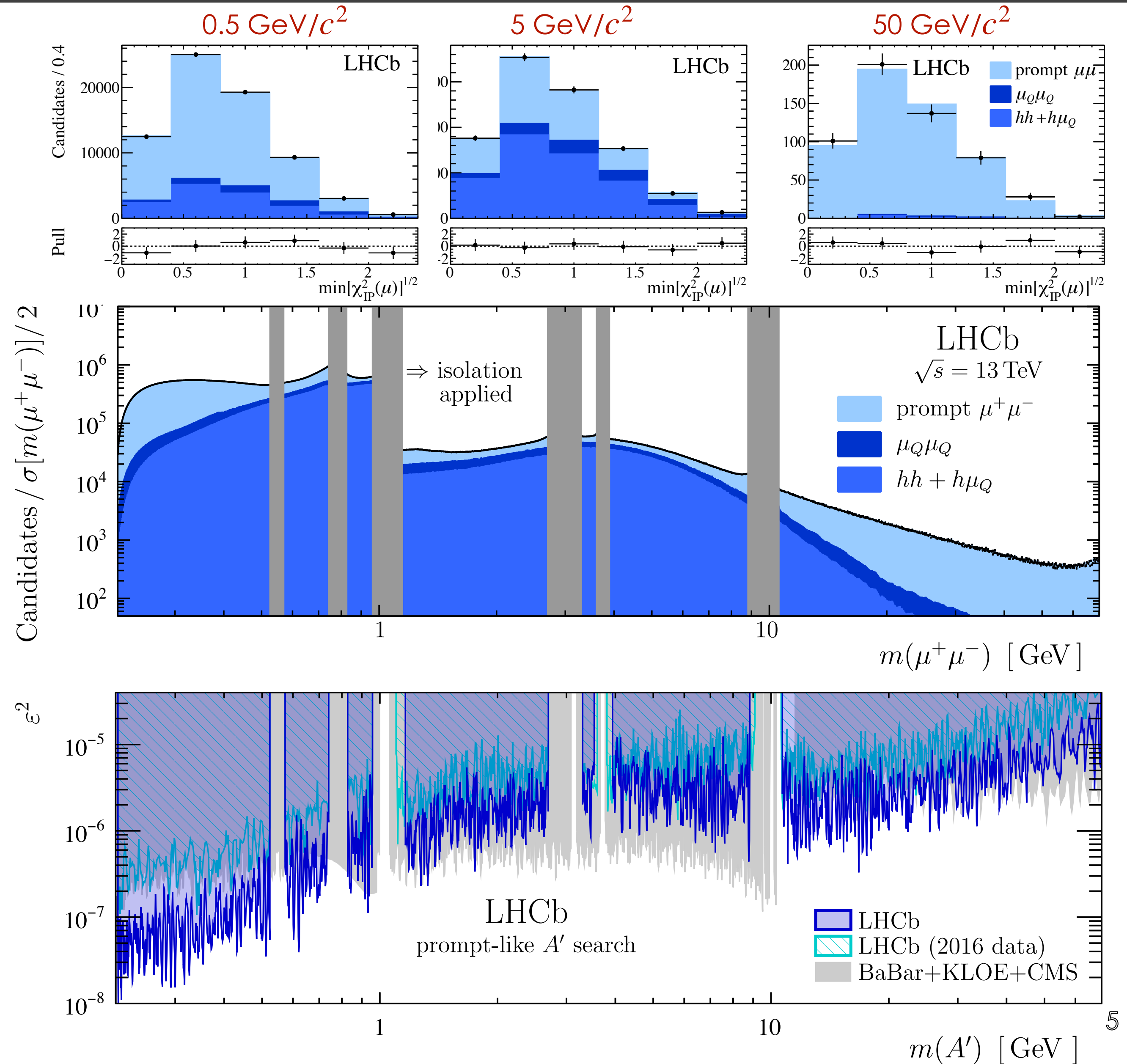
Dark Photon / Prompt-like [PRL\(2020\) 124 041801](#)

- Mass spectrum scanned in steps of $\sigma[m(\mu^+\mu^-)]/2$ searching for $A' \rightarrow \mu^+\mu^-$ contributions

- prompt $\mu\mu$ \rightarrow from $m(J/\psi)$ and $m(Z)^*$
- $\mu_Q\mu_Q$ \rightarrow from simulation
- $hh + h\mu_Q$ \rightarrow from same-sign dimuons

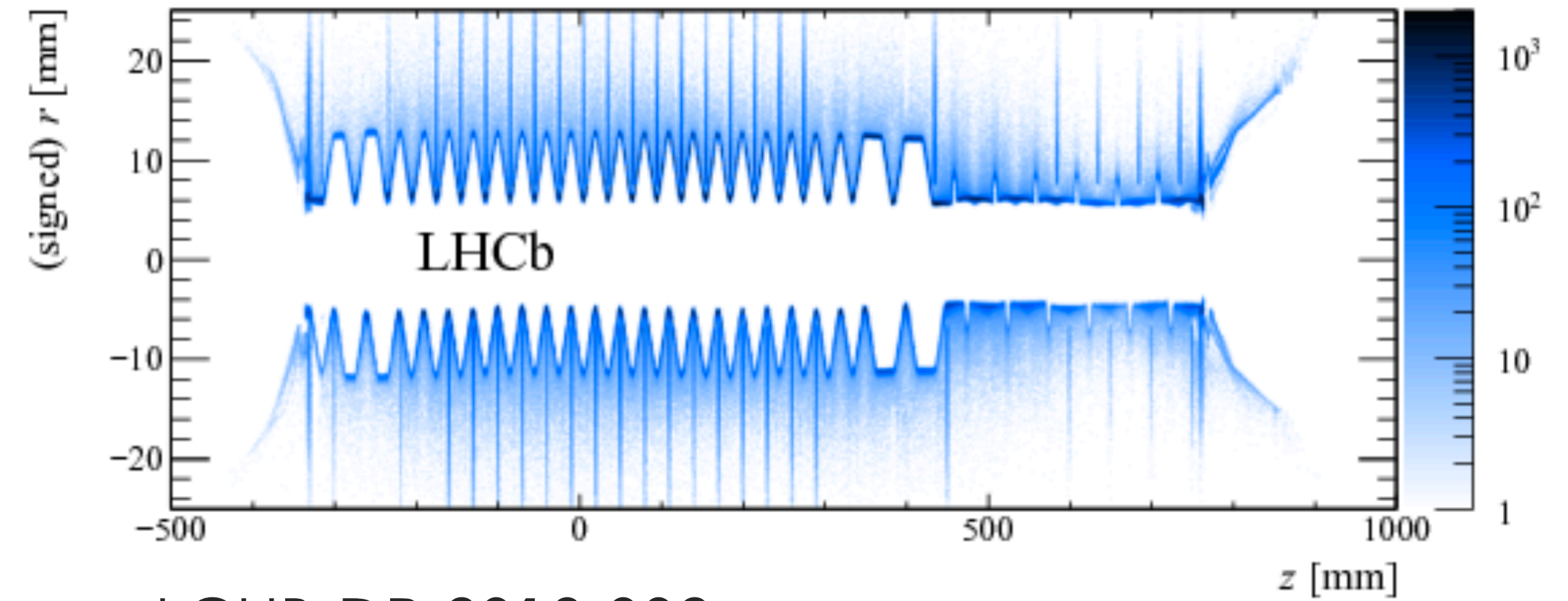
- Regions with known resonances are removed

* validated on $m(\phi)$ and $m(\Upsilon(1S))$



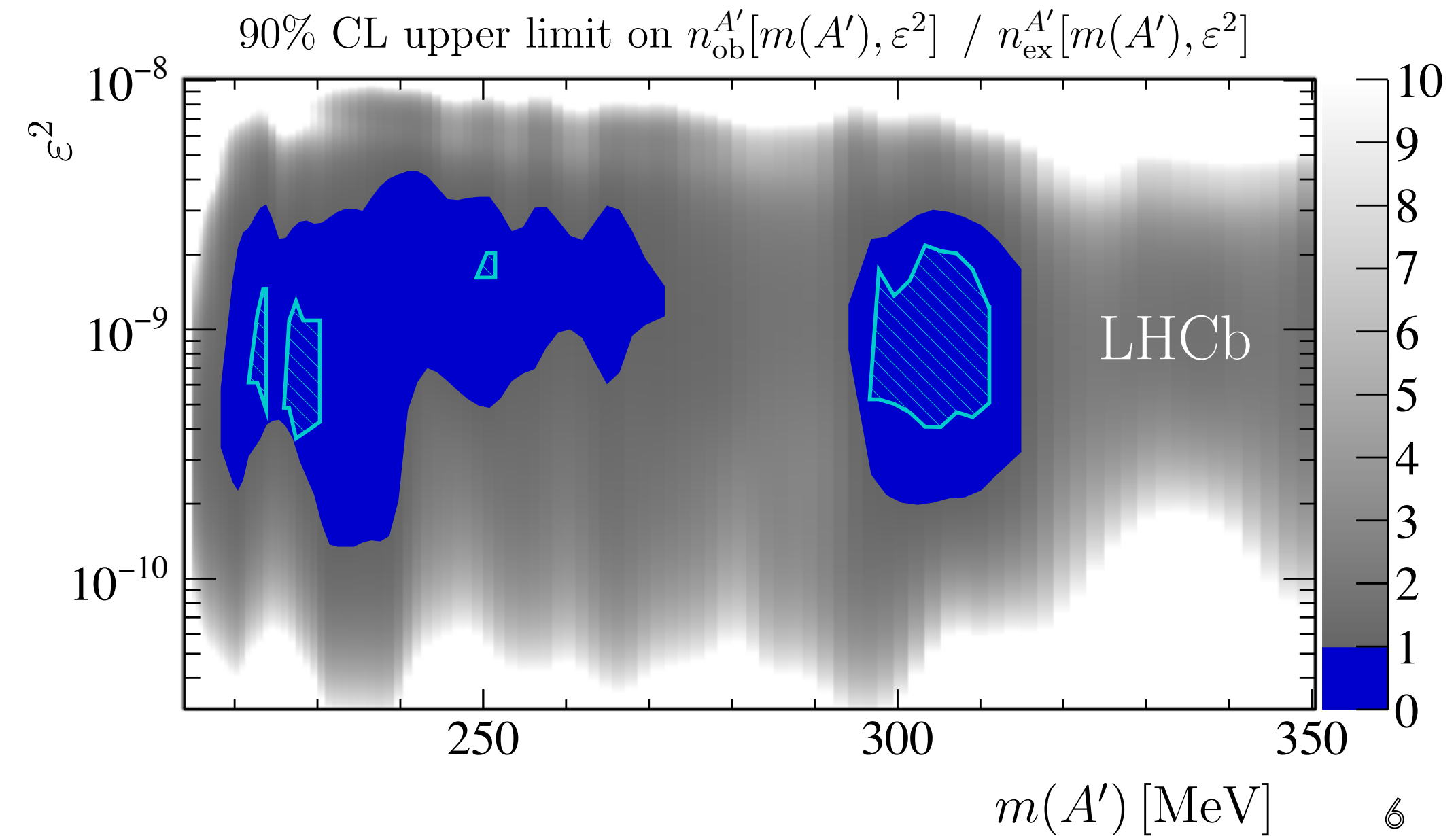
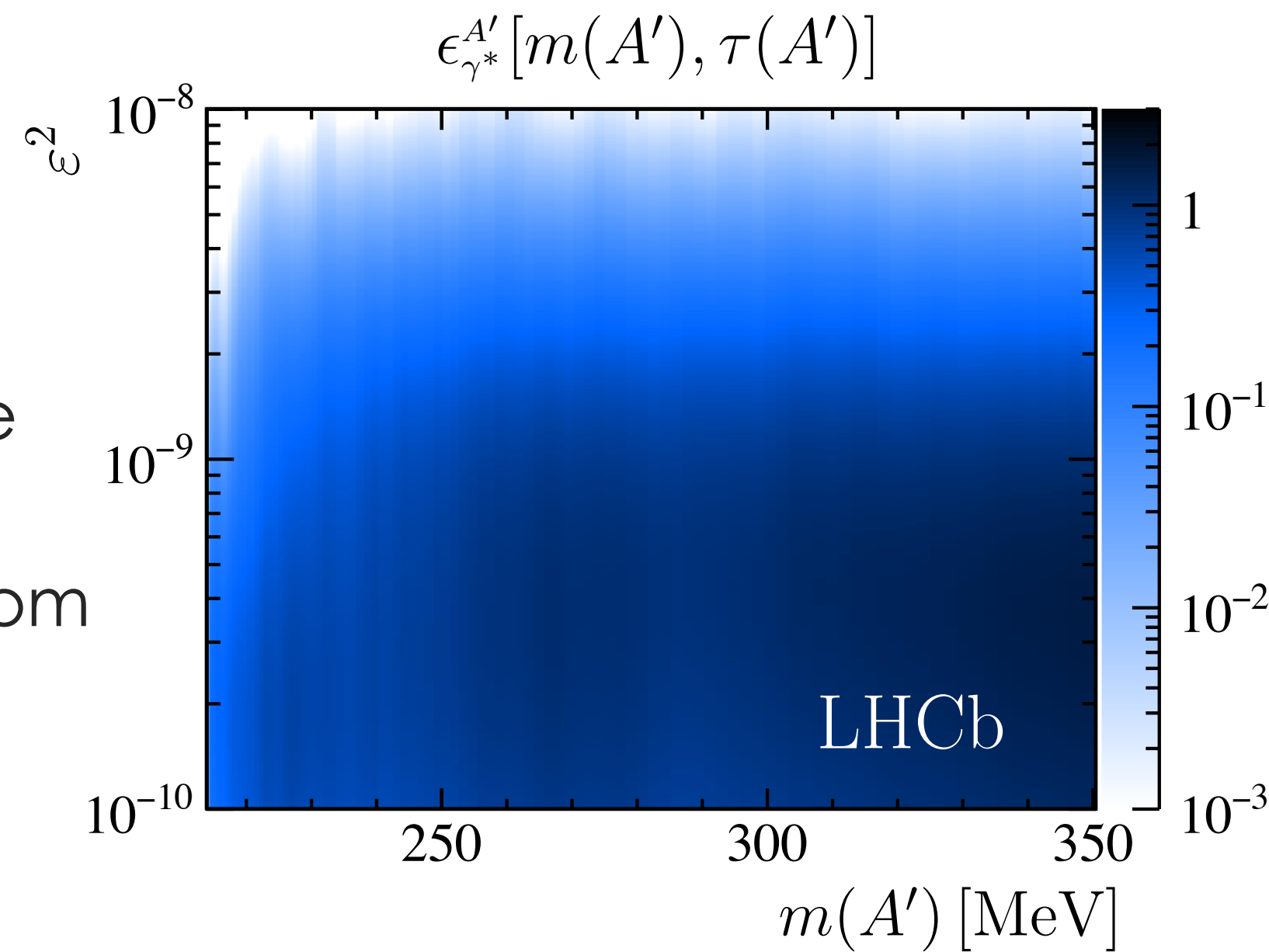
Dark Photon / Displaced-like [PRL\(2020\) 124 041801](https://arxiv.org/abs/1204.1801)

- Displaced $\mu\mu$ in Vertex Locator ($d < 20$ cm)
- Loose online requirements on $p_T(\mu)$
- Main backgrounds:
 - from γ conversion in the VELO
 - b decays with 2μ , and misID $K_s^0 \rightarrow \pi^+\pi^-$
- Fit in bins of mass, lifetime and χ_{DF}^2 (consistency of decay topology)

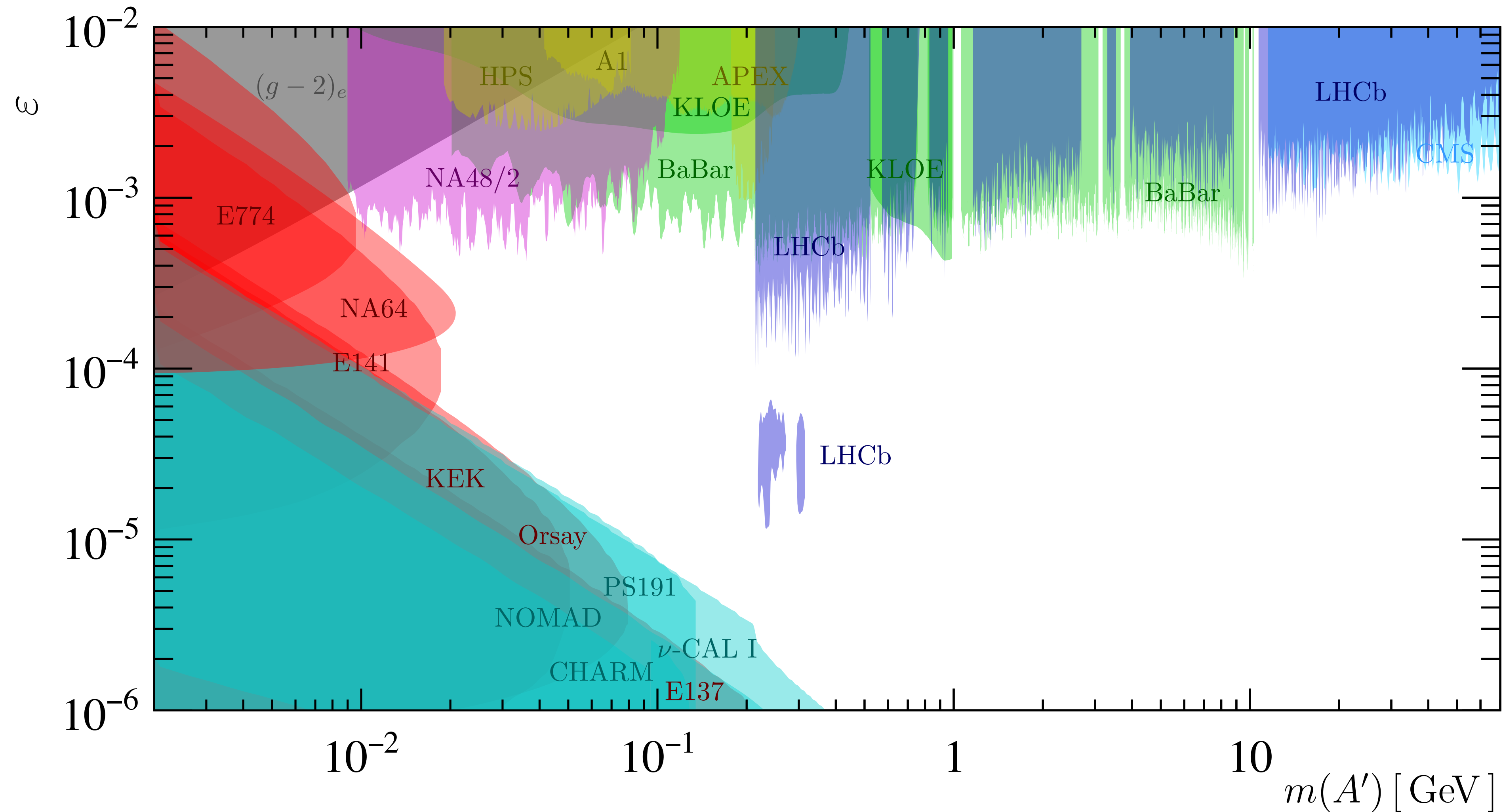


LCHB-DP-2018-002

- No significant excess is found \rightarrow
- Excluded region of phase space (ϵ^2, m) is the only displaced limit coming from not the beam-dump experiments!



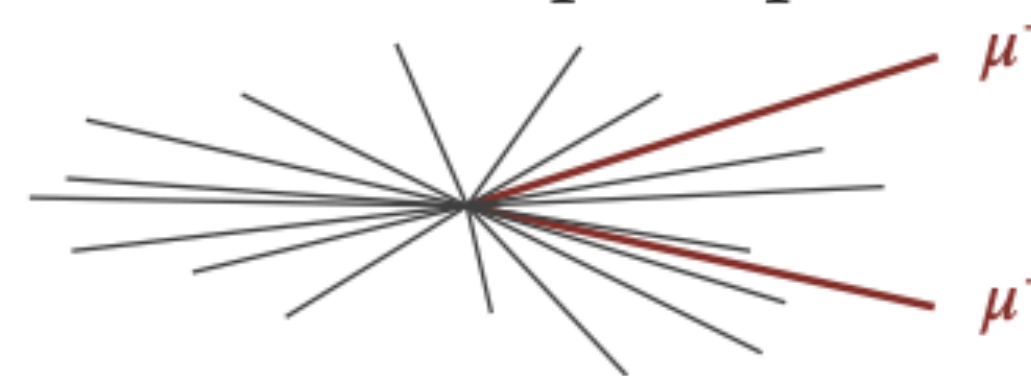
- Easy to recast to other vector models [JHEP 06 \(2018\) 004](#)
- In Run 3 we could also use $D^* \rightarrow D^0 A'(e^+e^-)$ [PRD 92, 115017 \(2015\)](#)



Inclusive $X \rightarrow \mu^+ \mu^-$ search [JHEP 10 \(2020\) 156](#)

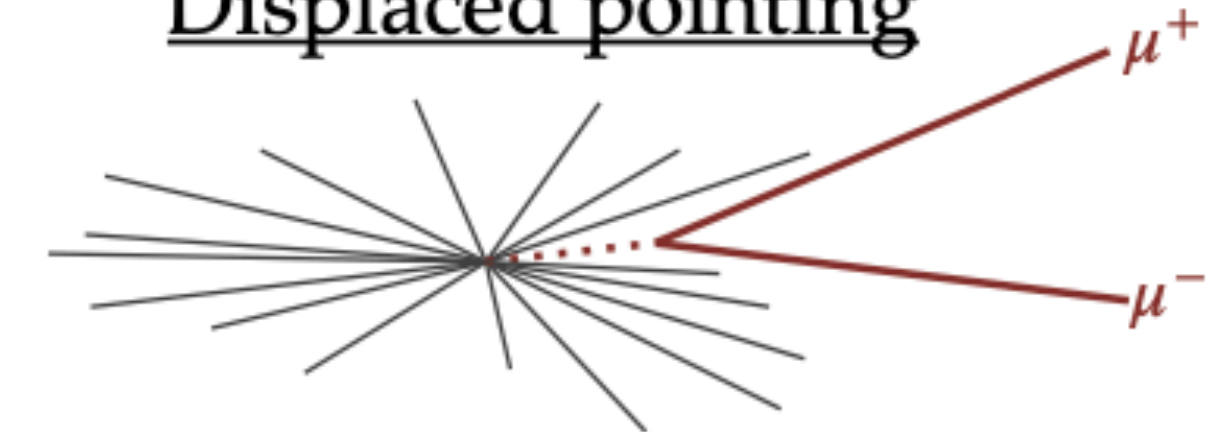
- Probe additional dark sectors in $\mu\mu$
 - Same trigger as the dark photon search
 - Drop assumption of kinetic mixing with γ^*
 - Minimise assumptions on production mechanism and the requirements placed on the event

Inclusive prompt

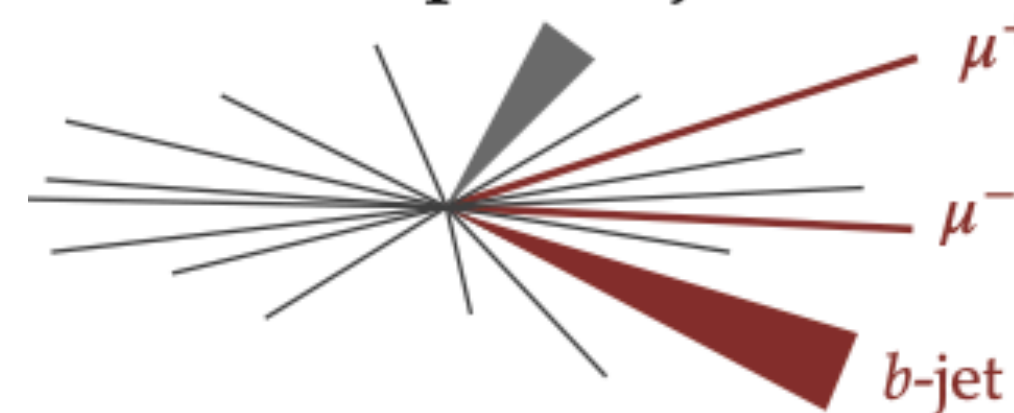


- No isolation requirements
- Non-zero width considered

Displaced pointing

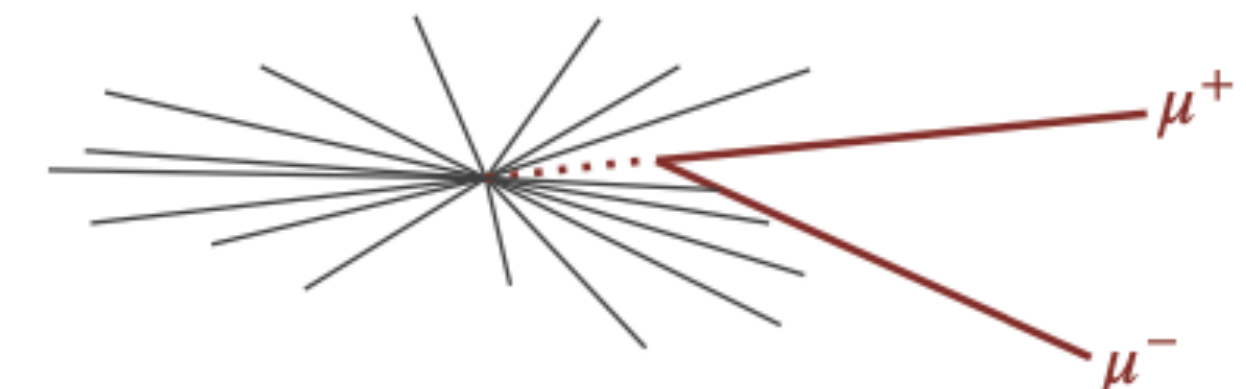


Prompt + b-jet

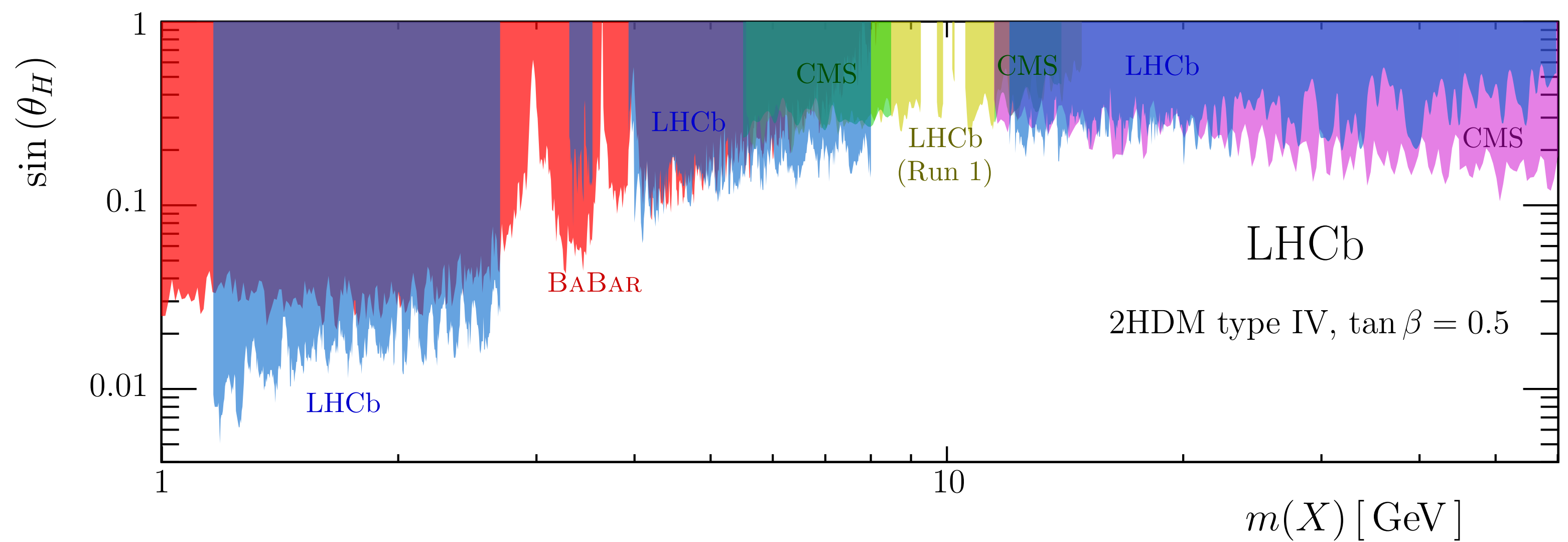
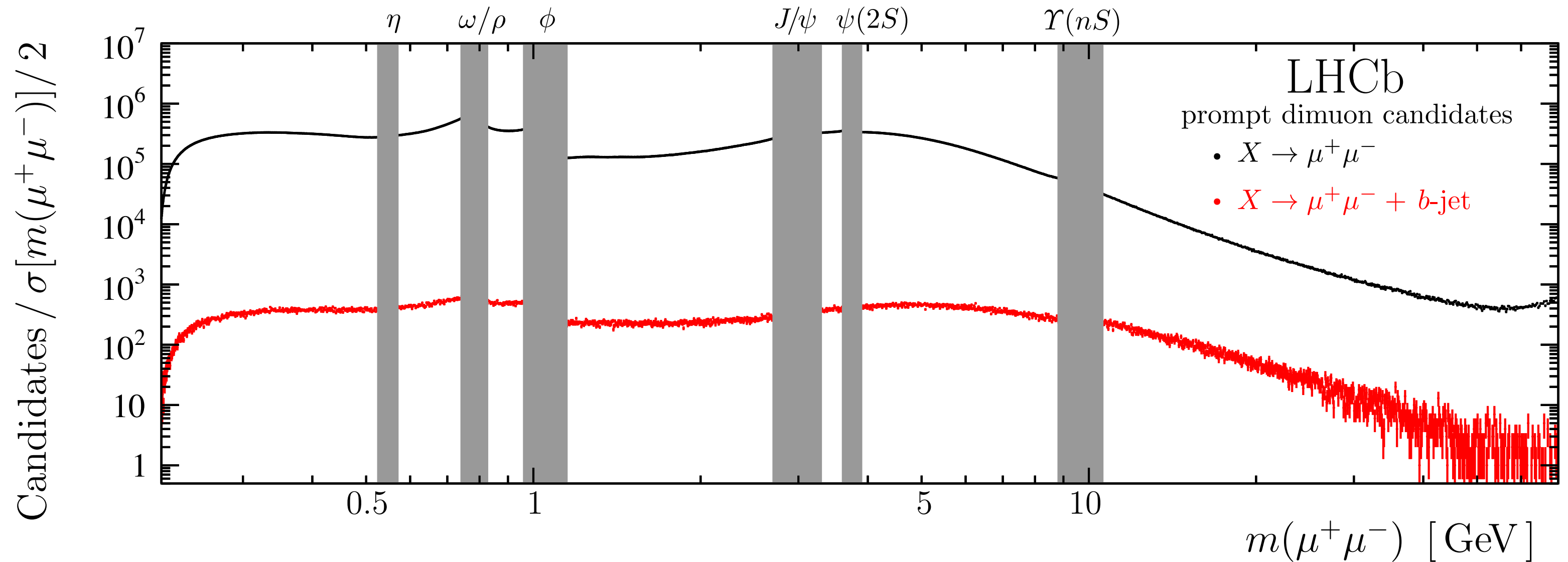


- Non-zero width considered

Displaced non-pointing

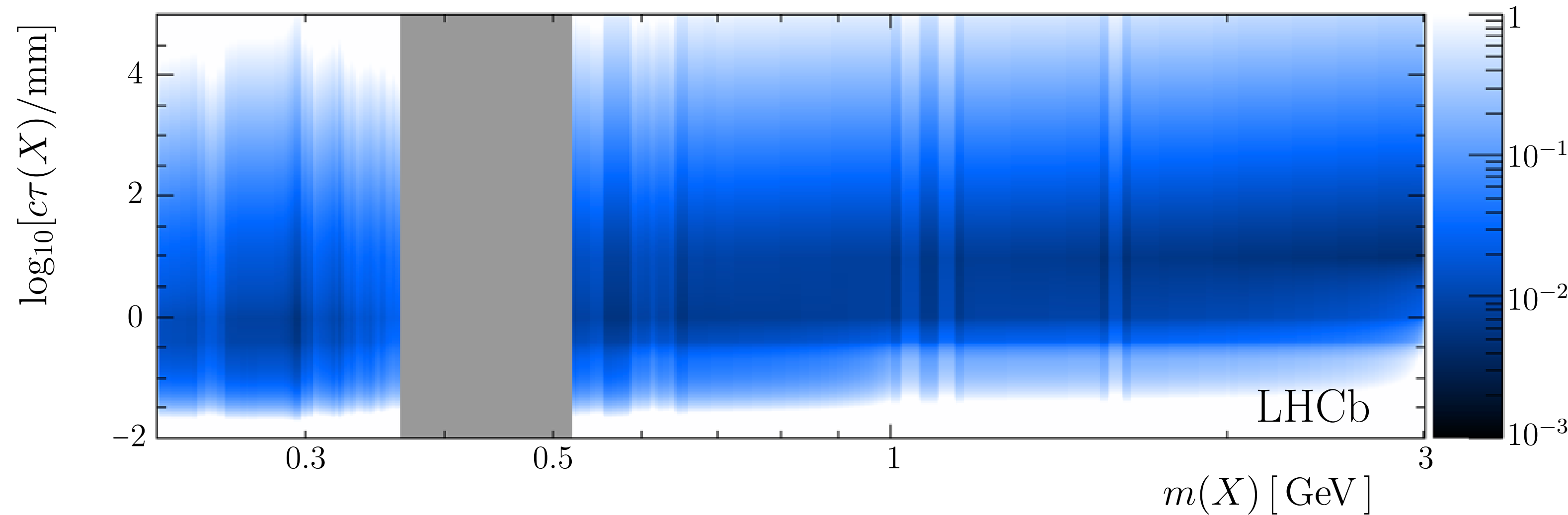
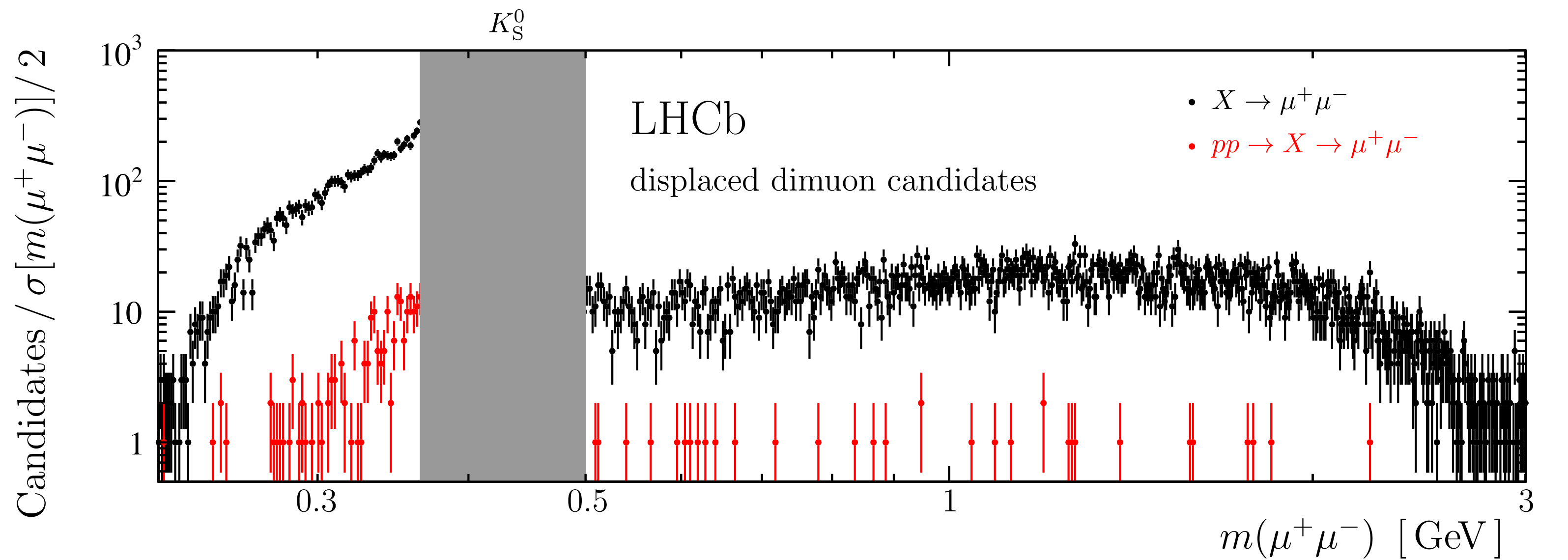


- **Prompt** search results interpreted onto limits on the two-Higgs doublet (**2HDM**) + complex scalar singlet
- World-best UL on mixing angle with the SM Higgs $\sin(\theta_H)$
- LHCb R1: [JHEP 09 \(2018\) 147](#)
- CMS R1: [PRL 109\(2012\)121801](#)
- CMS R2: [PRL 124 131802\(2020\)](#)
- BaBar $\Upsilon \rightarrow \gamma X$: [PRD 87\(2013\)031102](#)

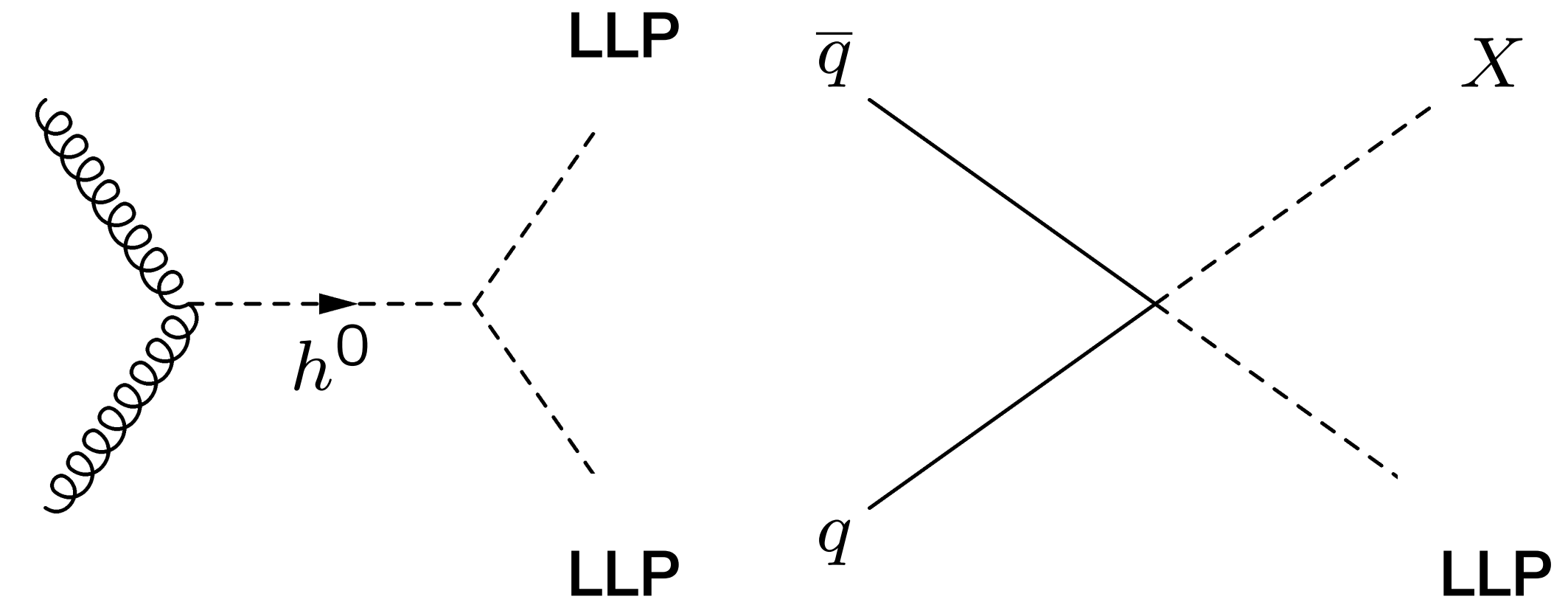


Inclusive $X \rightarrow \mu^+\mu^-$ search / Displaced-like [JHEP 10 \(2020\) 156](#)

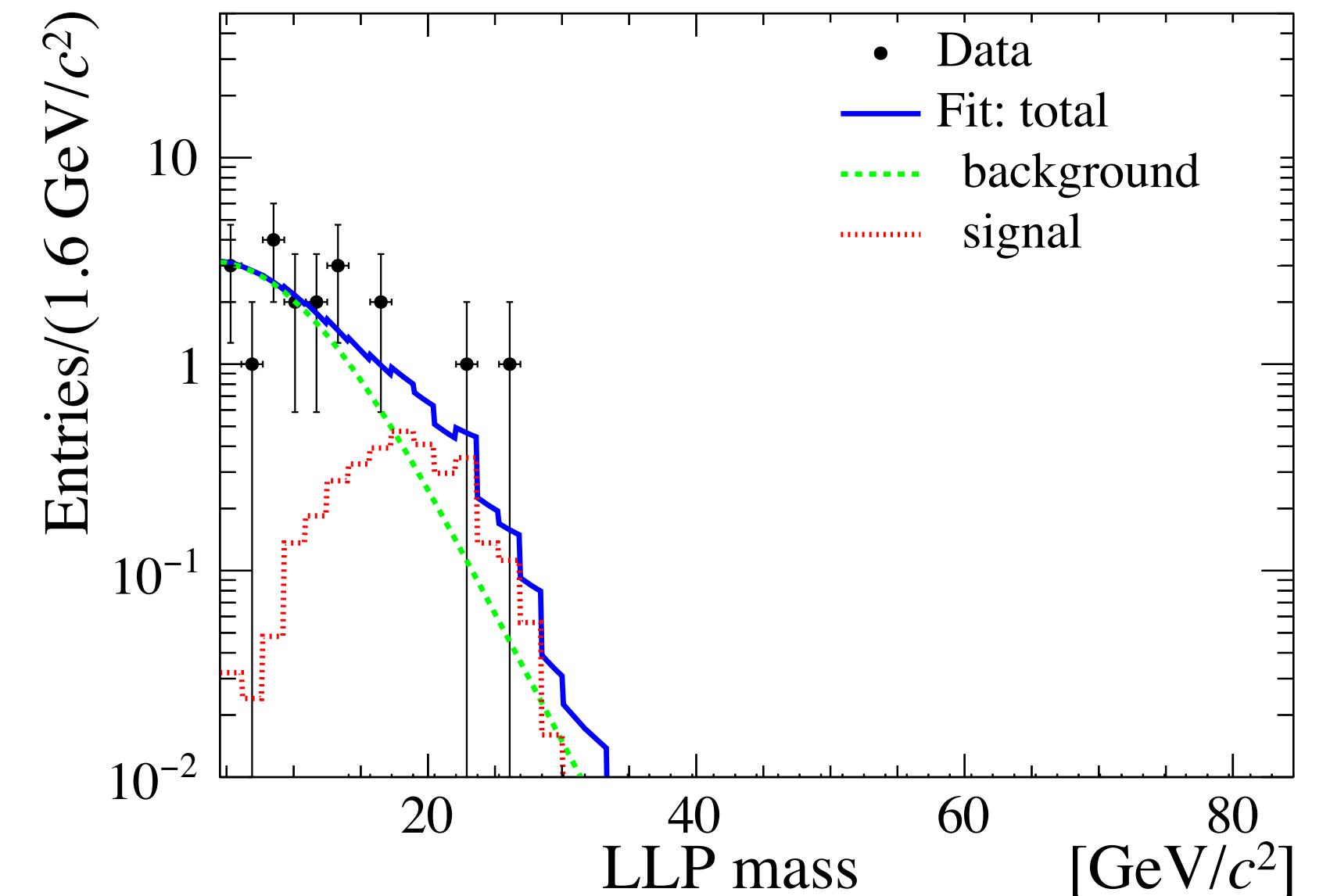
- **Displaced** search results interpreted onto limits on **Hidden Valley** model with dark showers of light **hidden hadrons**
 - 90% CL UL on kinetic mixing between γ and Z_{HV}
 - Result depends on hidden hadron multiplicity ($\langle N_{HV} \rangle \simeq 10$)
 - World-first constraints with minimal model dependence



- Two LLP production processes considered, where $\text{LLP} \rightarrow \mu^+ q_i q_j$
- Testing models:
 - Higgs-like boson decay to two LLPs
 - LLP produced directly from the quark interactions

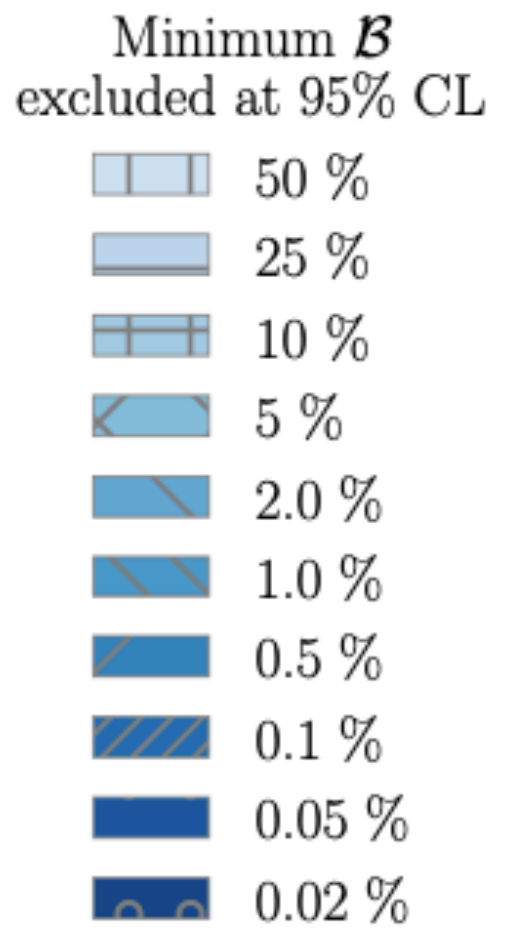
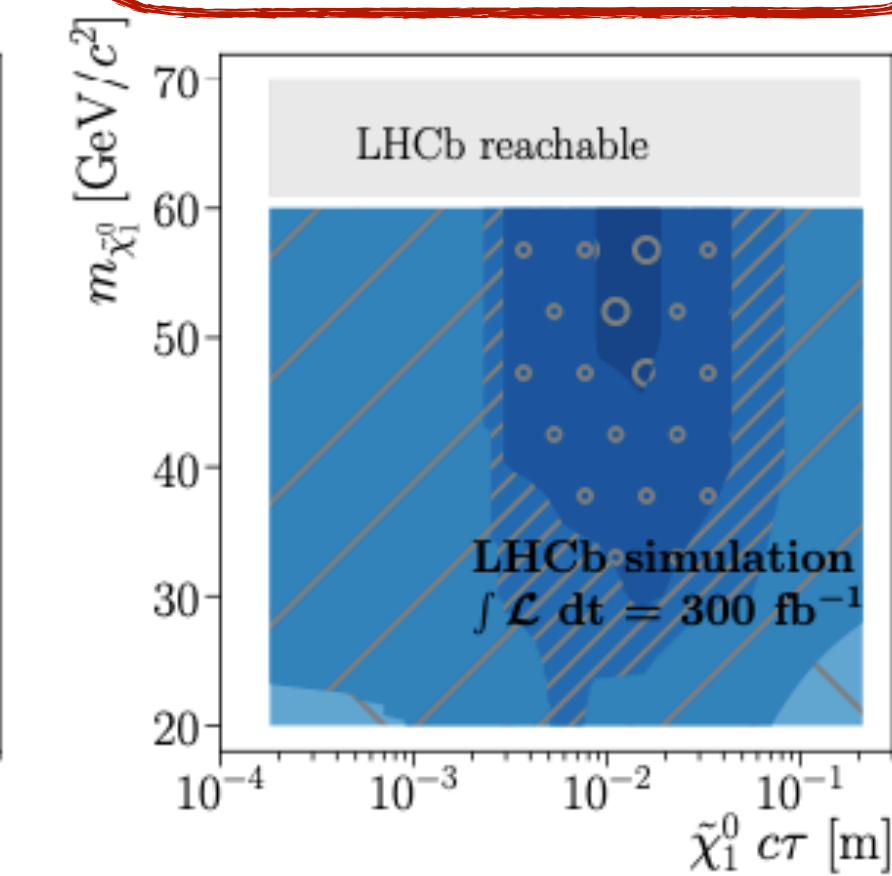
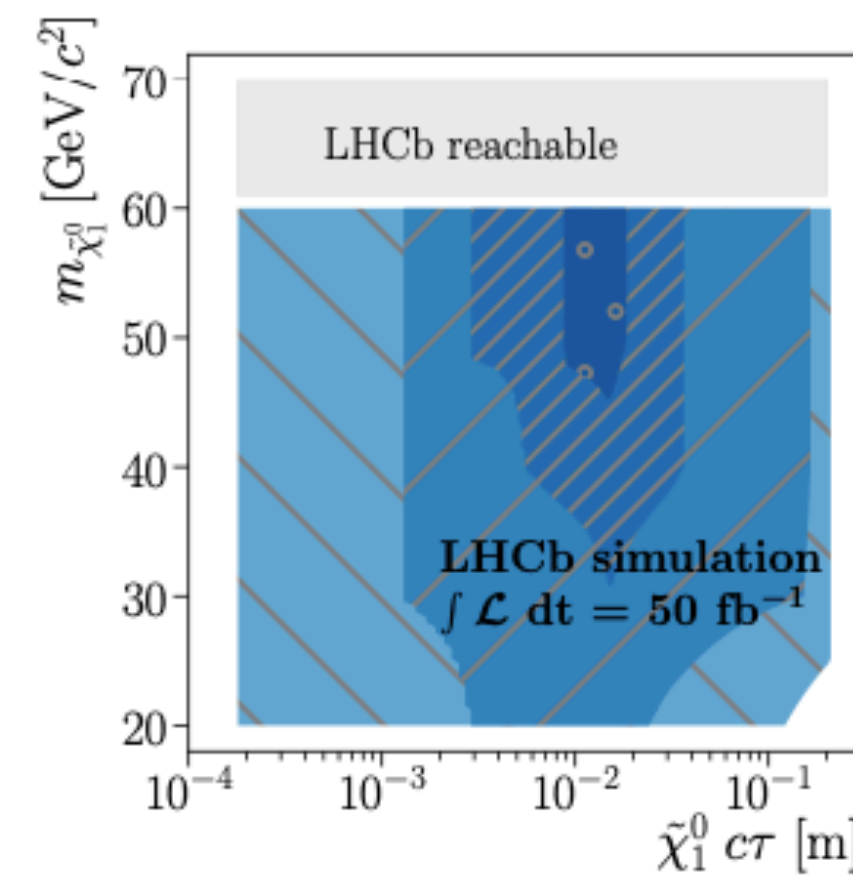
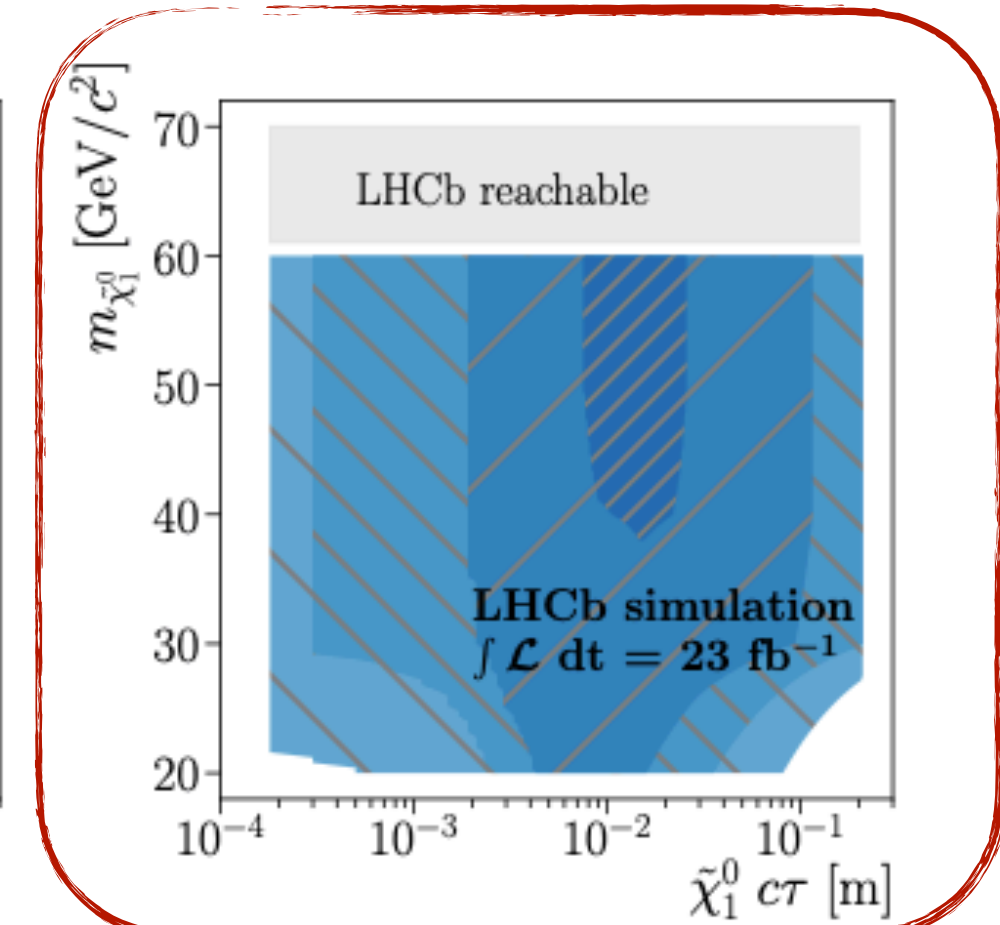
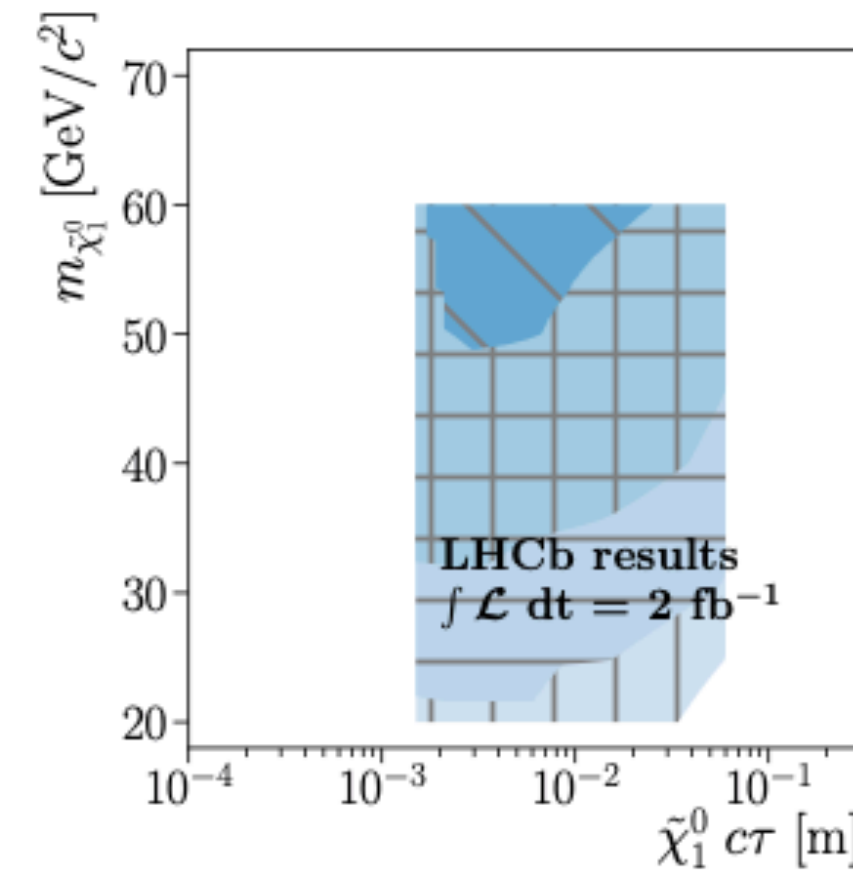
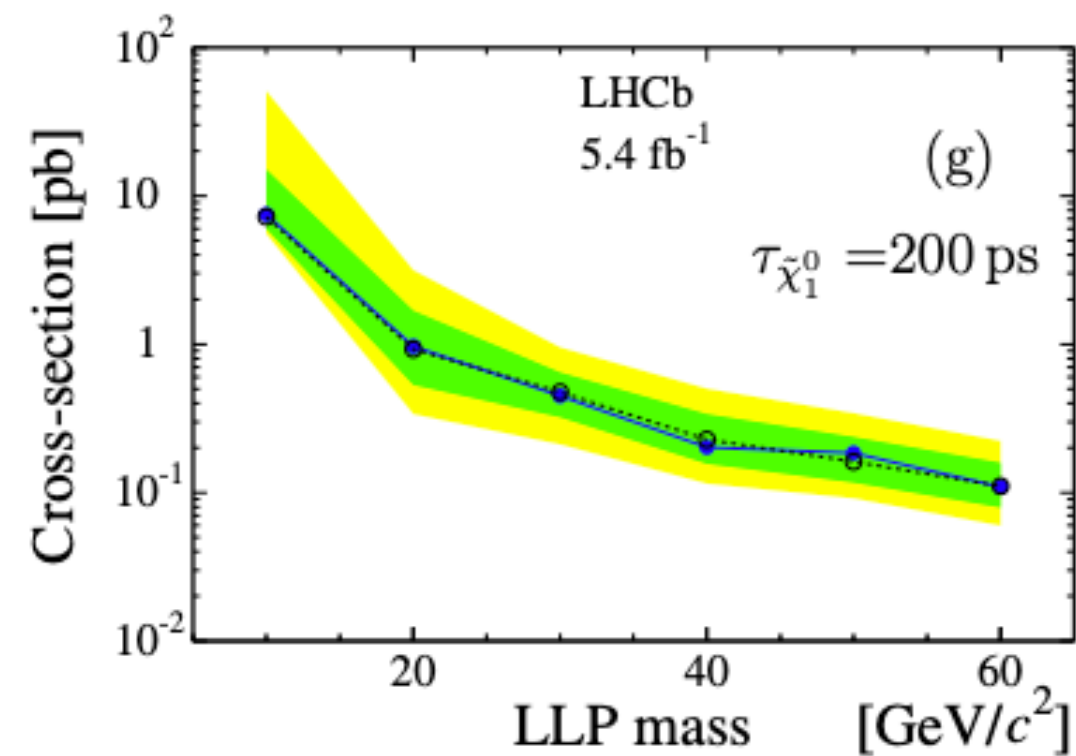
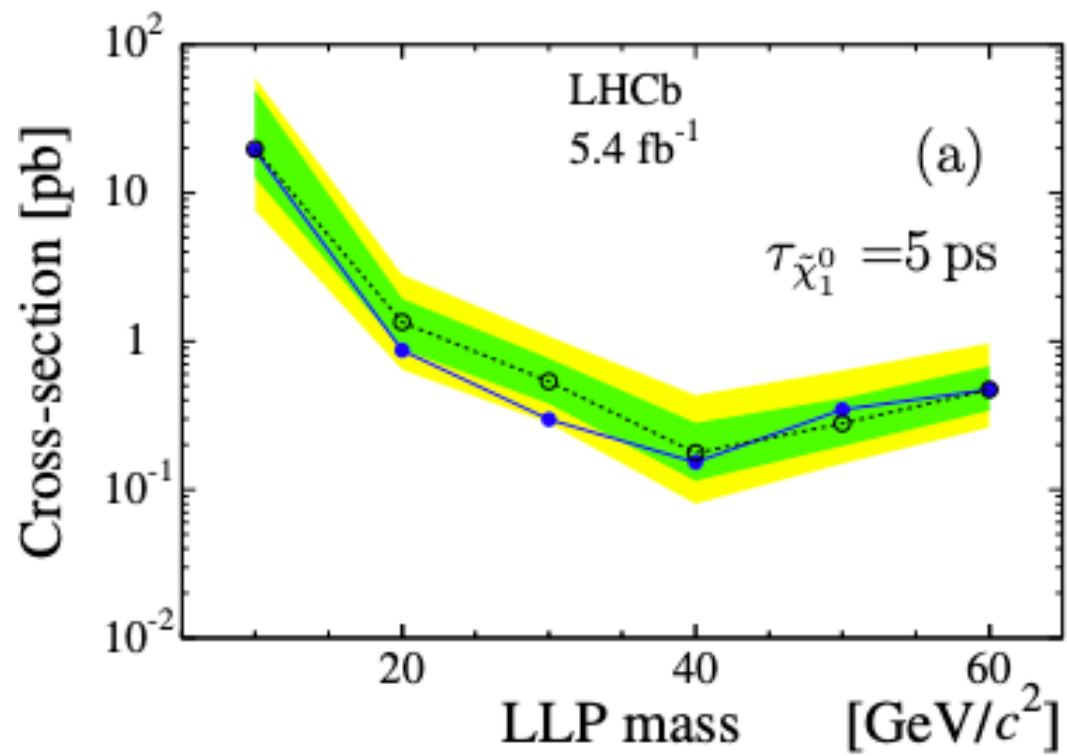


- Trigger on displaced vertex containing several tracks + muon with high p_T
- MVA selection is based on BDT with 7 variables
- Background dominated by $b\bar{b}$ and material interactions
- UL is set from fits to the LLP mass spectrum
 - Background modelled with two exponentials
 - Signal model is obtained from simulation



- 5.4 fb^{-1} of LHCb Run 1 and 2 data is used
- Results interpreted in $H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ model
- Excluded production cross-section down to $\mathcal{O}(0.1)$ pb
- Exclude $\mathcal{B}(H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ down to 0.1%

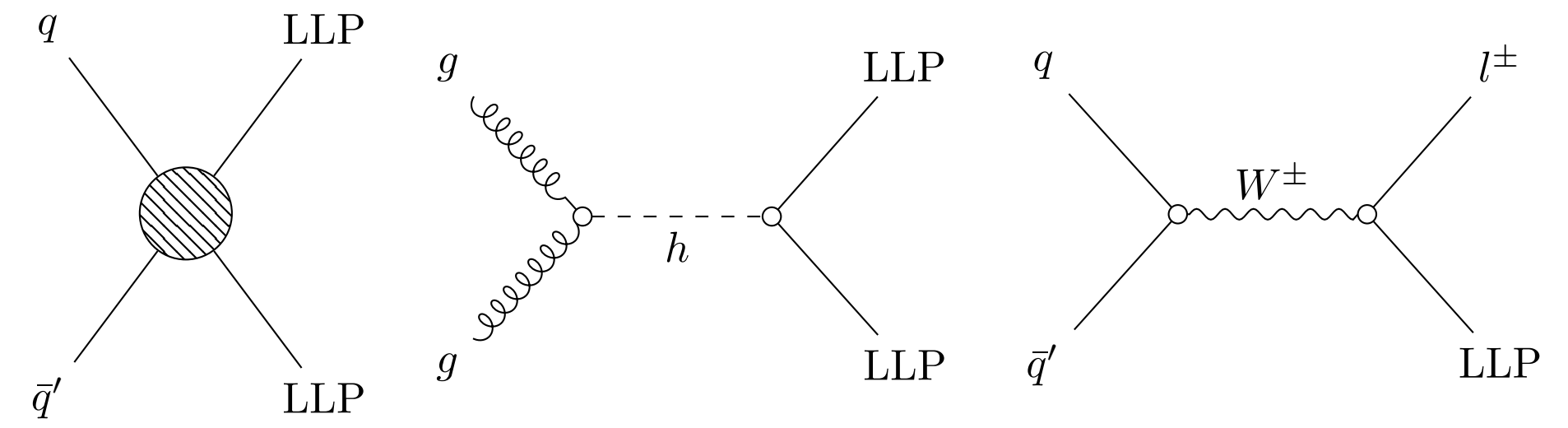
by the end of Run 3 [LHCb-CONF-2018-006](#)



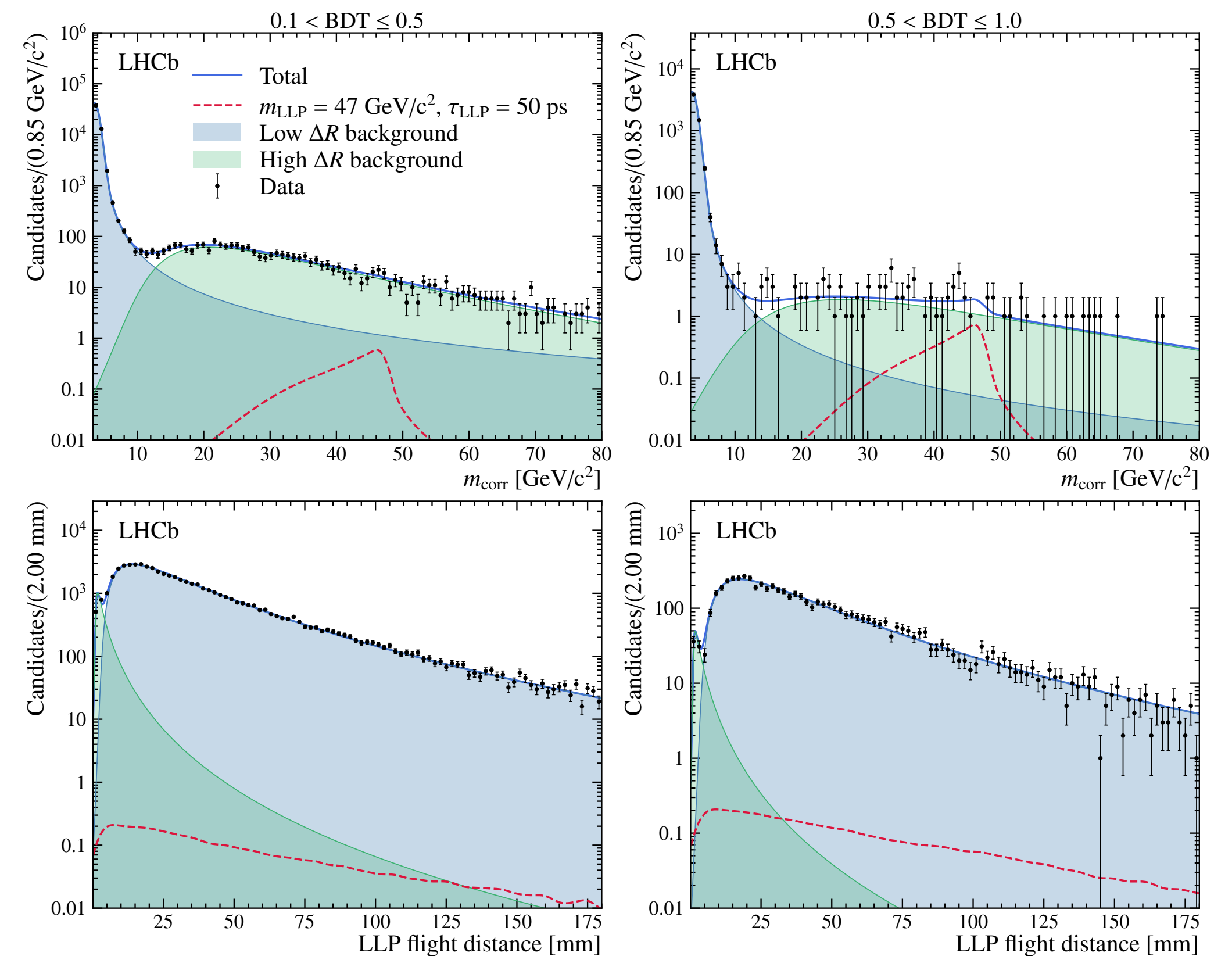
Search for LLPs $\rightarrow e^+\mu^-\nu$ [[EPJC \(2021\) 81 261](#)]

- Search for LLPs decaying into $e^+\mu^-\nu$, and the following production mechanisms:

- via direct pair production (DPP) from pp collisions,
- from and exotic Higgs-like particle decay (HIG),
- From a charged current process (CC)

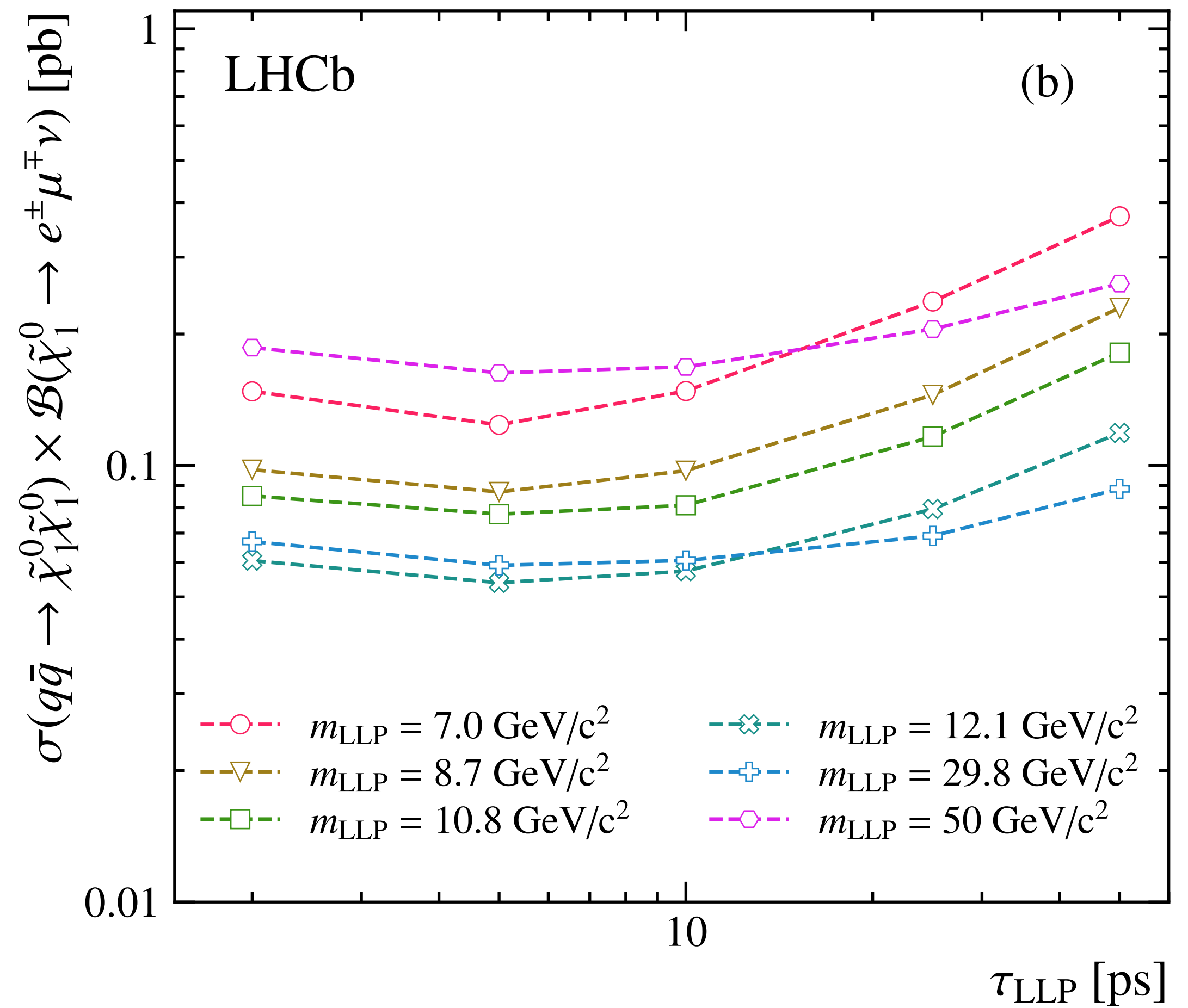
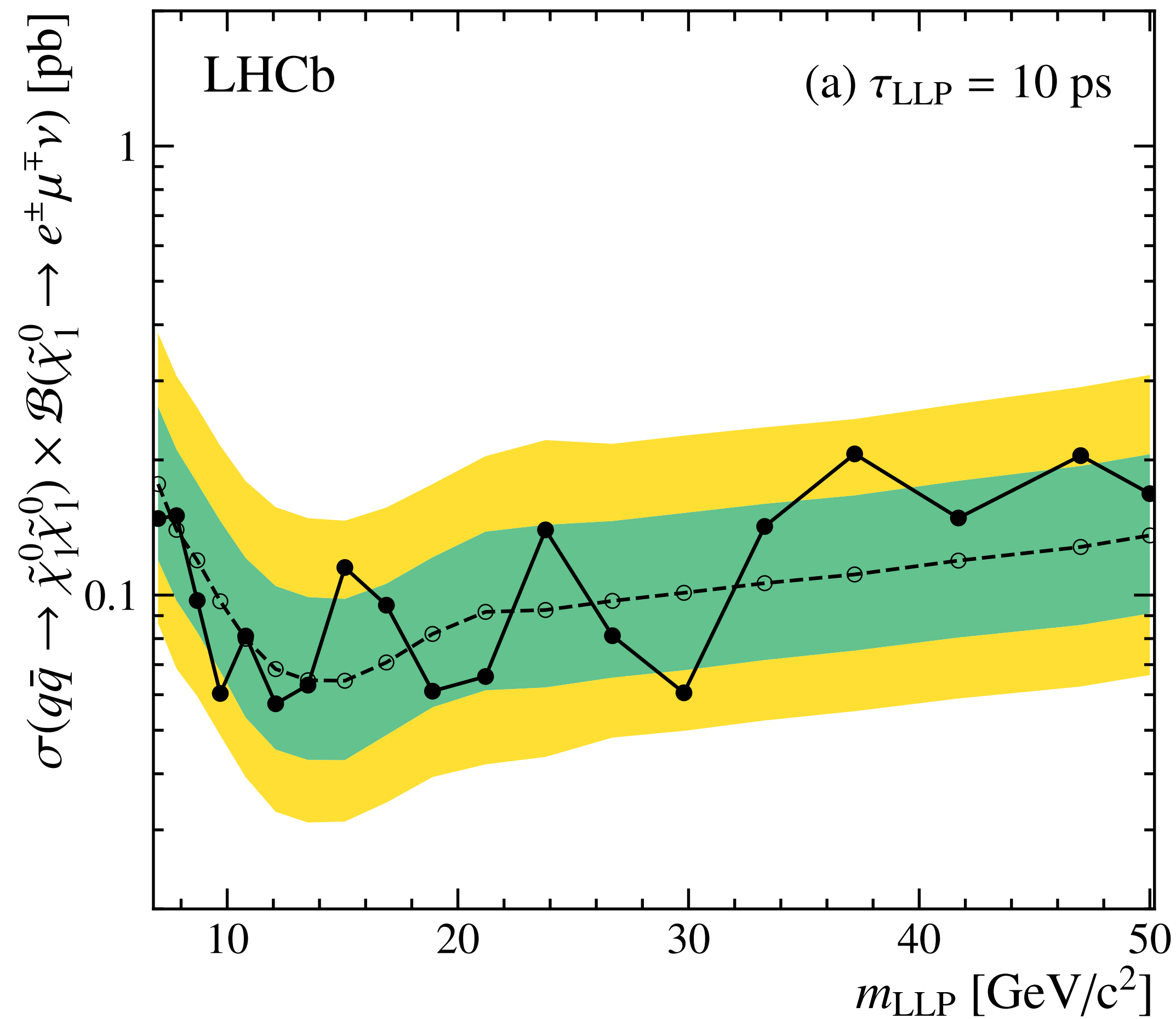


- Using LHCb Run 2 dataset (5.38 fb^{-1} at 13 TeV)
- Trigger on leptons with low p_T requirements allows for small LLP masses
- Test masses between 7 and $50 \text{ GeV}/c^2$ and lifetimes between 2 and 50 ps
- Signal efficiencies obtained from simulation
- UL is set from the simultaneous fits to the LLP mass and flight distance (in bins of the BDT response)



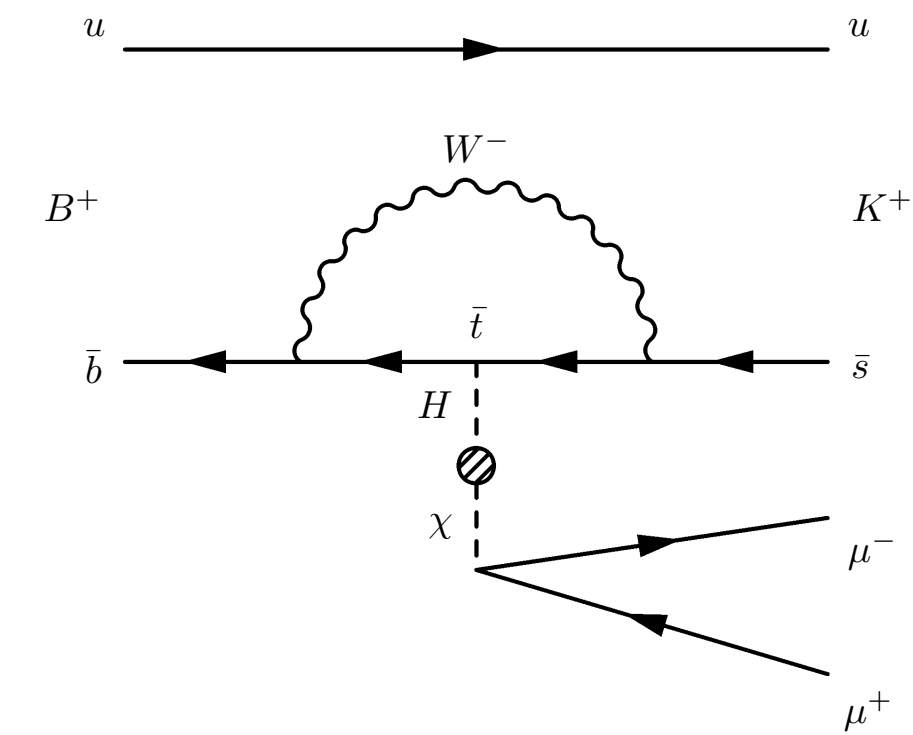
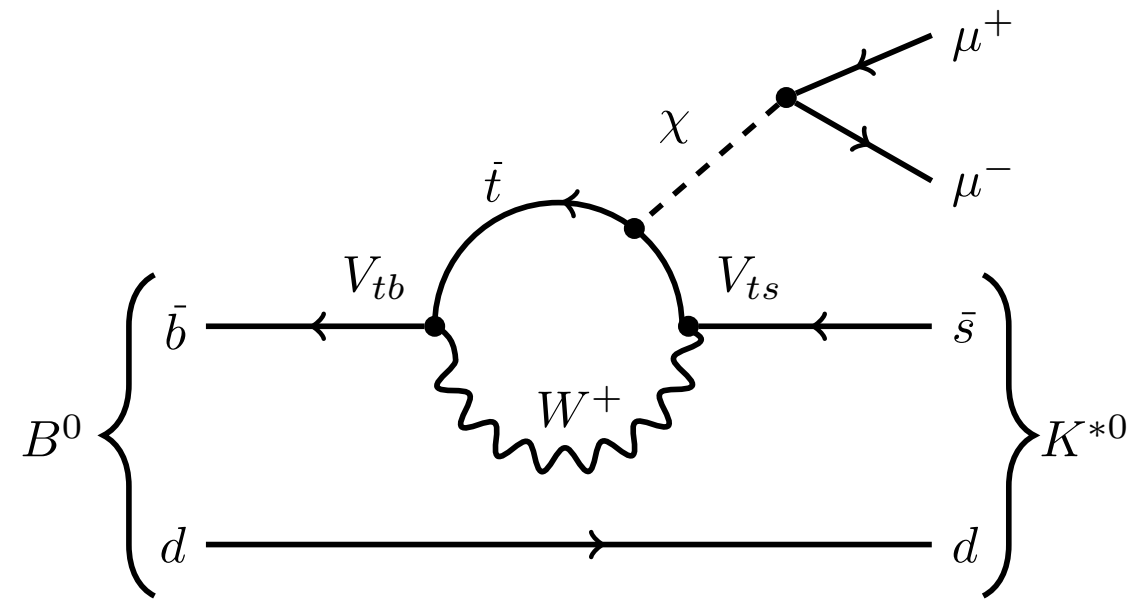
Search for LLPs $\rightarrow e^+\mu^-\nu$ / Results [\[EPJC \(2021\) 81 261\]](#)

- No excess found - UL at 95% CL on $\sigma \times BR$ for each model
- Best UL for **DPP** with lifetimes below 10 ps and masses above 10 GeV

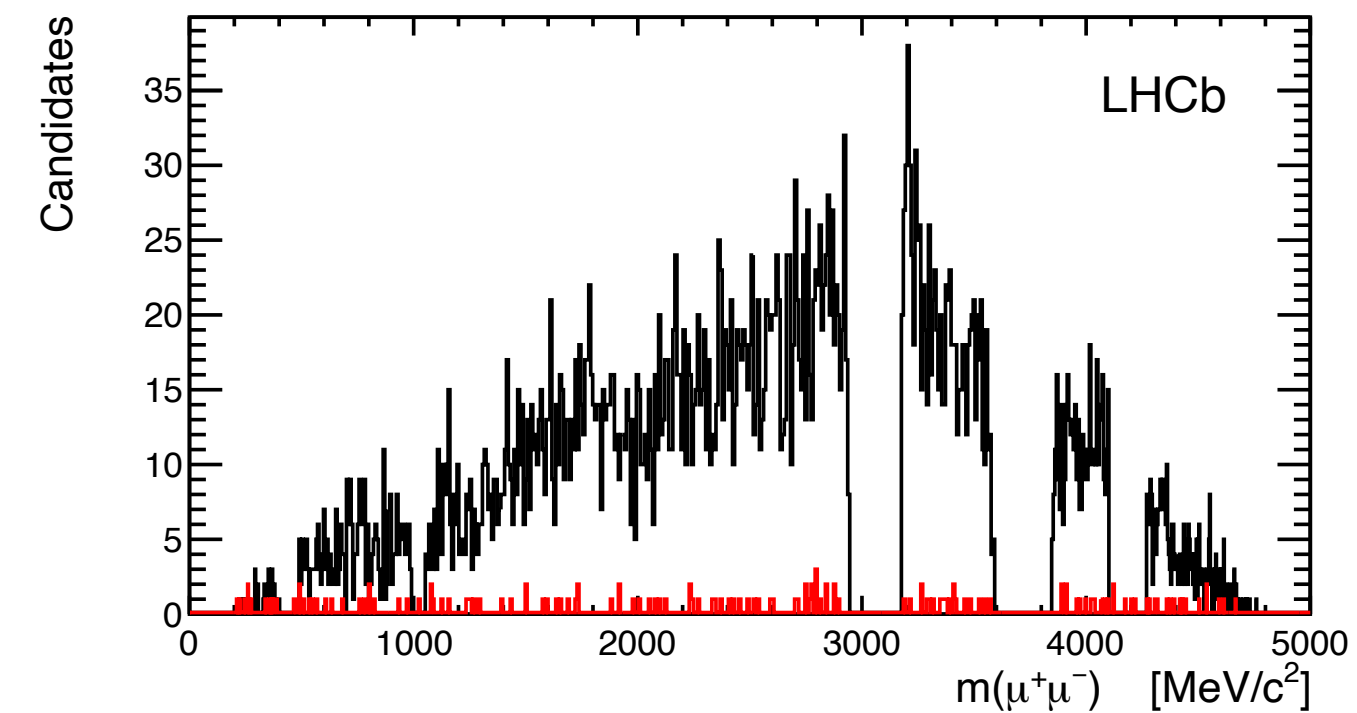
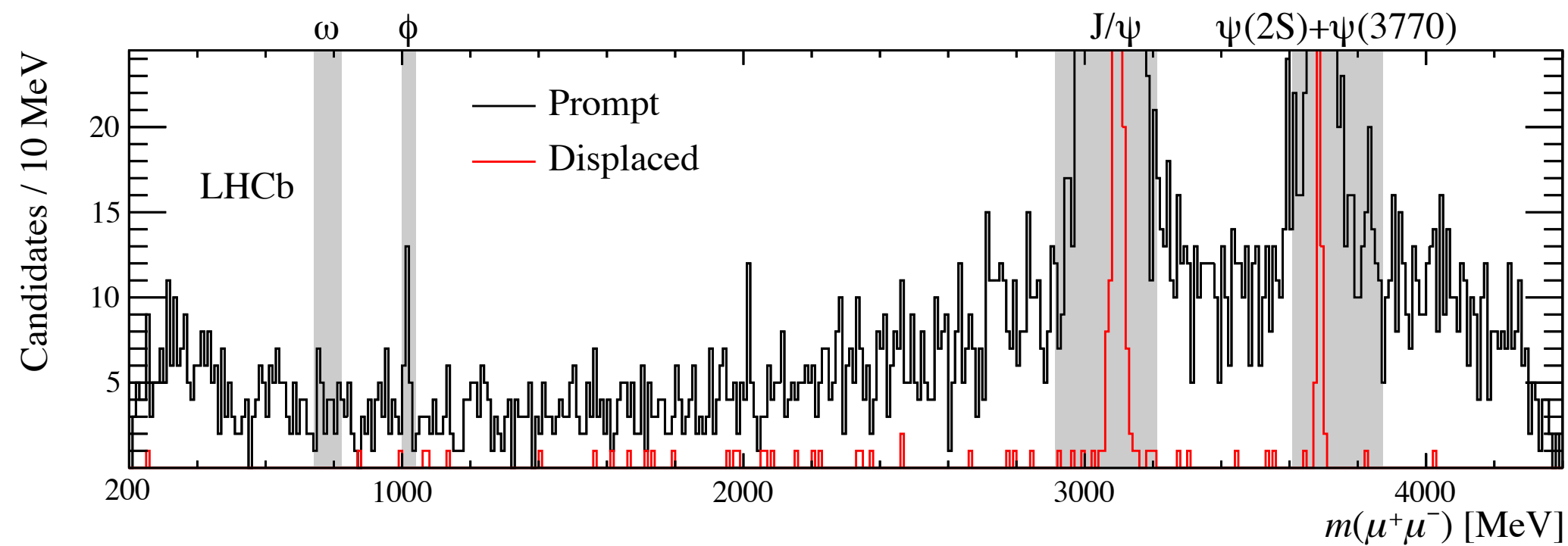


Searches for dark bosons in $B \rightarrow K^{(*)}\chi(\mu^+\mu^-)$

- Considered $B^0 \rightarrow K^{*0}\chi$ [PRL 115 (2015) 161802] and $B^+ \rightarrow K^+\chi$ [PRD 95 (2017) 071101 (R)]

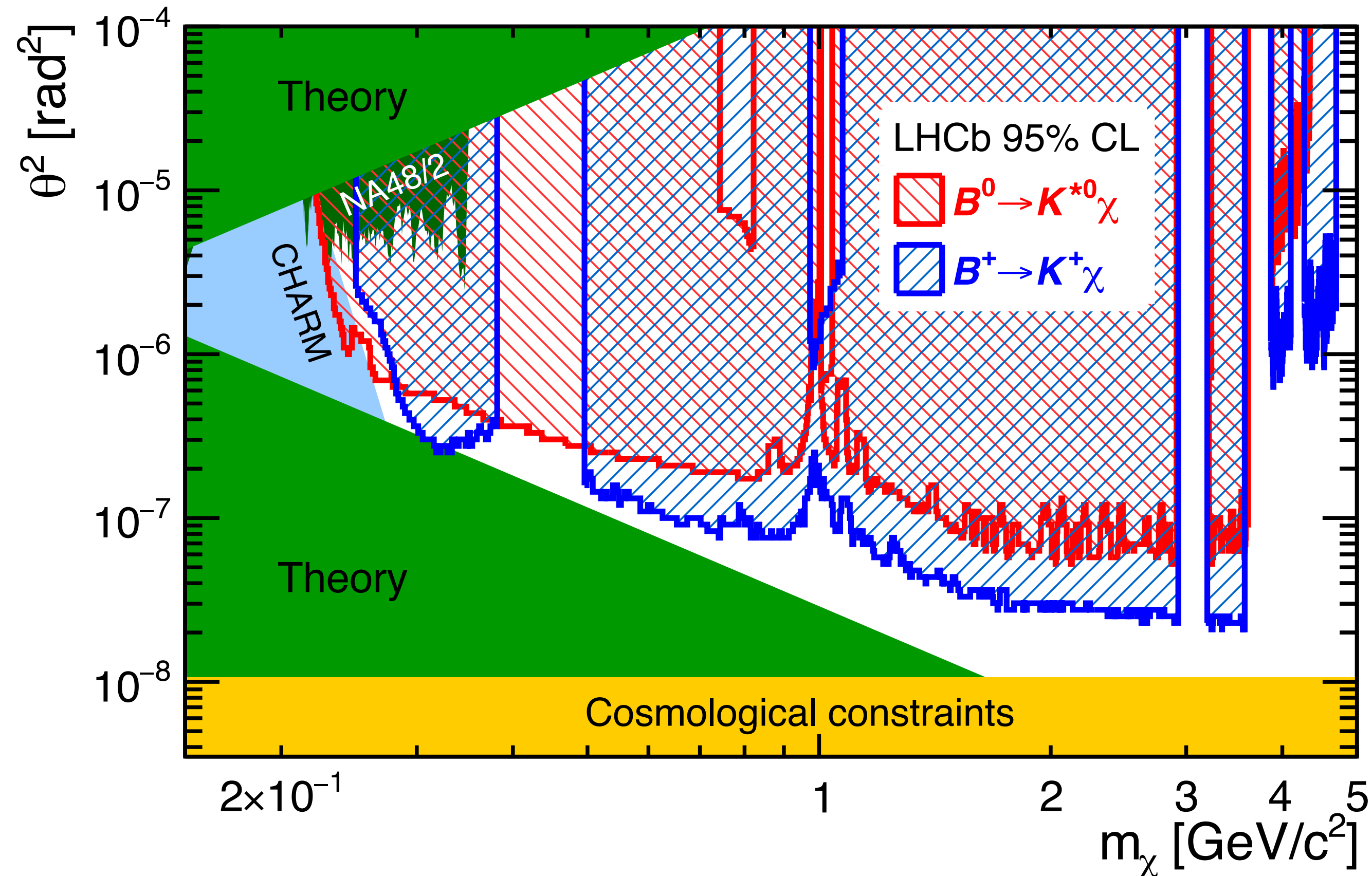


- Searches for hidden-sector bosons $\chi \rightarrow \mu^+\mu^-$ in $b \rightarrow s$ penguin decays, with considered models:
 - Axial-vector portal and scalar (Higgs) portal
- Both searches set UL comparing S+B to B only hypothesis, combining two decay-time regions



Searches for dark bosons in $B \rightarrow K^{(*)}\chi(\mu^+\mu^-)$

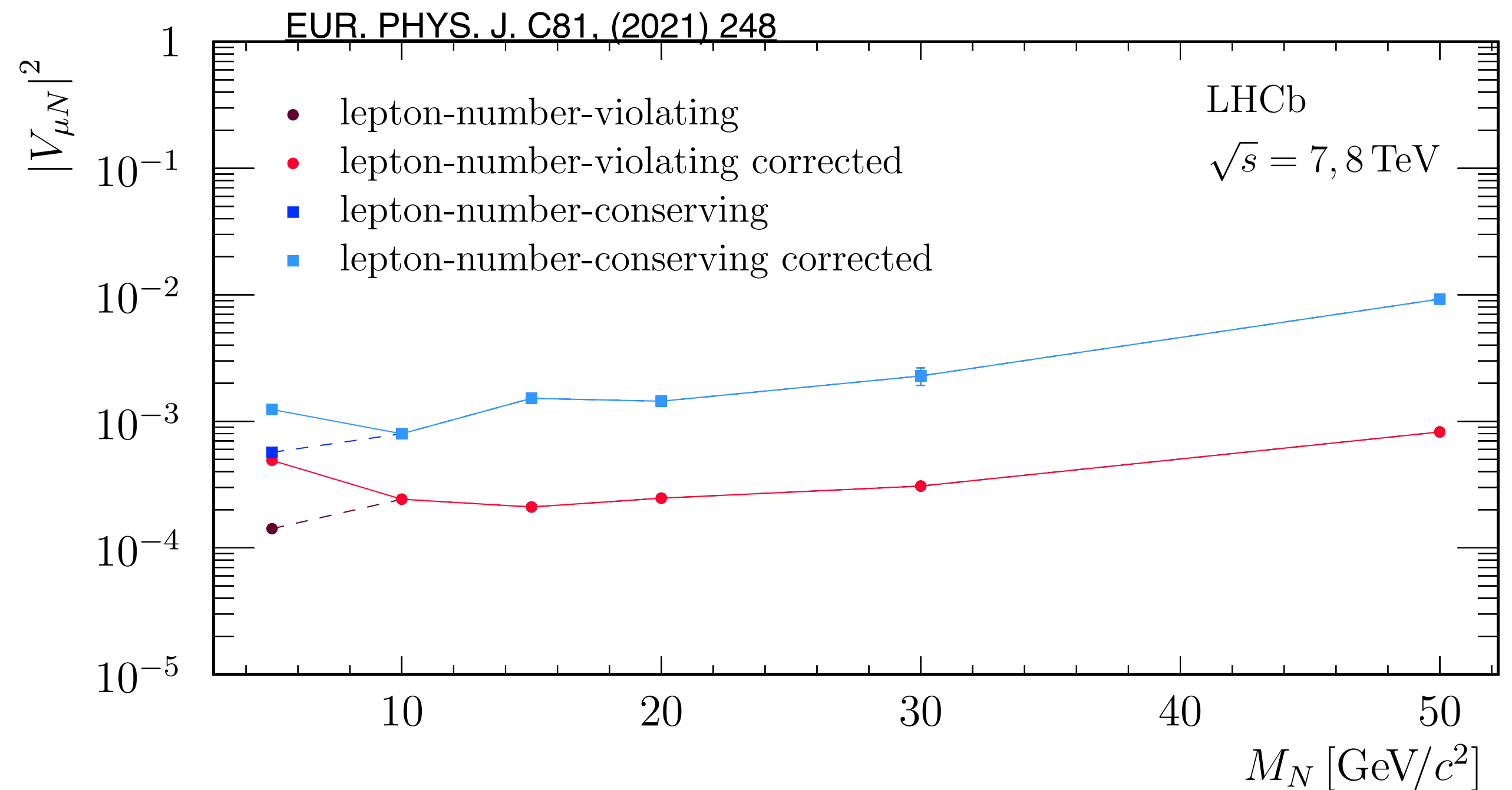
- Full LHCb Run 1 dataset (3fb^{-1}) used in both searches
- BR normalised to $\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$ or $\mathcal{B}(B^+ \rightarrow K^+J/\psi)$
- No evidence for signal observed \rightarrow UL on BR set and interpreted in the inflaton model:



Searches for HNLs

- Heavy neutral leptons decays could be detected with LHCb
 - In B decays:
 - Exclusive $B^- \rightarrow \mu^- \mu^- \pi^+$ (Run 1) was not yet competitive with LEP [PRL. 112 \(2014\) 131802](#)
 - Ongoing inclusive $B \rightarrow X \mu N$ with $N \rightarrow \mu \pi$ is quite promising

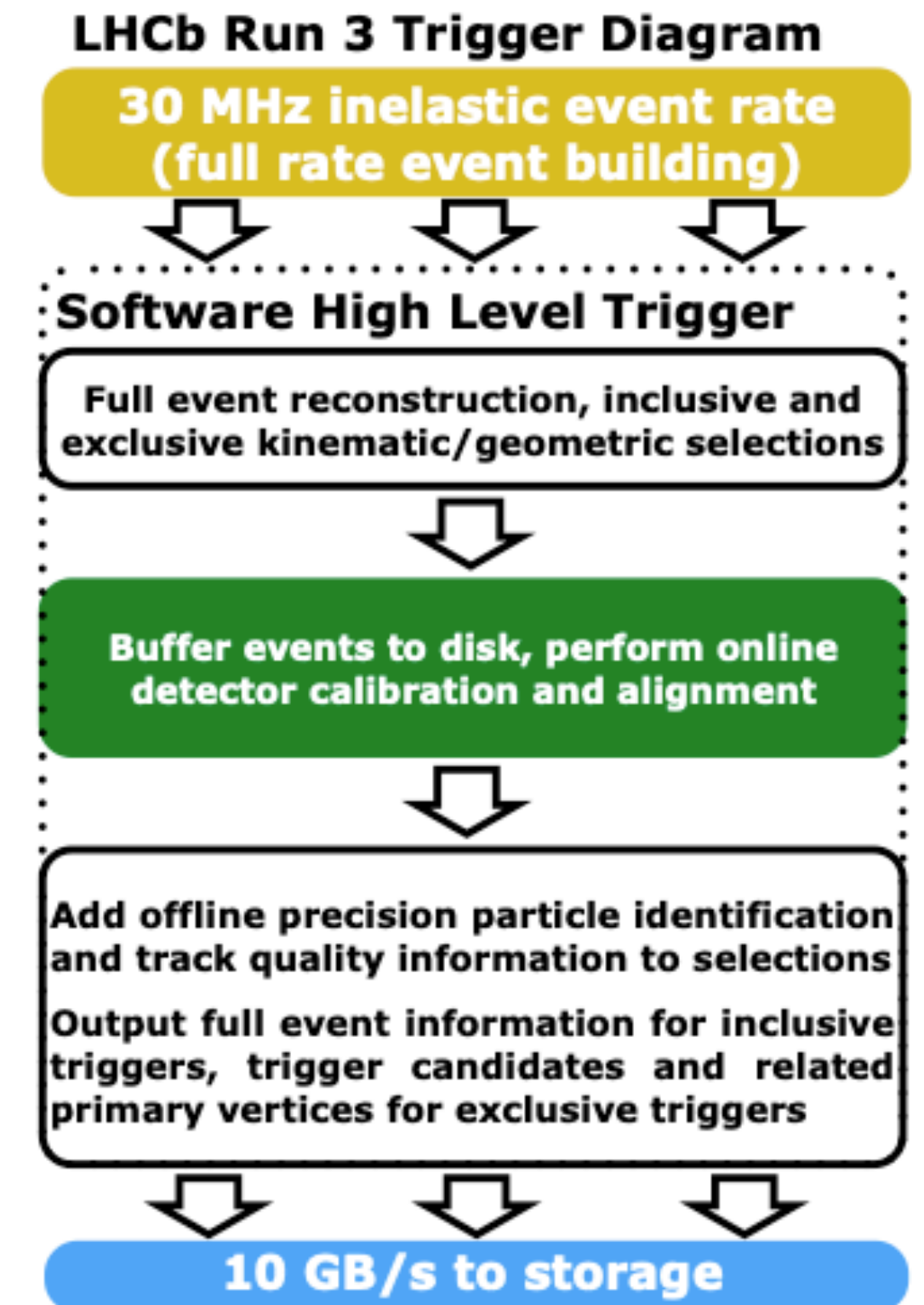
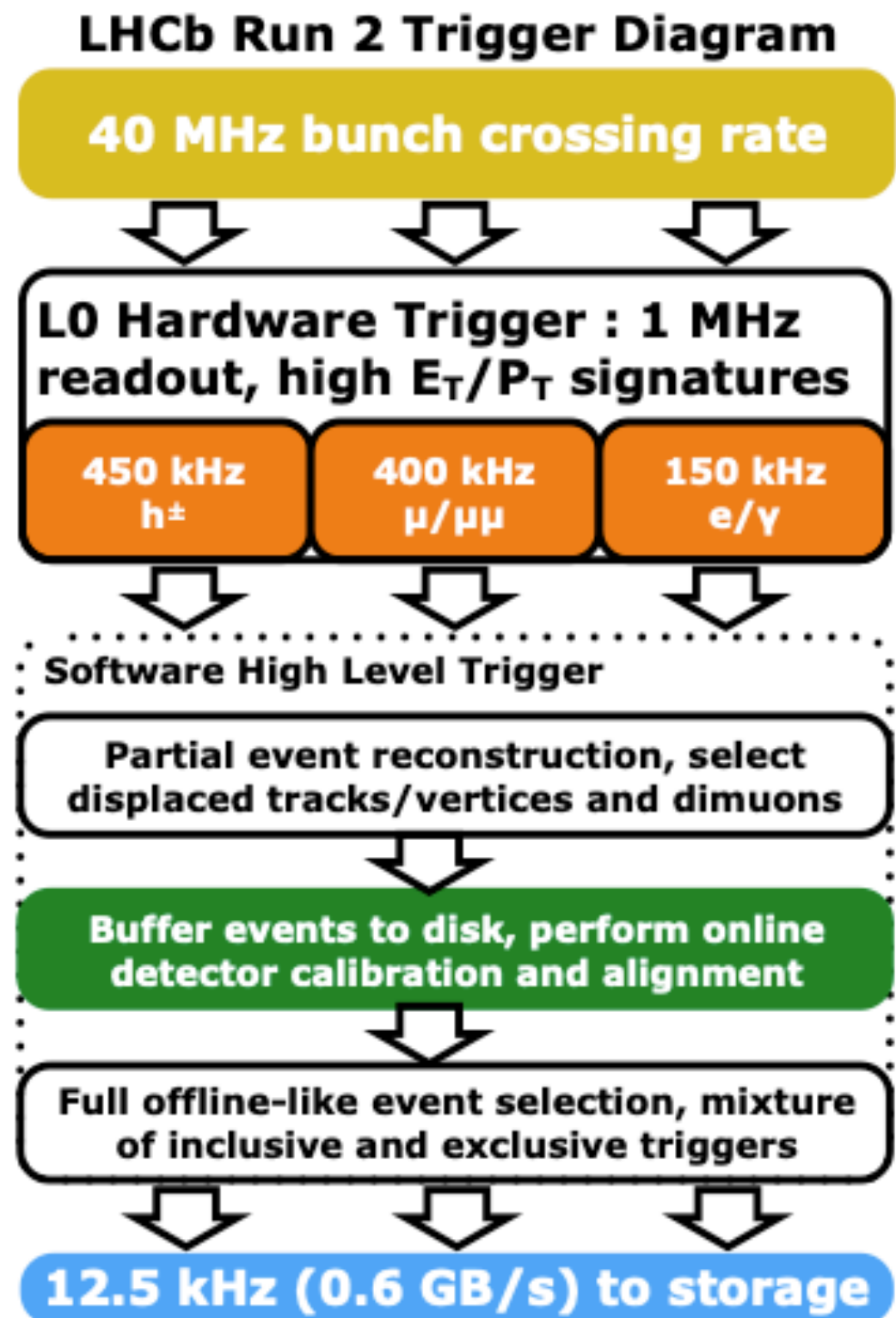
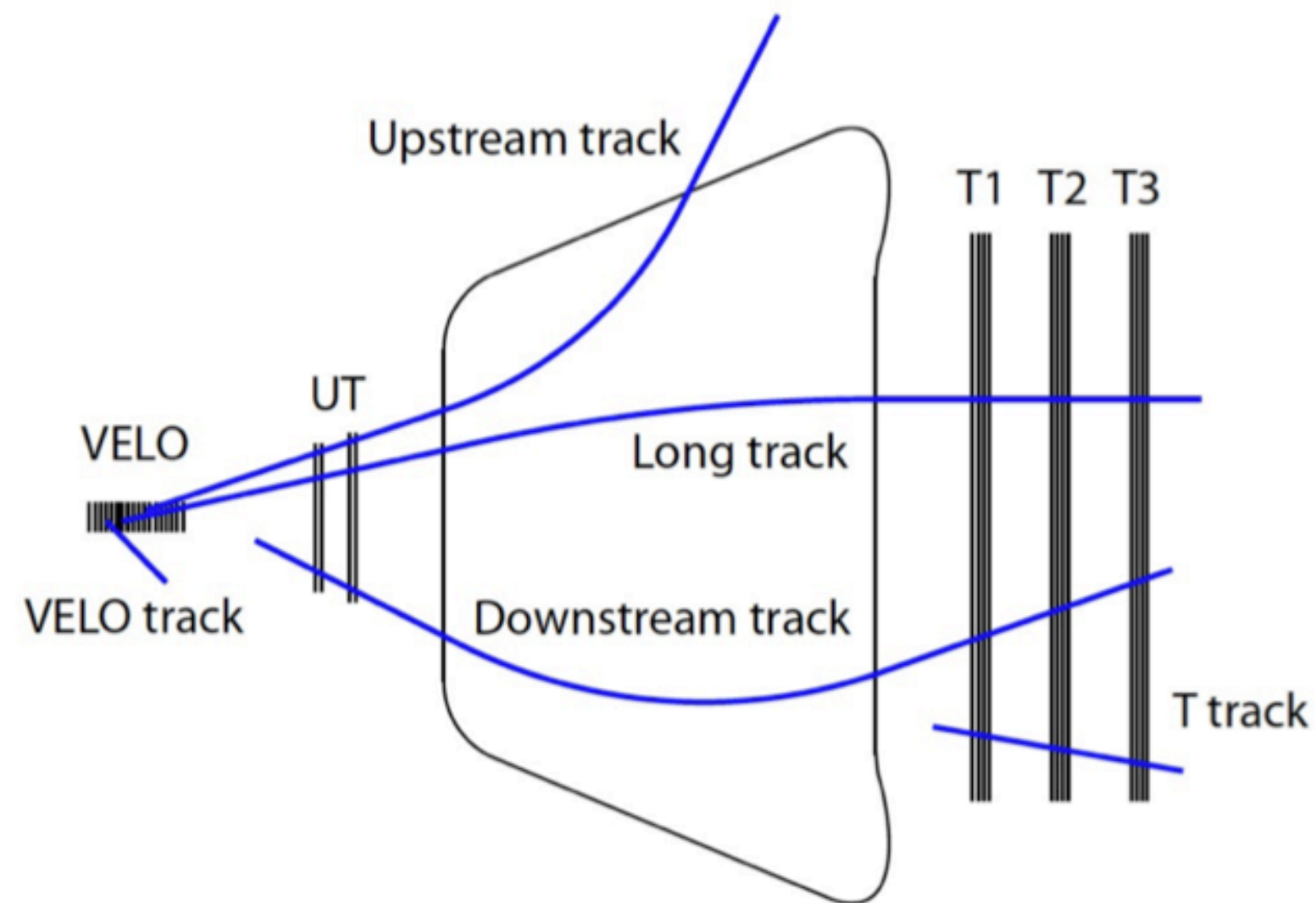
- In $W^+ \rightarrow \mu^+ \mu^\pm jet$ decays, with $N \rightarrow \mu^\pm q \bar{q}'$
 - Using LHCb Run 1 dataset
 - Background dominated by SM $pp \rightarrow W(\rightarrow \mu \nu) X$
 - Set UL on mixing with muon neutrino $|V_{\mu N}|^2$



Prospects for the future

- Removal of hardware trigger gives access to softer kinematics for searches
- Better vertex resolution with new VELO
- Work ongoing on usage of downstream and T tracks at first trigger level

→ longer lifetimes can be tested



LHCb-FIGURE-2020-016

Conclusions

- LHCb has an extensive program of searches in the Dark Sector
 - Dimuon resonances in very broad parameter space
 - Long-lived particles reaching low masses
 - Light portal particles in heavy flavour decays $b \rightarrow s$ and $b \rightarrow c$
- LHCb Dark Sector searches aim for the gap between the energy and intensity frontiers
 - Important phase space region that has to be covered
 - Several world-best limits
- LHCb White paper on Stealth physics [\[ROPP \(2022\) 85 024201\]](#)
 - Published in Reports on Progress in Physics
 - More than 20 proposed searches on different models are described