Dark sector searches at LHCb

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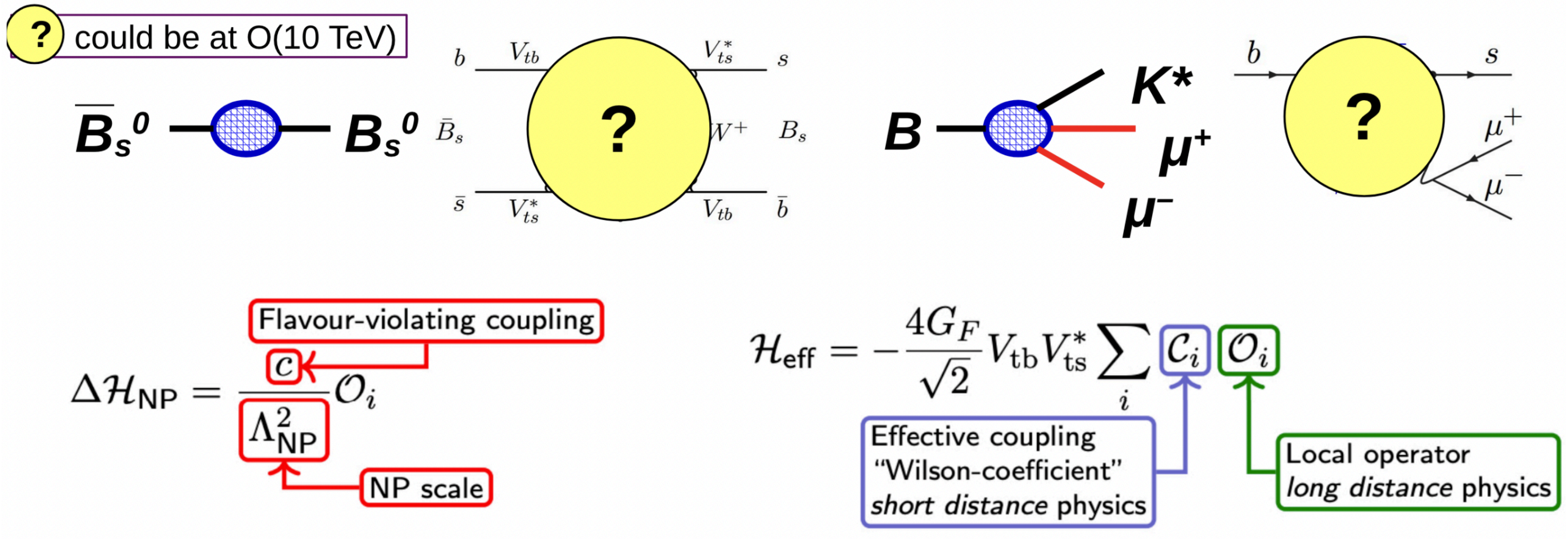
Quest for NP at LHCb search

With heavy new degrees of freedom **above EW scale** integrated out

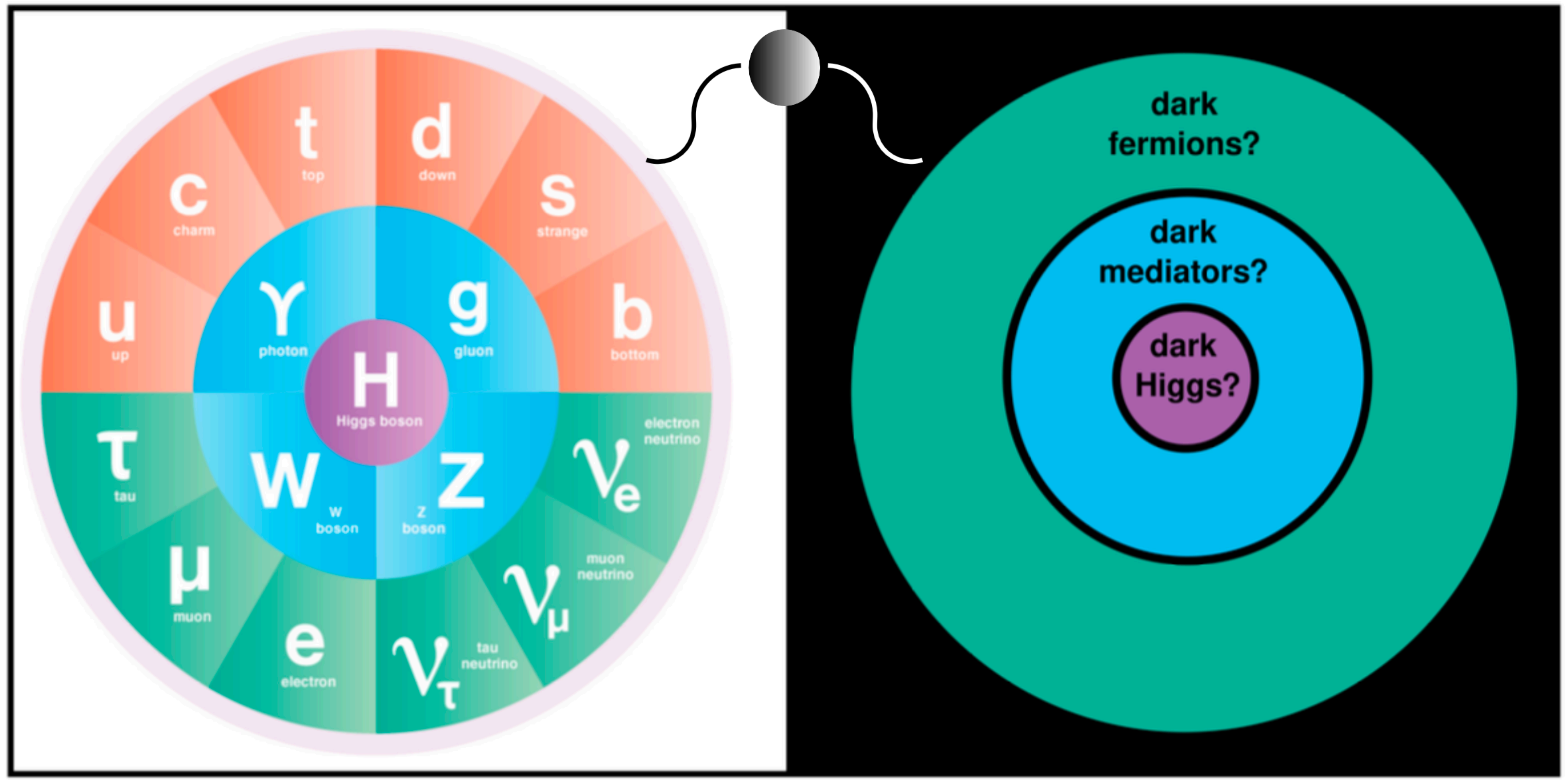


$$\Delta\mathcal{H}_{NP} = \frac{C}{\Lambda^2_{NP}}\mathcal{O}_i \qquad \mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts}\sum_i \mathcal{C}_i \mathcal{O}_i$$

Stress-test of SM searching for deviation from theory with **precision measurement**

Portals to **DS at low energies**, NP **below EW scale**

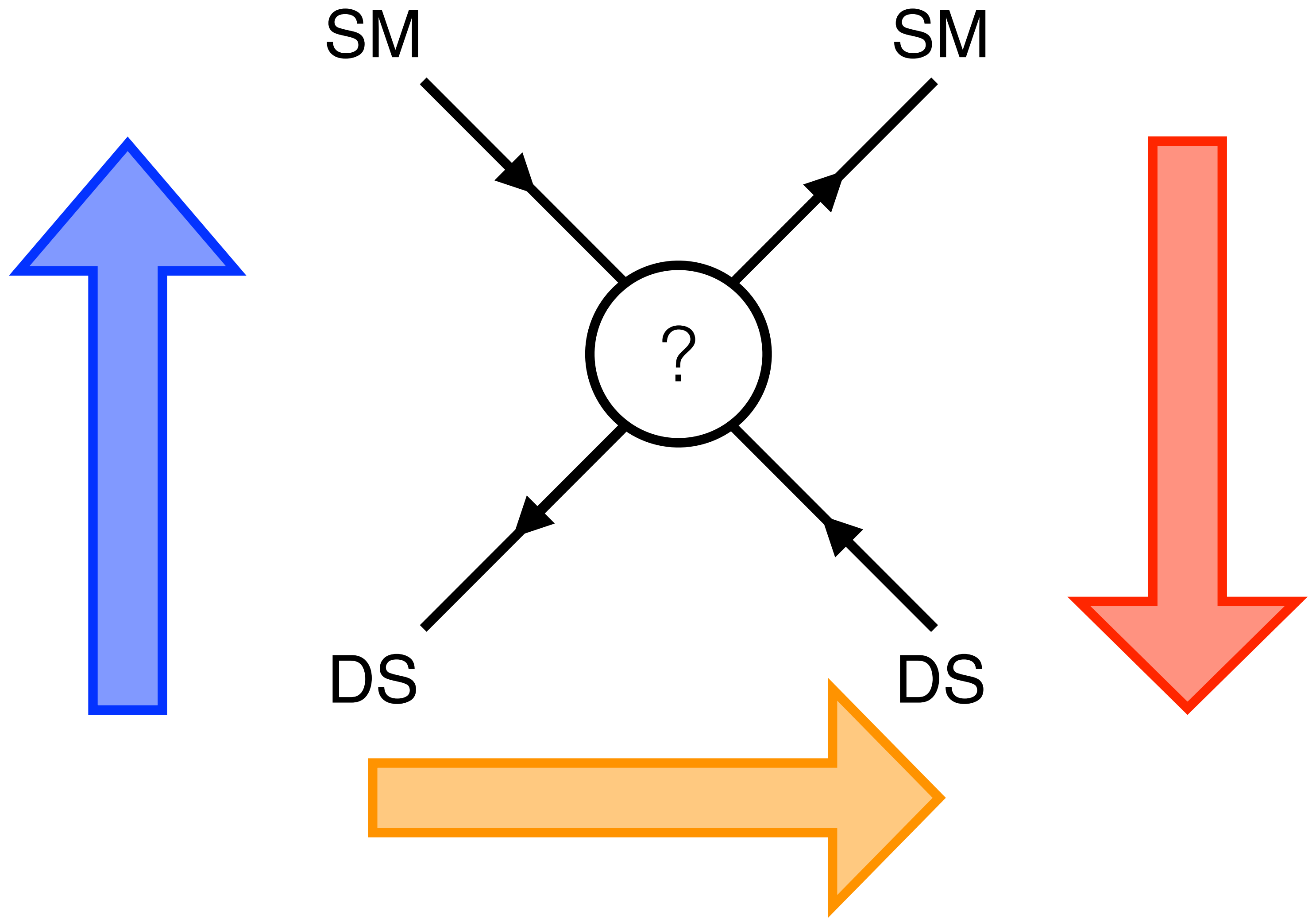
$$\mathscr{L} = \sum \mathcal{O}_{SM} \times \mathcal{O}_{DS}$$



How to look for it?

Indirect detection

Credit: H.E.S.S. collaboration



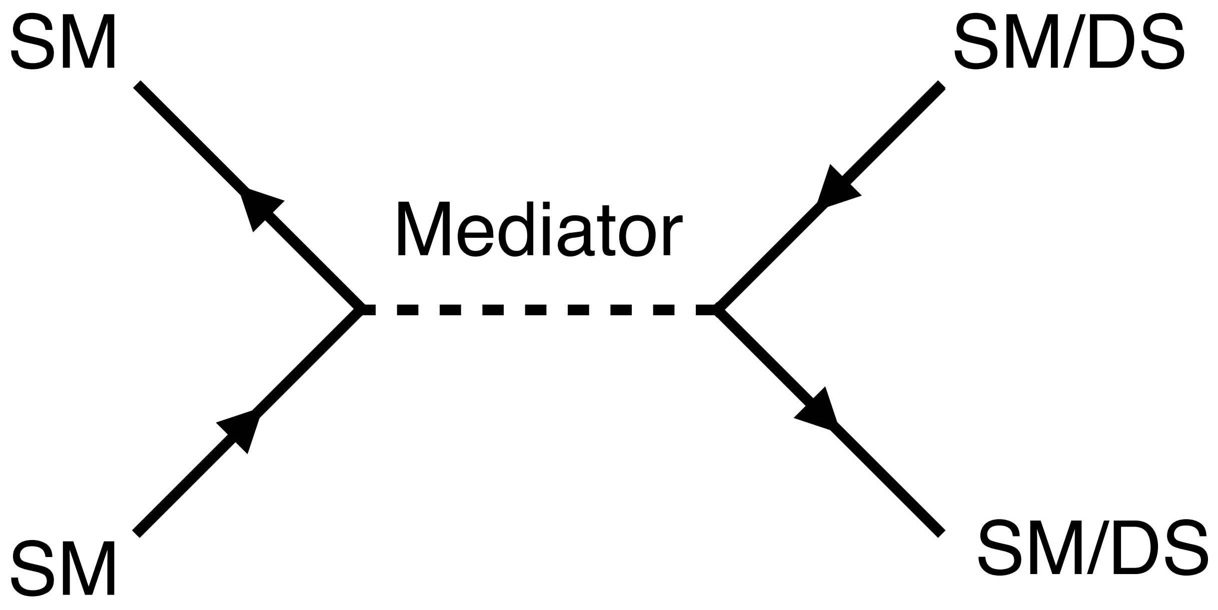
Collider searches

Credit: CERN

Direct detection

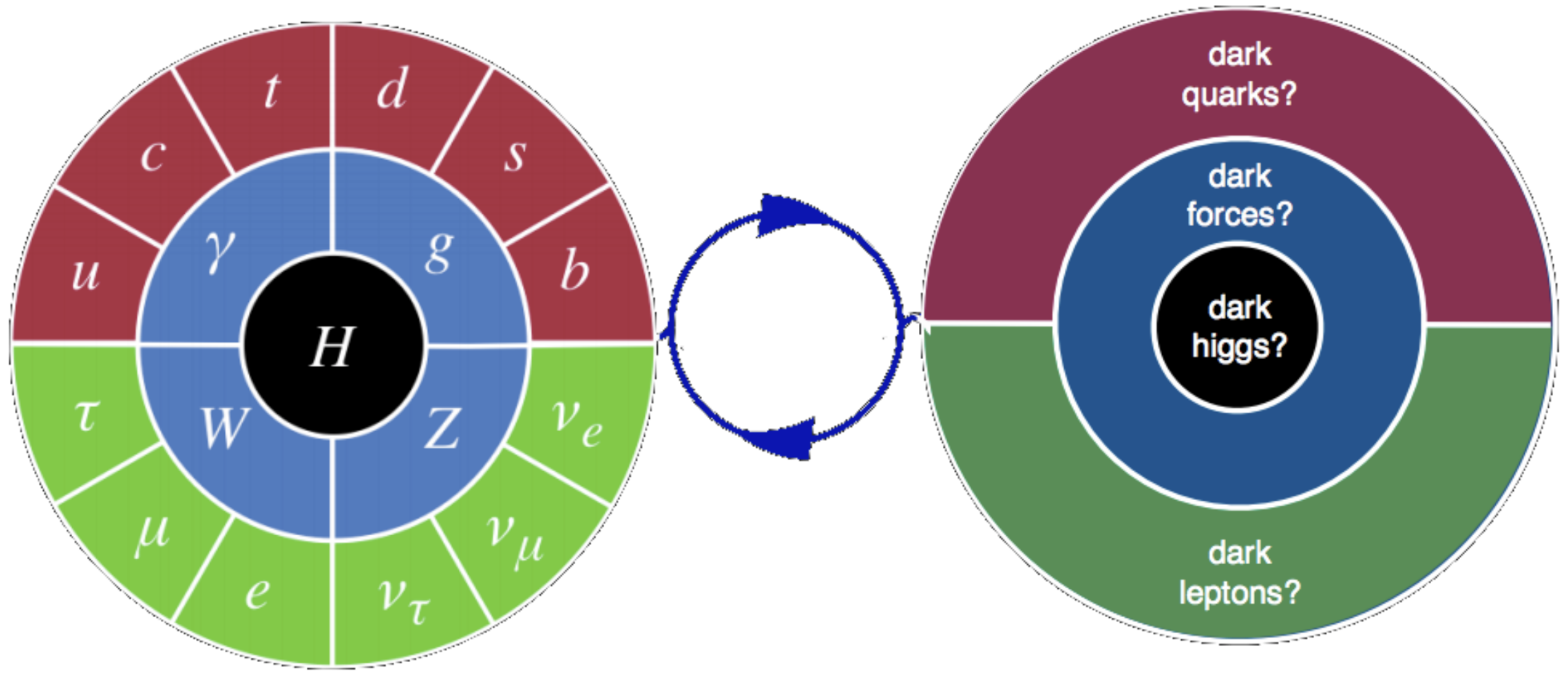
Credit: XENON collaboration

- DS production
- mediator resonances (peak search)

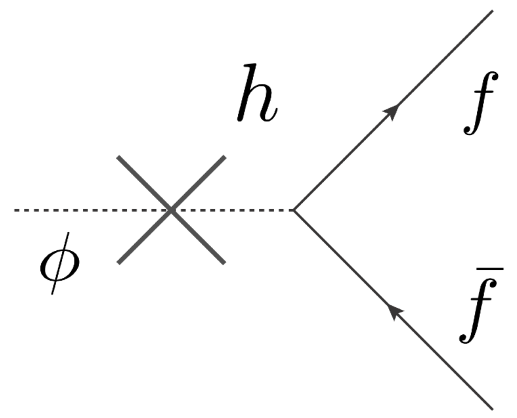


Portals between the visible and dark sectors

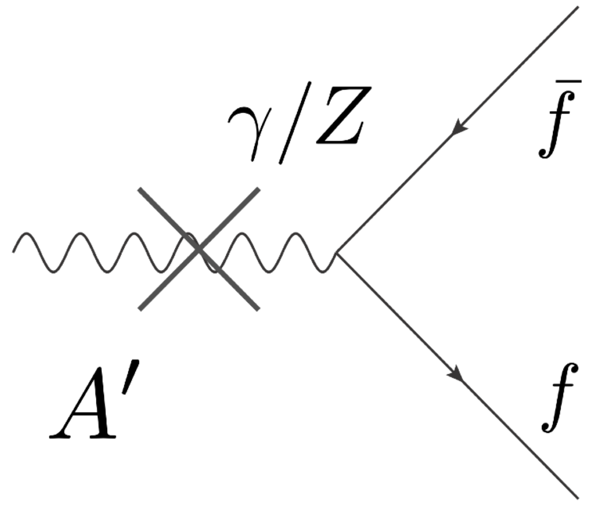
What if NP is light instead and capable to elude the detectors?



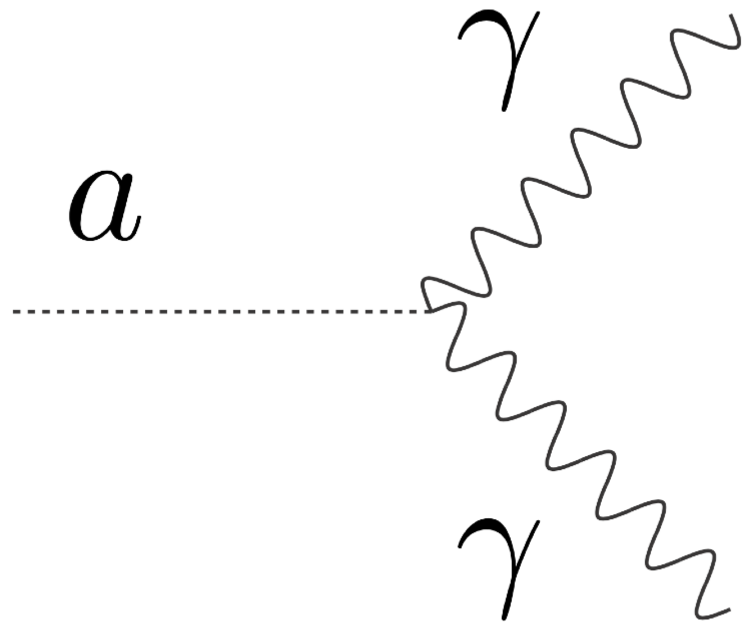
Examples:



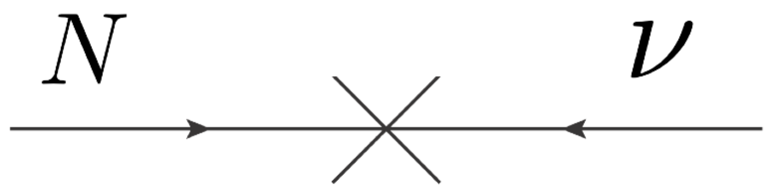
Scalar portal (ϕ)



Vector portal (A')



Axion portal (a)



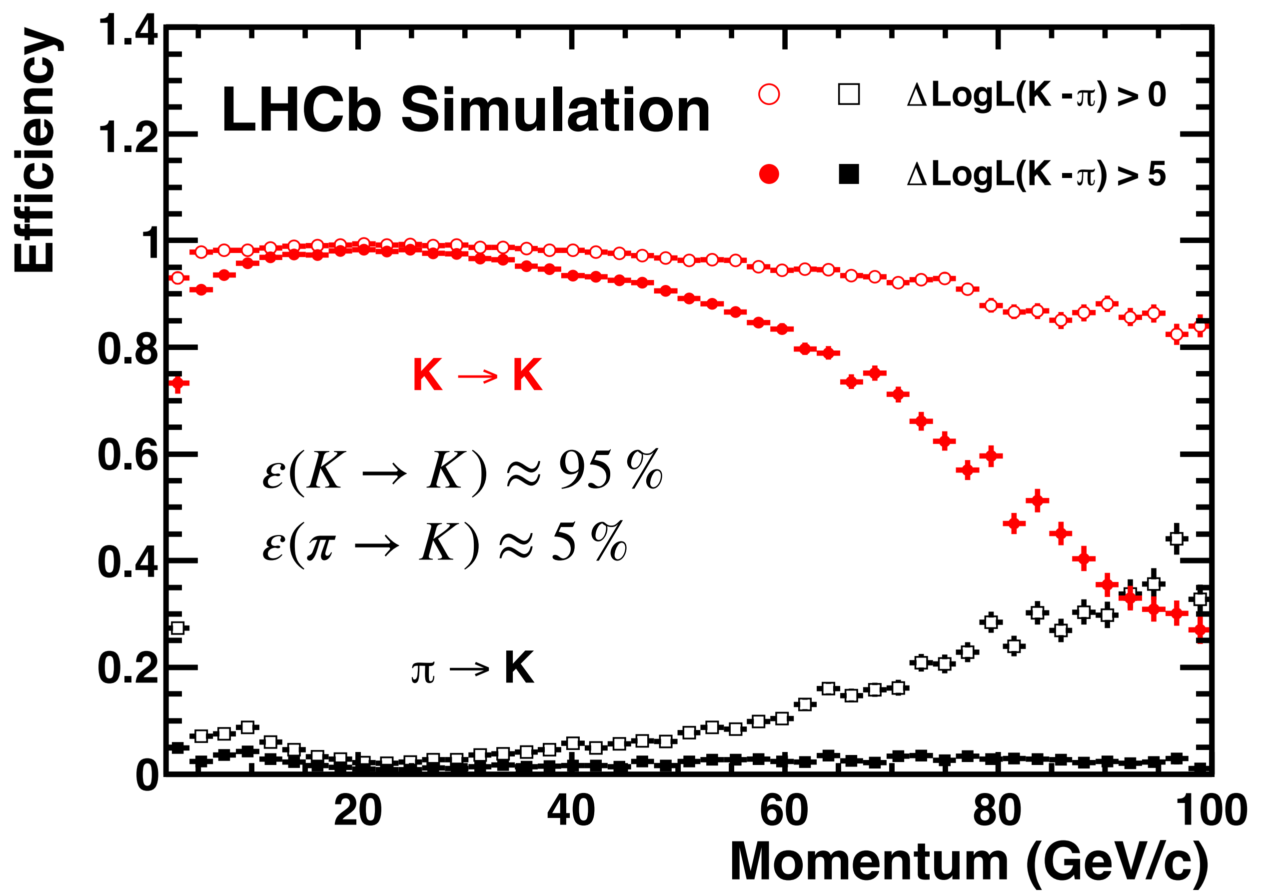
Neutrino portal (N)

Typically:

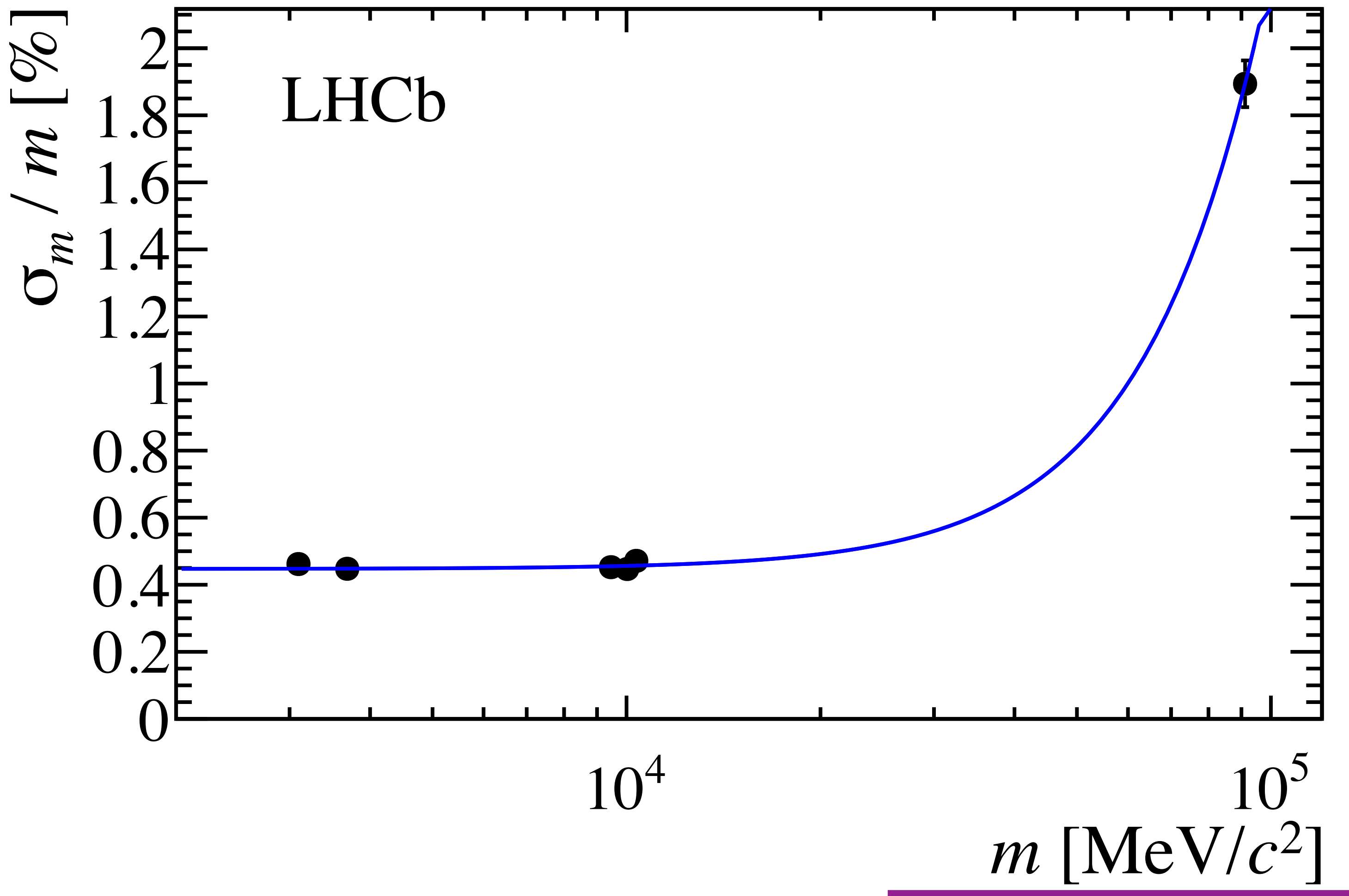
- Very weak couplings to SM particles
- Long-lived, i.e. decay vertices displaced from primary interaction

What do we need to detect such signatures?

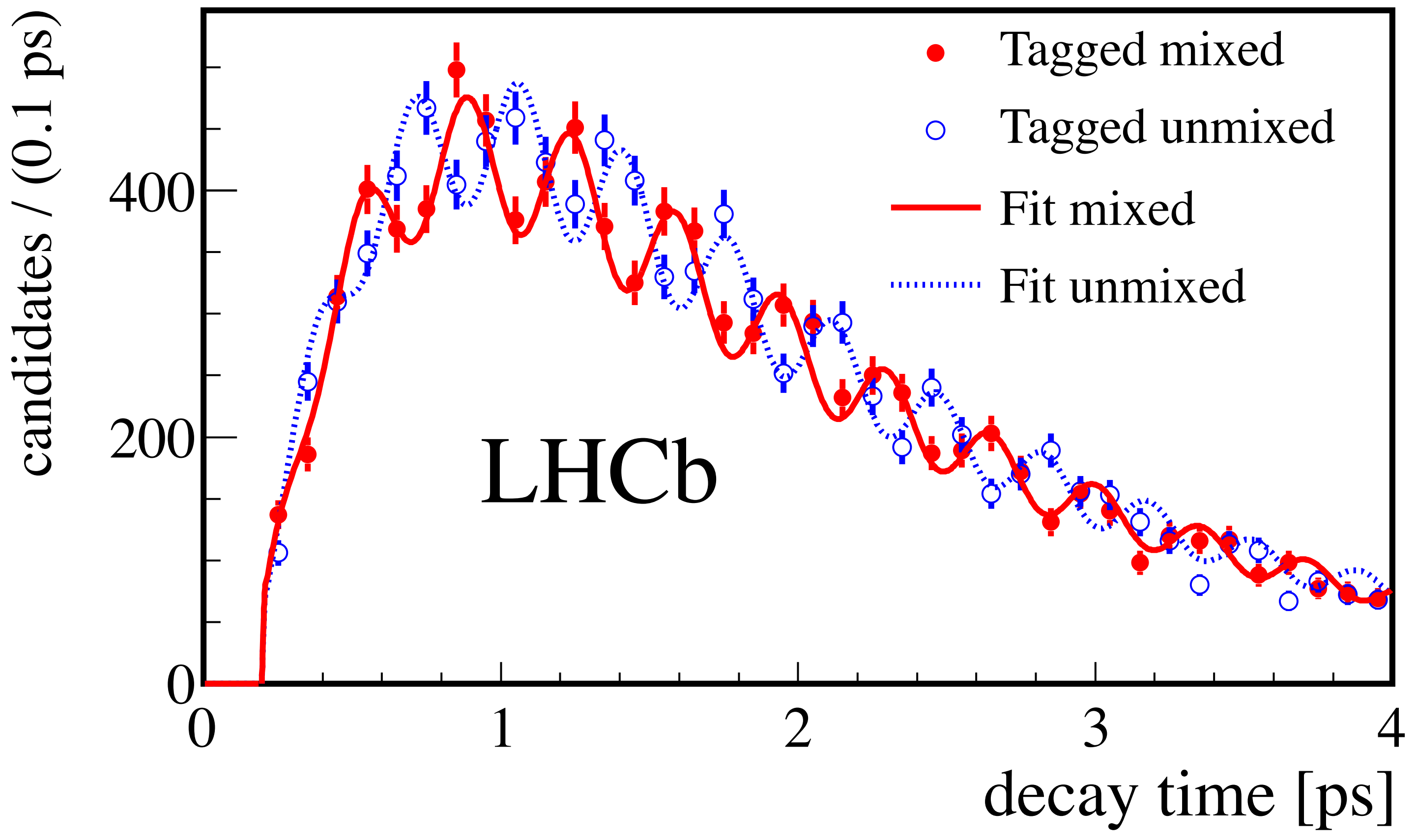
Particle identification



Mass resolution

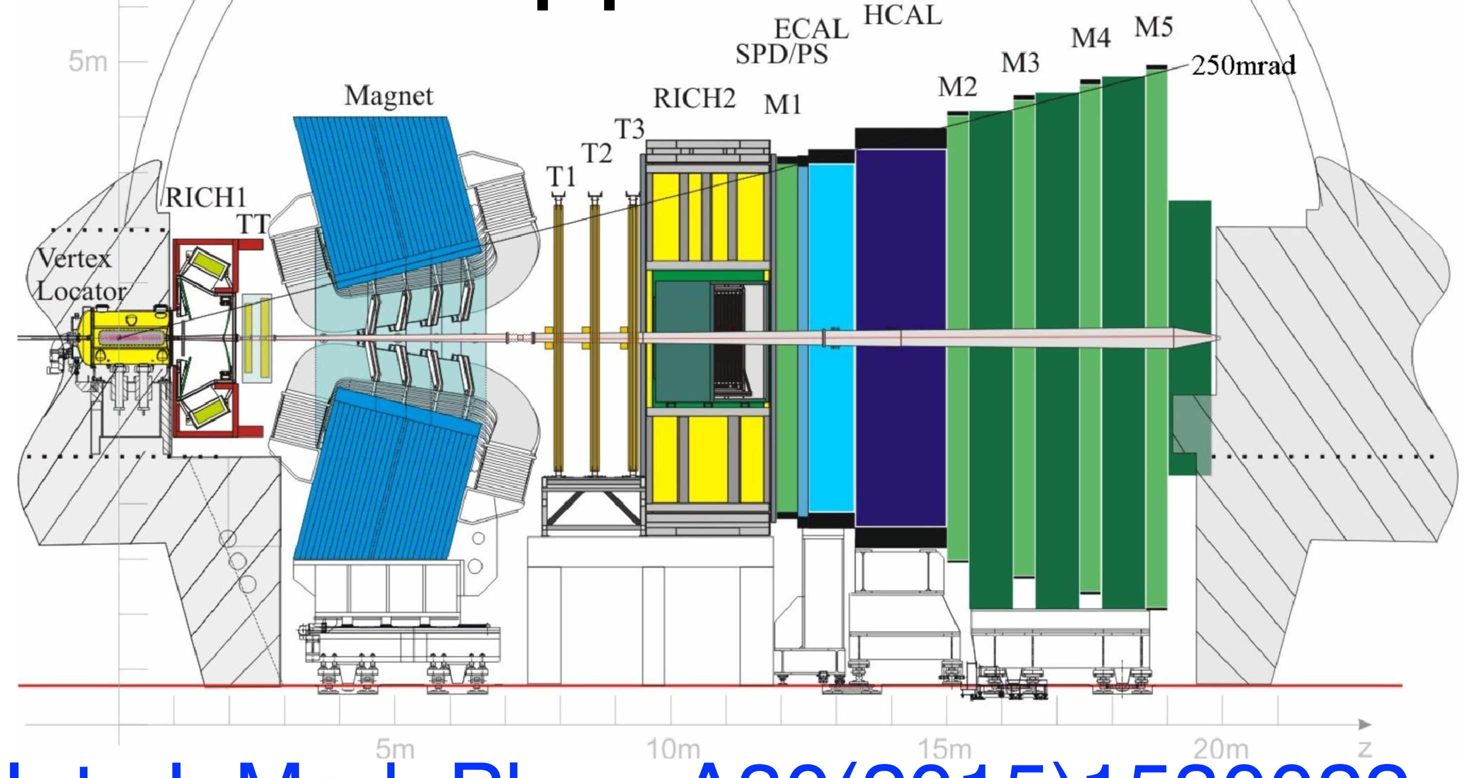


Decay time resolution



Balance large luminosity and soft trigger thresholds, especially important for low-mass searches

LHCb is excellent for low mass searches in pp collisions

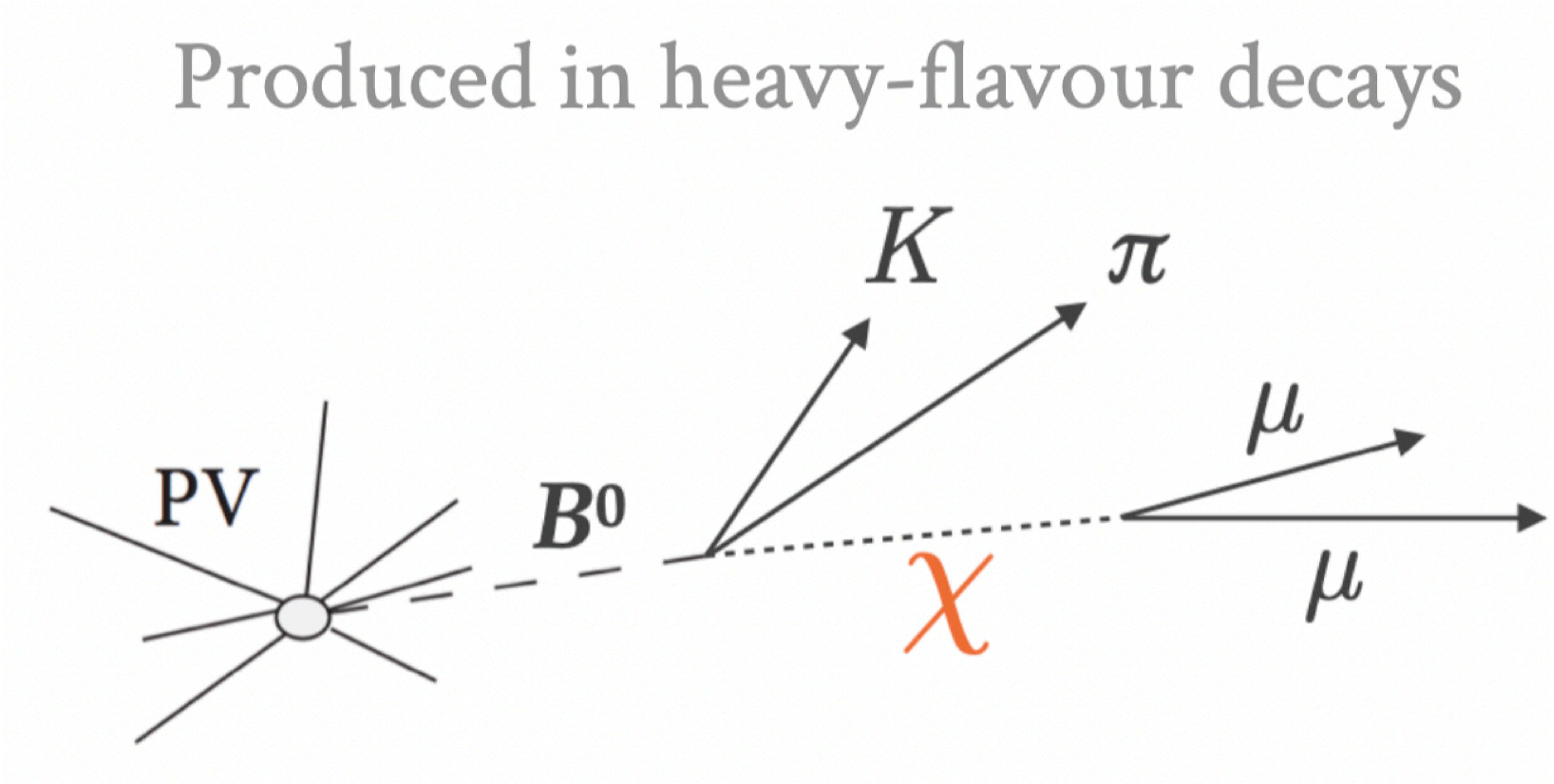


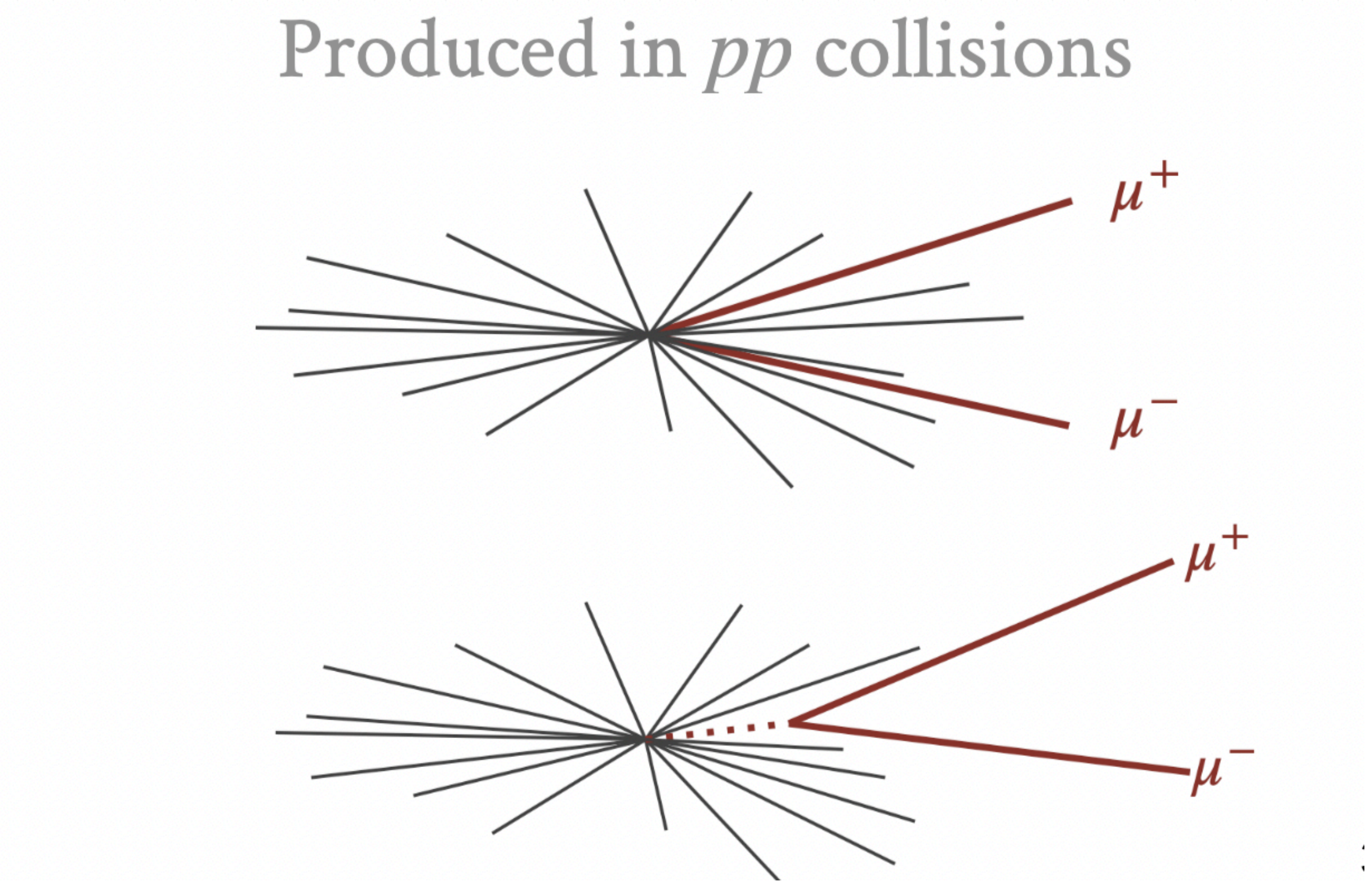
[Int. J. Mod. Phys. A30(2015)1530022]

Dark sector searches in LHCb

Why LHCb? Advantages:

- Light masses search: triggers with low p_T
- Boost in fwd region -> higher acceptance
- Hunt low mass di-leptons resonances
- LLP: long-lived particles capabilities
- In B meson decays [hidden sector bosons, HNLs]



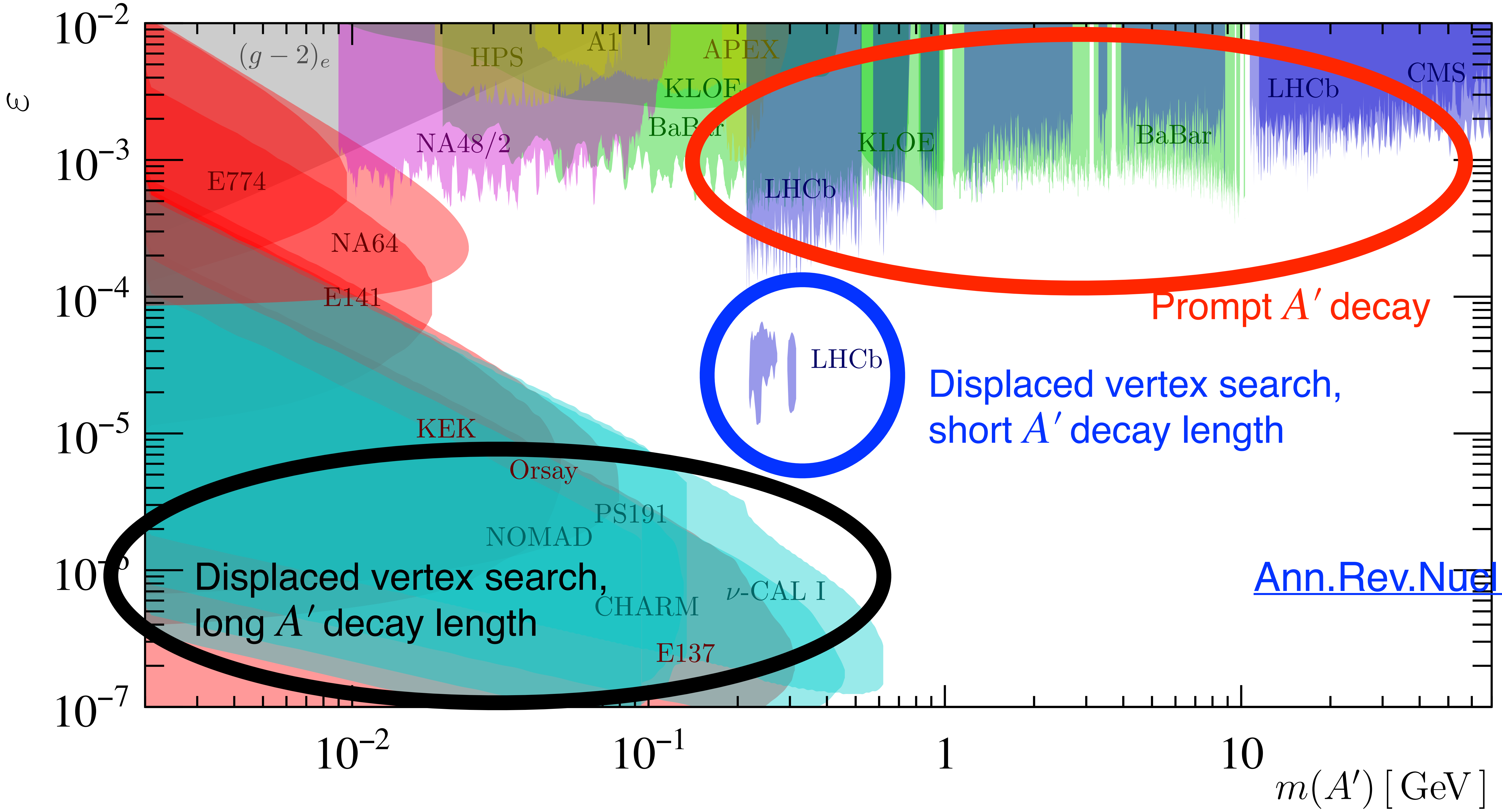


Dark photon search

- **Kinetic mixing** between dark and SM hypercharge fields:

$$\mathscr{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{A'}{}^2}{2}A'^{\mu}A'^{\mu} + g_e J^{\mu}A_{\mu} + \epsilon g_e J^{\mu}A'_{\mu}$$

- DP mass, $m_{A'}$, and kinetic-mixing strength, ϵ, are free parameters

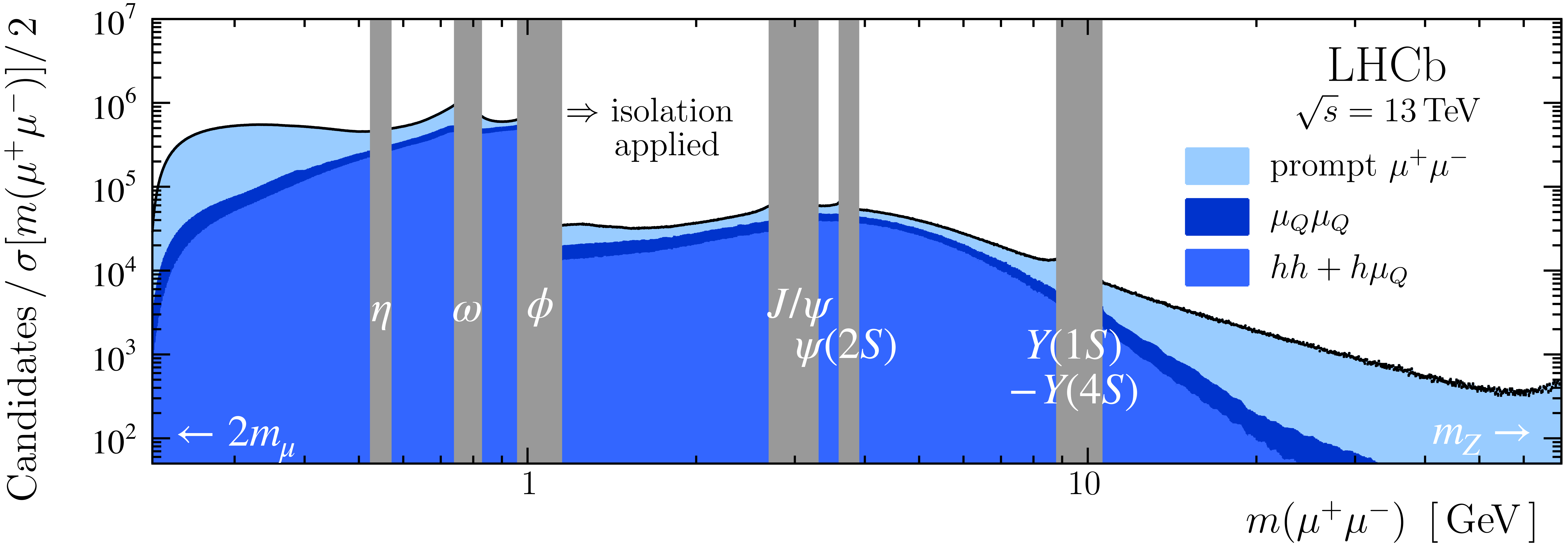


[Ann.Rev.Nucl.Part.Sci. 71 (2021) 37-58]

Prompt $A' \to \mu^+\mu^-$ search

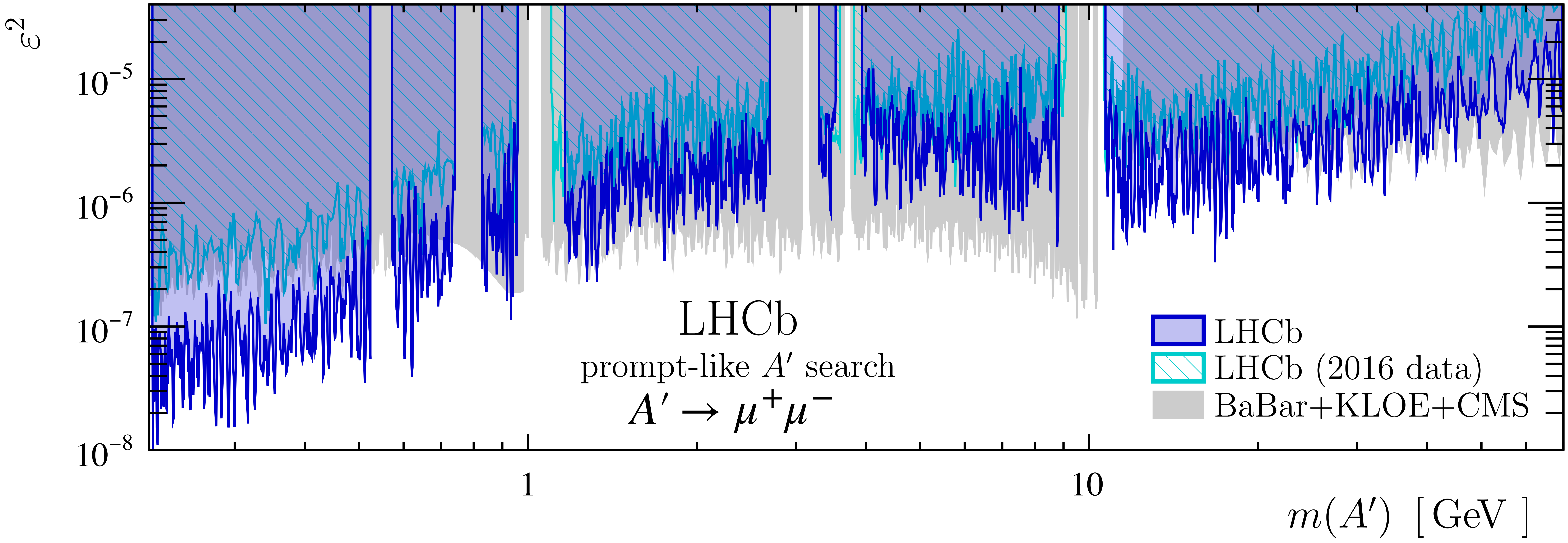
PRL 124 (2020) 041801

- Analysis exploits 5.5 fb^{-1} of Run 2 dataset
- Normalisation to $\gamma^* \to \mu^+\mu^-$ yield cancels most experimental systematics
- Templates from data (prompt $\mu\mu$, hh + $h\mu_Q$) and simulation ($\mu_Q\mu_Q$)
- $\mu_Q = \mu$ from b/c-hadron decays
- h = misidentified hadrons(mainly π's)
- Prominent resonance-peak regions are vetoed, and only tail modeled



Result dark photon search / prompt

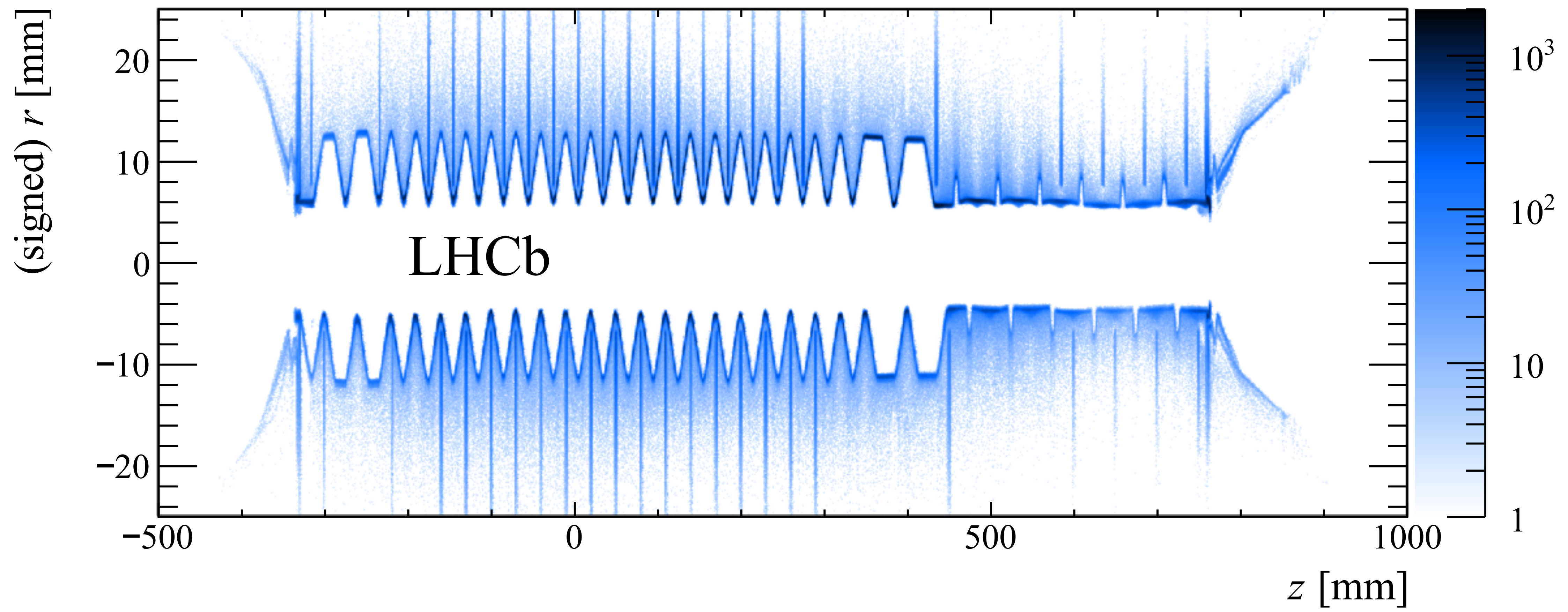
- No significant excess found - exclusion regions at 90% C.L. [PRL 124 (2020) 041801]
- First limits on masses above 10 GeV & competitive limits below 0.5 GeV

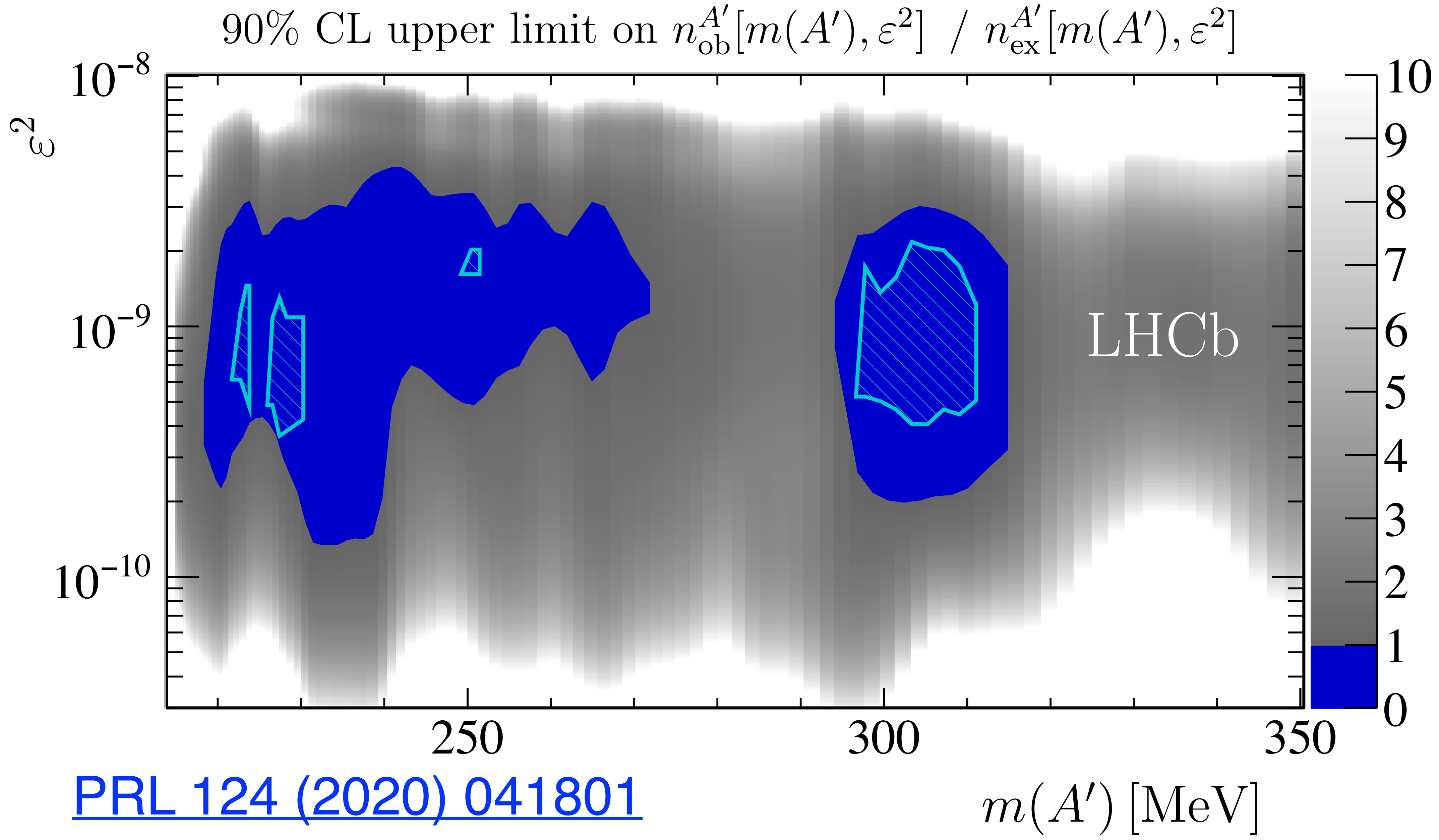


Displaced $A' \to \mu^+\mu^-$ search

- **Material background** 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 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 in a displaced region**

JINST 13, P06008 (2018)



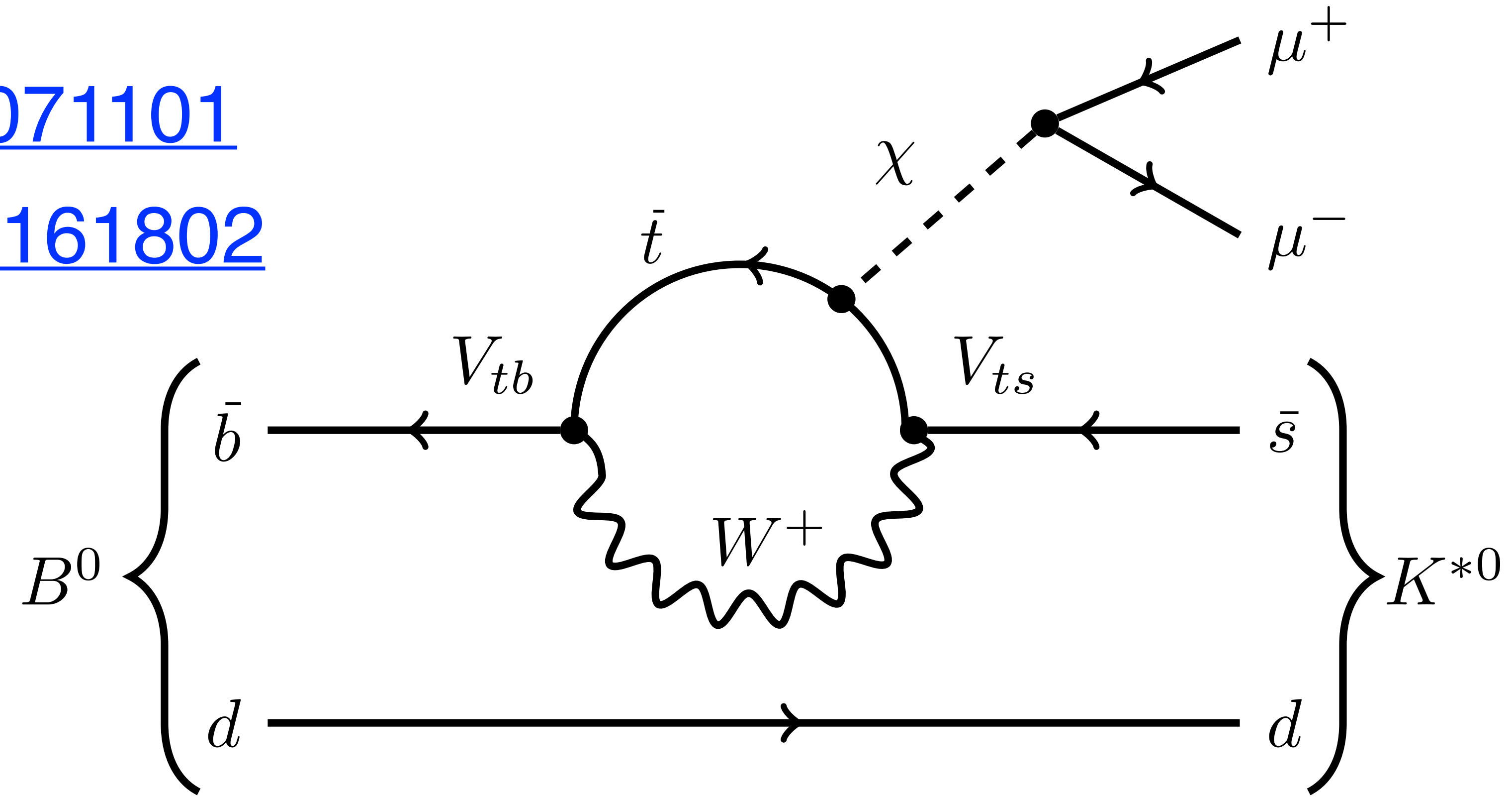


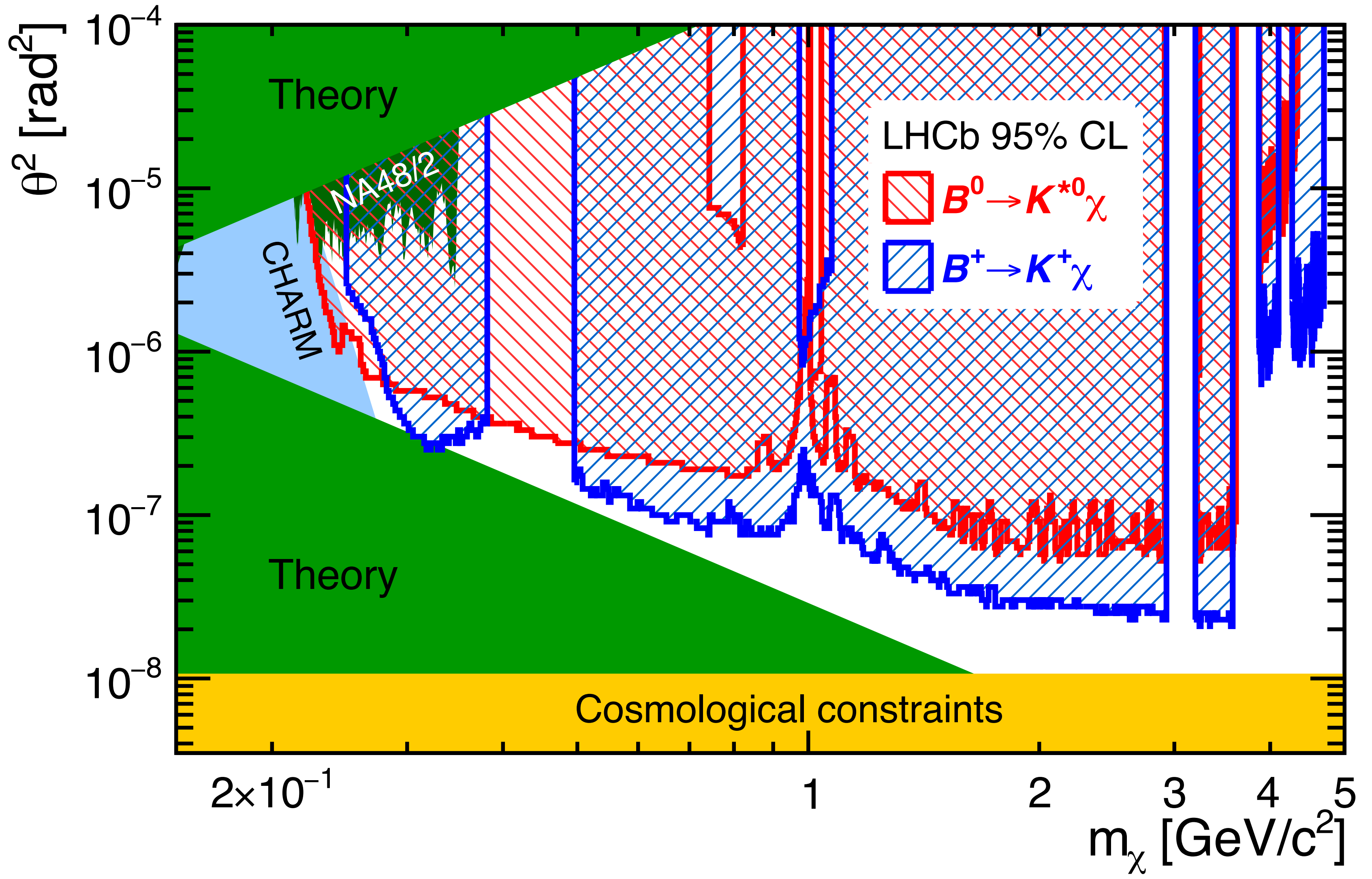
PRL 124 (2020) 041801

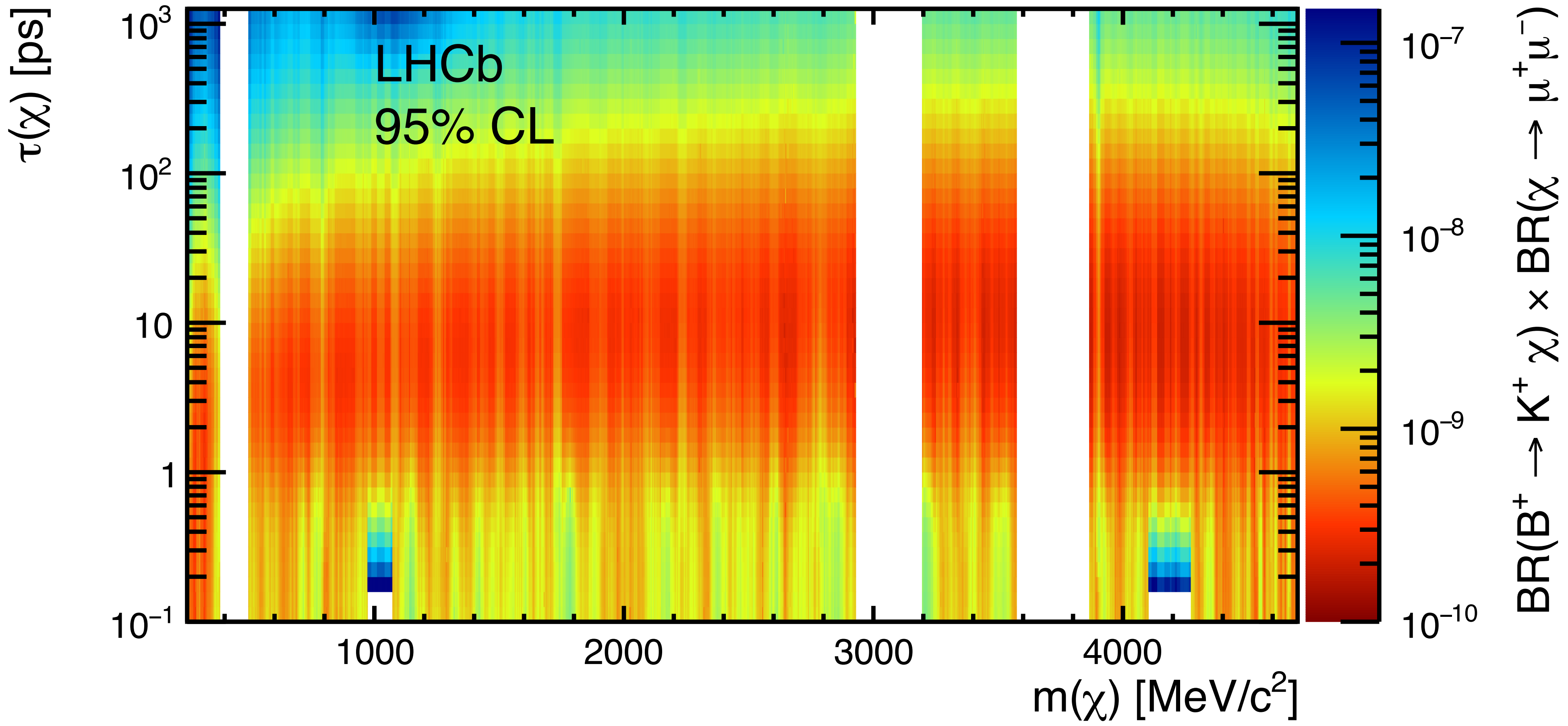
Dark boson searches in $B \to K^{(*)}\mu^+\mu^-$ decays

PRD 95 (2017) 071101

PRL 115 (2015) 161802







- Both analyses exploit full Run 1 dataset
- Search for prompt and detached $\chi \to \mu\mu$ decays
- $\mathscr{B}$ normalised to $\mathscr{B}(B^+ \to K^+ J/\psi)$ or $\mathscr{B}(B^0 \to K^{*0}\mu^+\mu^-)$
- In inflation model, mixing angle $\theta^2 \propto \mathscr{B}(B^+ \to K^+\chi)$ and $\tau_\chi \propto 1/\theta^2$

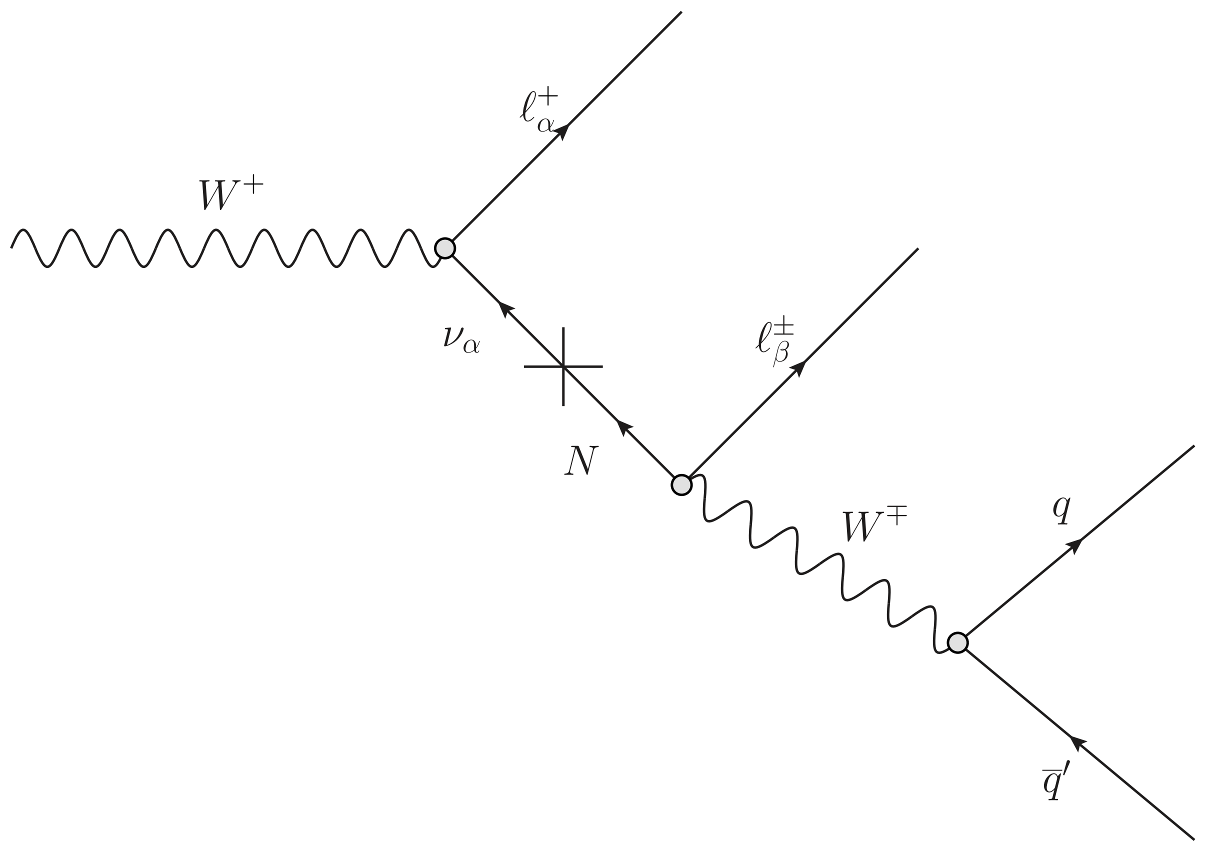
- No evidence of signal observed. Constraints on θ^2 in inflation model and τ_χ

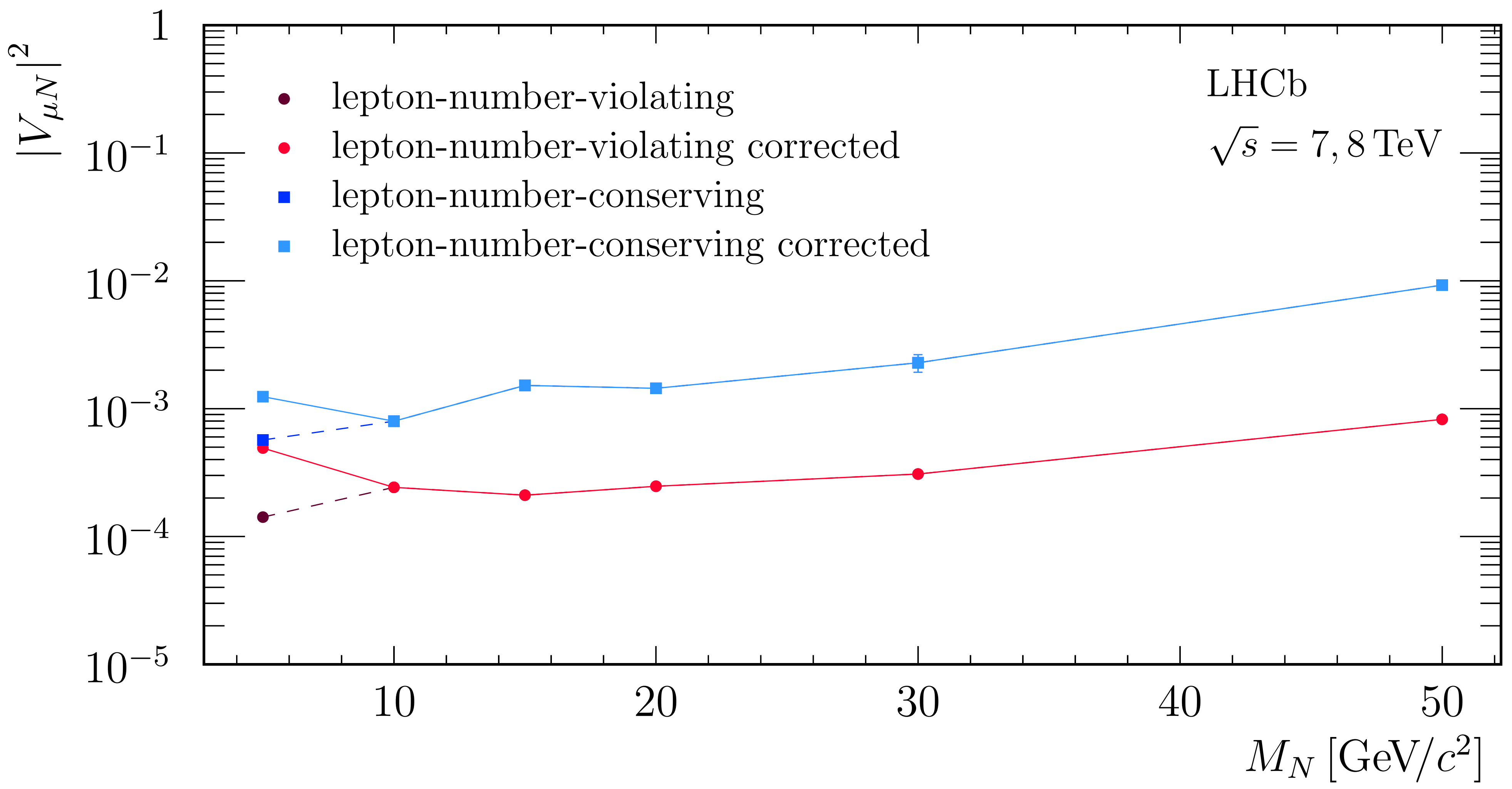
Search for heavy neutral leptons

EPJC 81 (2021) 248

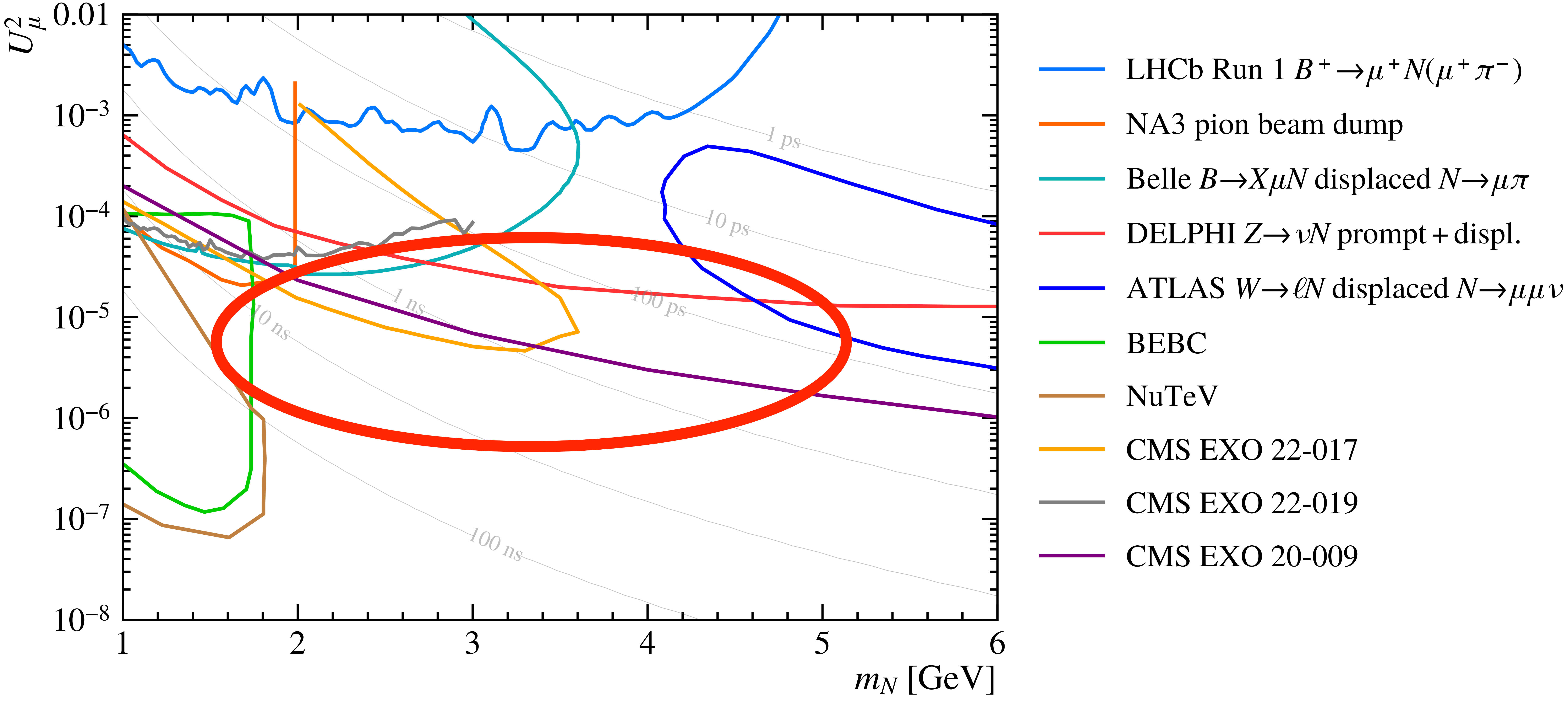
- Heavy neutral leptons (HNL) as explanation for smallness of m_ν
- Mix with SM ν_ℓ with a coupling strength of $V_{\ell N}$
- Searches for prompt HNL in $W^+ \to \mu^+ N(\to \mu^\pm q\bar{q}')$ decays with full Run1 dataset
- Cover $m_N \in [5,50]$ GeV/c²

No excess observed. Upper limit for $|V_{\ell N}|^2$





Search for heavy neutral leptons



Region where LHCb can contribute:

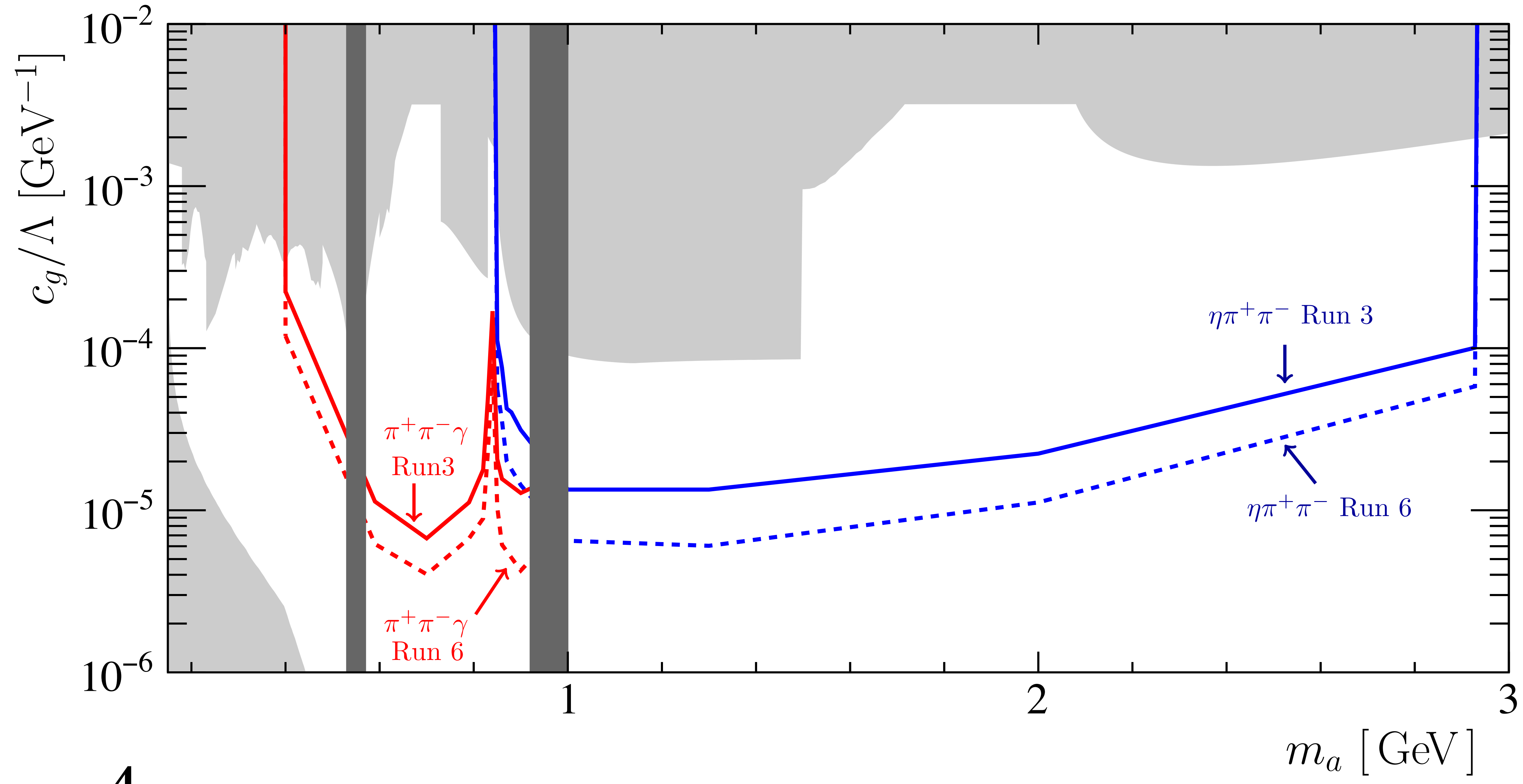
- HNL from B decays
- Low mass, low p_T thresholds

- Analysis of inclusive HNL search $B \to X\mu N(\to \mu\pi)$ in the LHCb pipeline

ALP searches at LHCb

PRL 123 (2019) 031803
arXiv:2203.07048

- Axion-like-particles can be searched for in $B \to K/K^{*0}a(\to \mu\mu)$
- Exploiting MeV-to-GeV m_a range



$$\mathscr{L} \supset -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu}$$

- Axion-like coupling to gluons

- Experimental target: $a \to \pi\pi\{\pi^0, \gamma, \eta\}$
- Currently scrutinised with Run2 data

LHCb detector in Run3

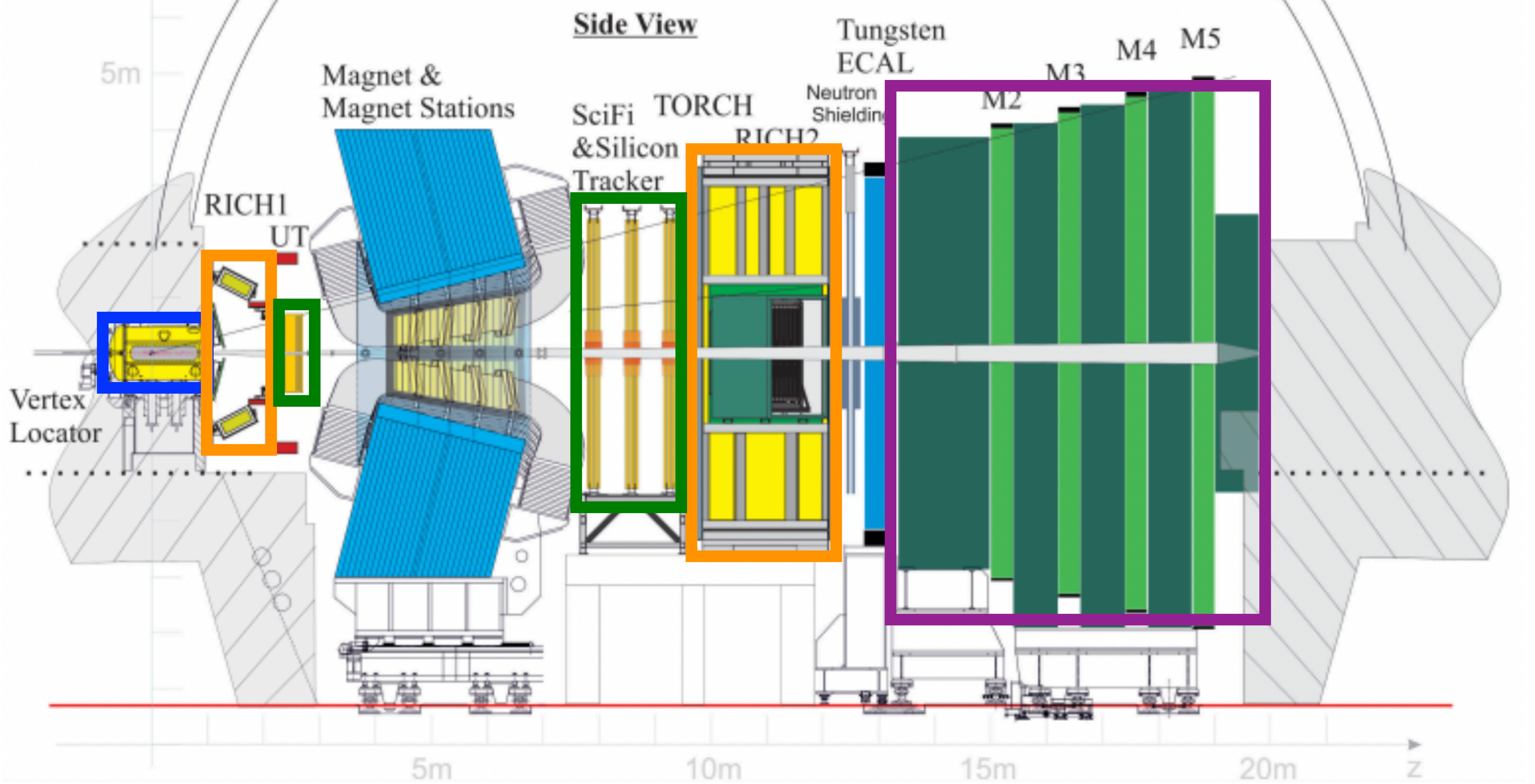
Increased instantaneous luminosity (pile-up≈6)

New vertex detector

New particle identification detector

New tracking system

New read-out



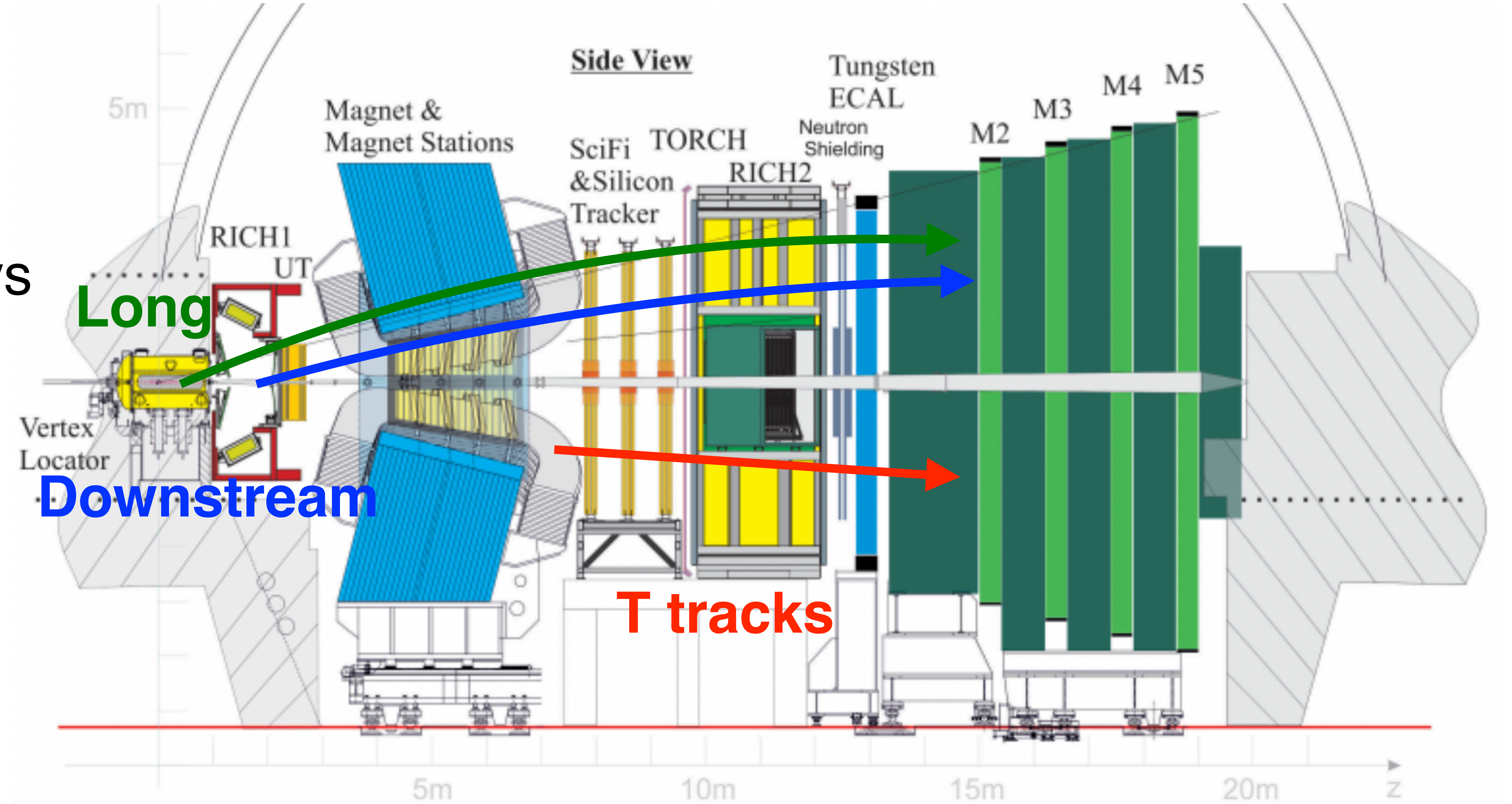
Removal of hardware trigger ⇒ Fully software-based trigger

- Reconstruction of all charged particles
- Potential for trigger on tracks starting outside of vertex detector ⇒ **Advantageous for long-lived particles**

New algorithms to reconstruct Long-Lived Particles

- For particles with $\tau > 100\,\mathrm{ps}$ many decays happen out of the VELO
- **Now LHCb can trigger on decays with downstream tracks** [Front.Big Data 5 (2022) 1008737]
- Sensitivity gained for hadrons and BSM particles
- **Effort to extend searches with T tracks**

[NEPTUNE project arXiv:2211.10920]

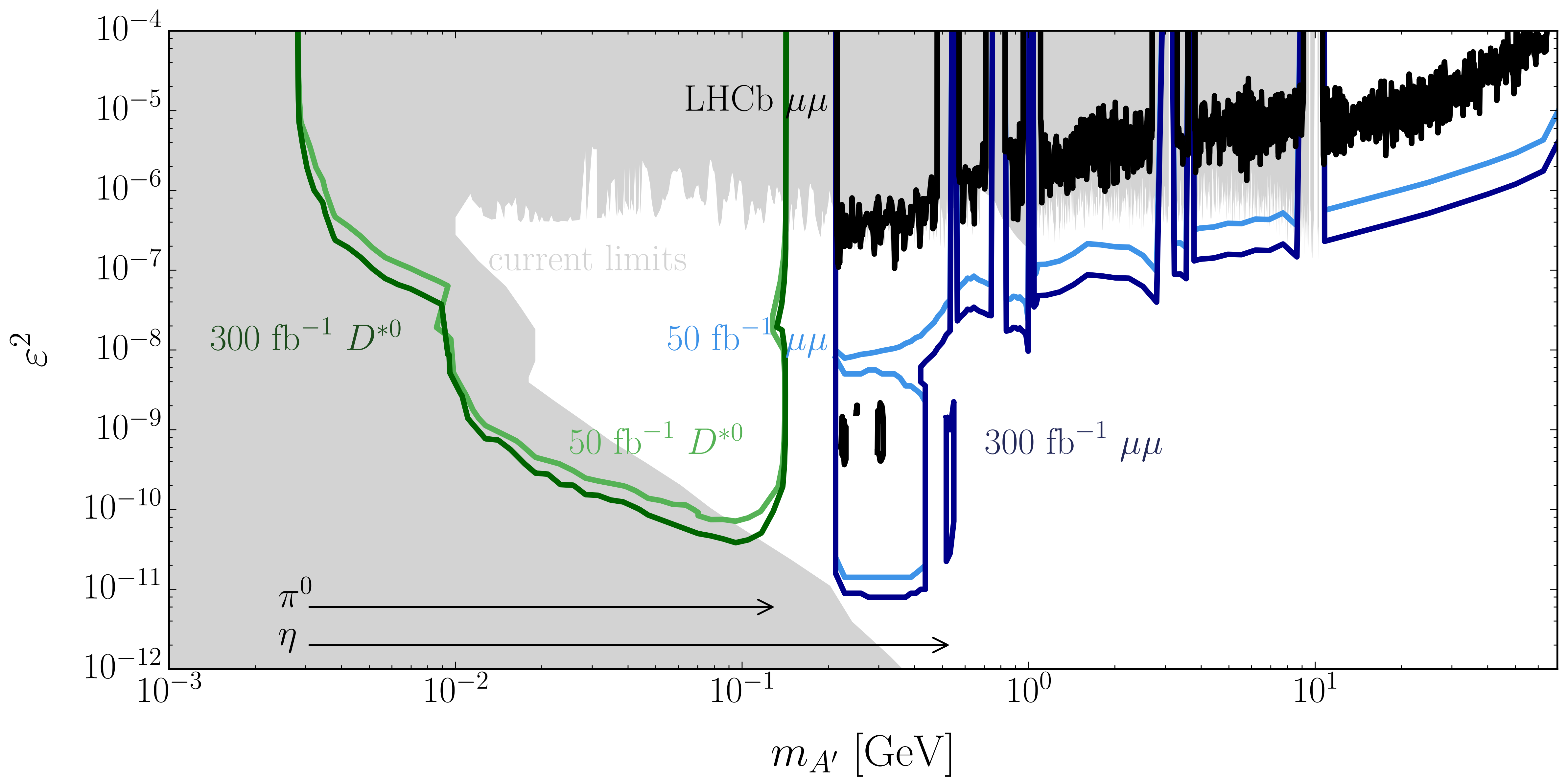


Maximum displacement

Long	$\sim 1\,\mathrm{m}$
Downstream	$\sim 2\,\mathrm{m}$
T tracks	$\sim 8\,\mathrm{m}$

Future prospects of dark photon searches

- Search for $A' \to e^+e^-$ to access $m_{A'}$ below dimuon threshold
- Background reduction via mass constraints of $D^{*0} \to D^0 A'(\to e^+e^-)$ decays
- Search of $\pi^0\eta \to A'(\to e^+e^-)\gamma$ decays complementary PRD 92 (2015) 115017
- In Run3, prompt $A' \to e^+e^-$ are saved to histograms without triggering, A''s from D^{*0} and π^0/η are kept for full analysis

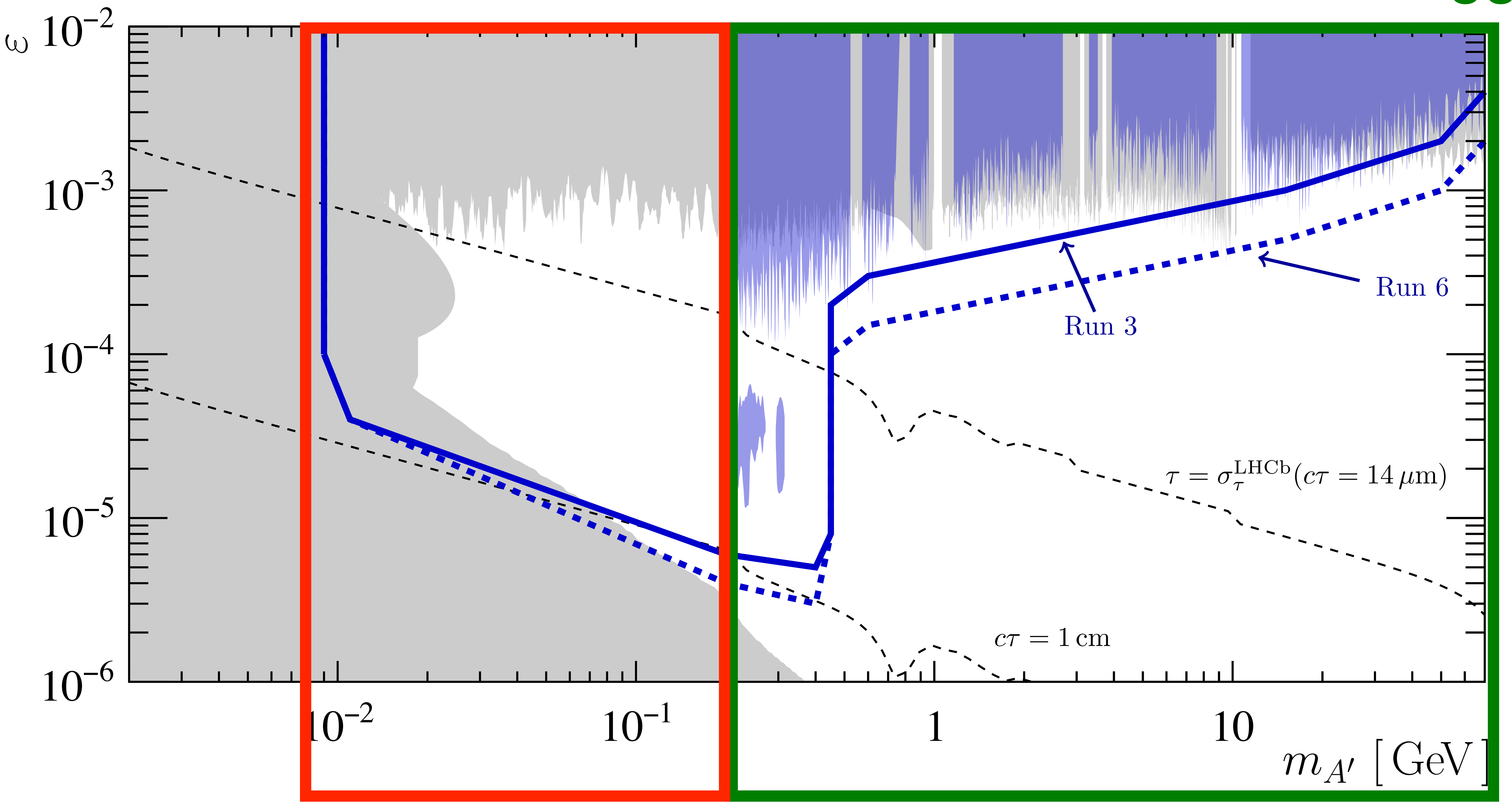


- LHCb could cover unexplored parameter space

arXiv:1812.07831

Future prospects of dark photon searches

Run 3: $\mathcal{O}(100\times)$ yield in low-mass region thanks to software trigger!



arXiv:1812.07831

Run 3: Lower masses probed by unlocking inclusive triggers for electrons ($A' \to e^+e^-$), and also radiative $D^* \to D^0 A'(\to e^+e^-)$

$D^* \to D^0 A'$ (lower bkg)

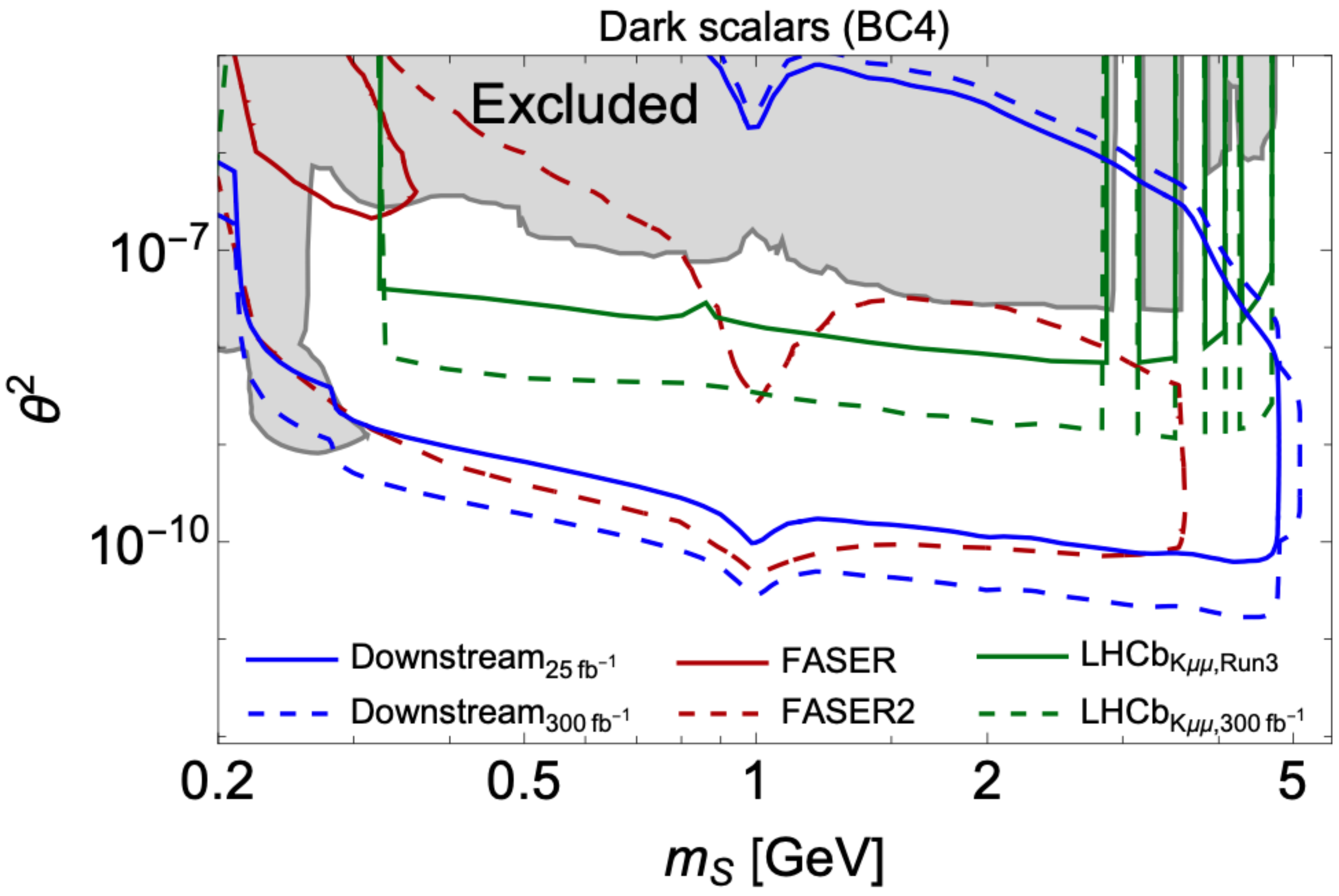
$\pi^0/\eta \to A'\gamma$ (higher bkg)

Future prospects of dark scalar searches

EPJC 84 (2024) 6, 608

Improved sensitivity for $B^+ \to K^+\chi(\mu\mu)$ search in Run3, where the μ's are long tracks

Further improvement if μ's reconstructed as downstream tracks



Heavy neutral leptons

- Downstream tracks (~2 m displacement) able to test unexplored regions able to unveil New Physics
- D/τ production ($m_N \lesssim 2\,\mathrm{GeV}$) not competitive, instead promising B ($2\,\mathrm{GeV} \lesssim m_N < m_{B_c} - m_\ell$) and W ($m_N > m_{B_c}$) production

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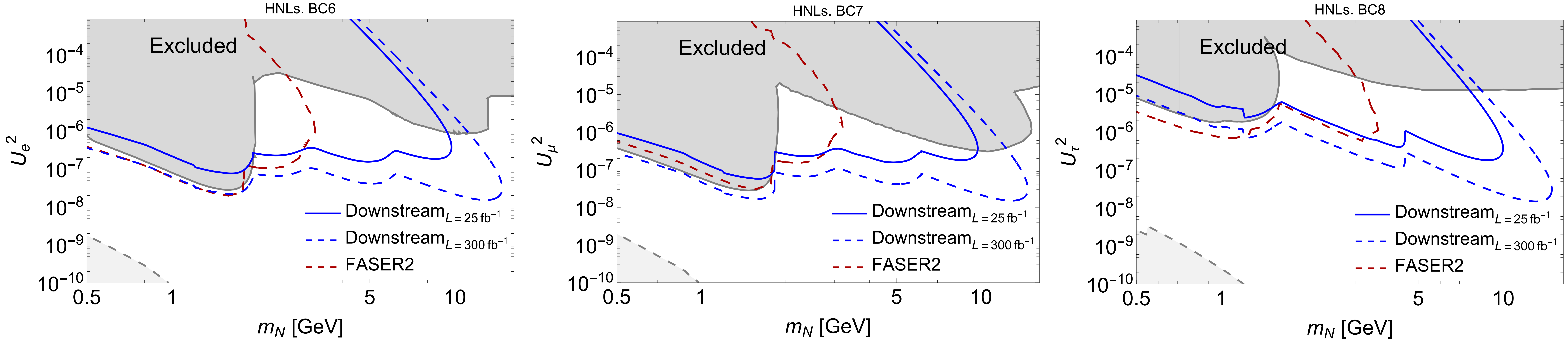


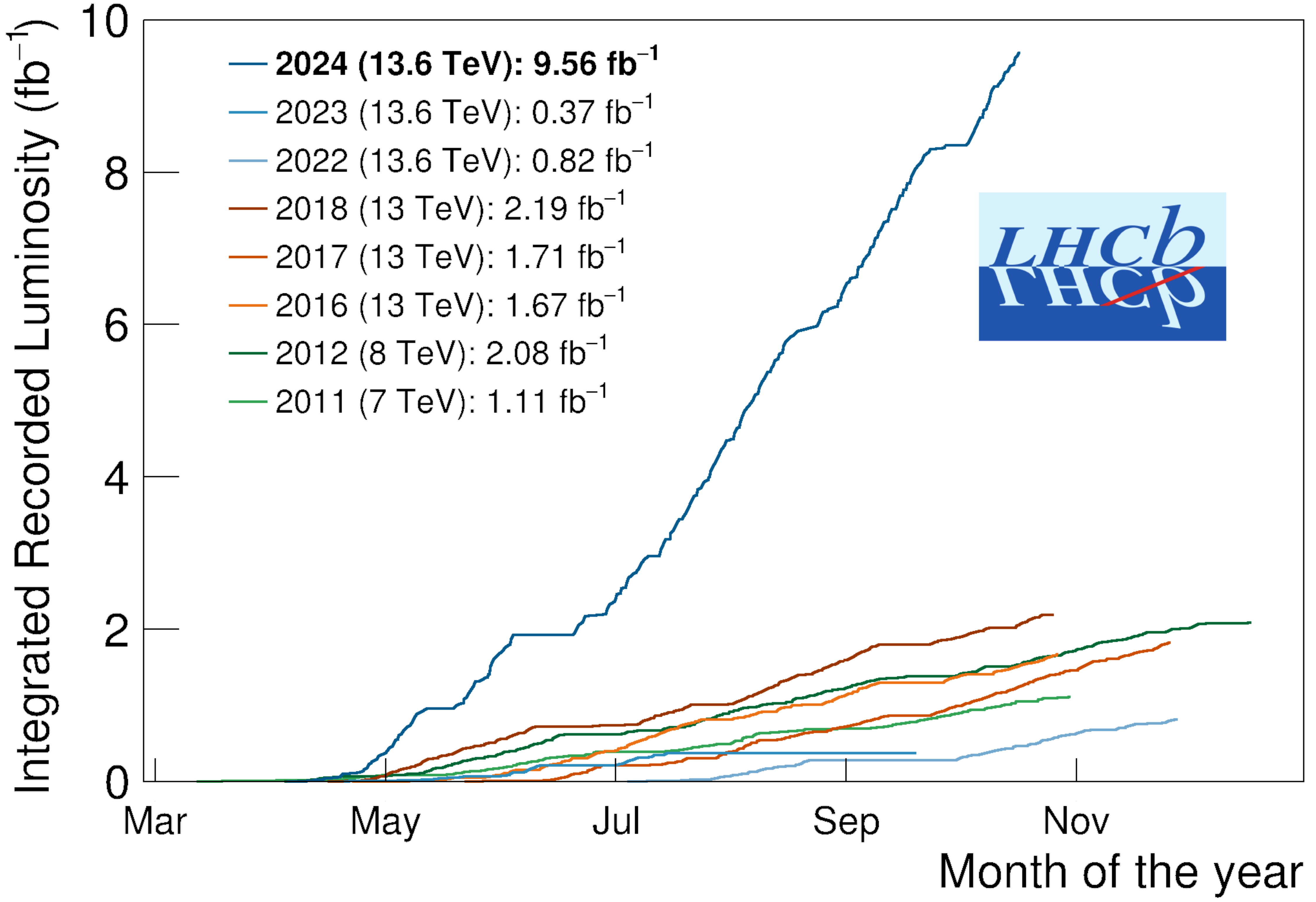
- Effort to extend searches to T tracks (~8 m displacement)

NEPTUNE project

Conclusions

Broad spectrum of searches at LHCb:

- Prompt and displaced decay topologies
- From resonances searches in di-lepton mass to exploitation of electroweak penguin decays



Exciting prospects for dark sector searches in Run3:

- Large data sample via luminosity increase
- Expected efficiency increase for decays with electrons final states
- Downstream stream tracking offers new possibilities for long-lived particles