Probing dark abelian gauge sector at the intensity frontier

arXiv: 2207.?????

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Motivations

- Searching for New Physics!

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- Light, weakly coupled dark sectors

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- Searching for New Physics!
- Light, weakly coupled dark sectors
- Model? Experiments?

The model

- Vector Portal: New vector Z_D associated to a new $U(1)_D$ gauge symmetry

- Simplest model: the *Dark Photon*

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[M. Fabbrichesi, E. Gabrielli, G. Lanfranchi, The Physics of the Dark Photon, Springer, 2021]

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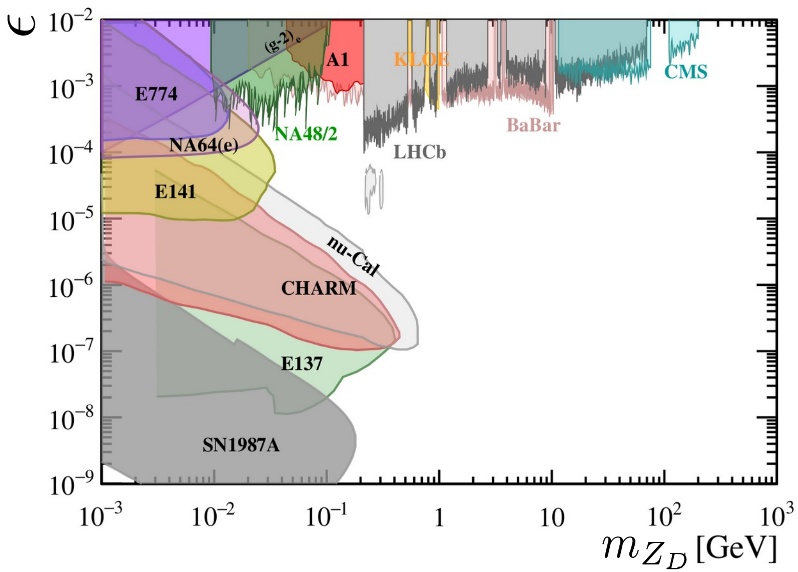

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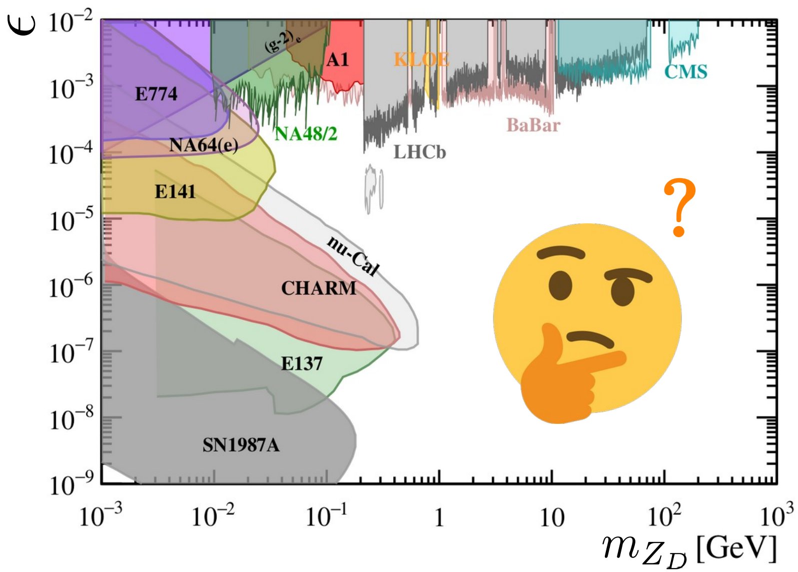

The model

- Add a *dark Higgs* S that breaks $U(1)_D$ spontaneously

$$\mathscr{L} = \mathscr{L}_{\text{scalar}} + \mathscr{L}_{\text{vector}}$$

$$\mathscr{L}_{\text{scalar}} \supset |D_\mu S|^2 - \kappa |S|^2 |H|^2$$

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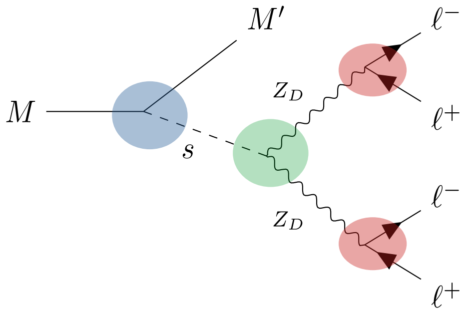
$$|D_\mu S|^2 \supset g_D m_{Z_D} s Z_D^\mu Z_{D\mu}$$

Phenomenology

- Exotic meson decays:



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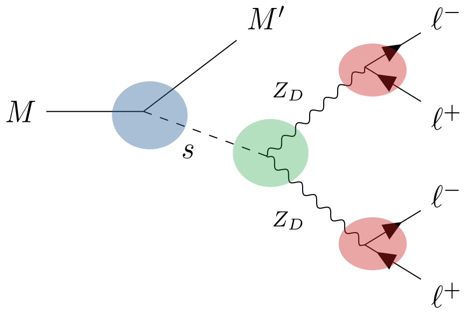


$K_L \to \pi^0 s$ $B \to K s$ $\Upsilon \to \gamma s$

Visible signatures – LHCb/Belle II

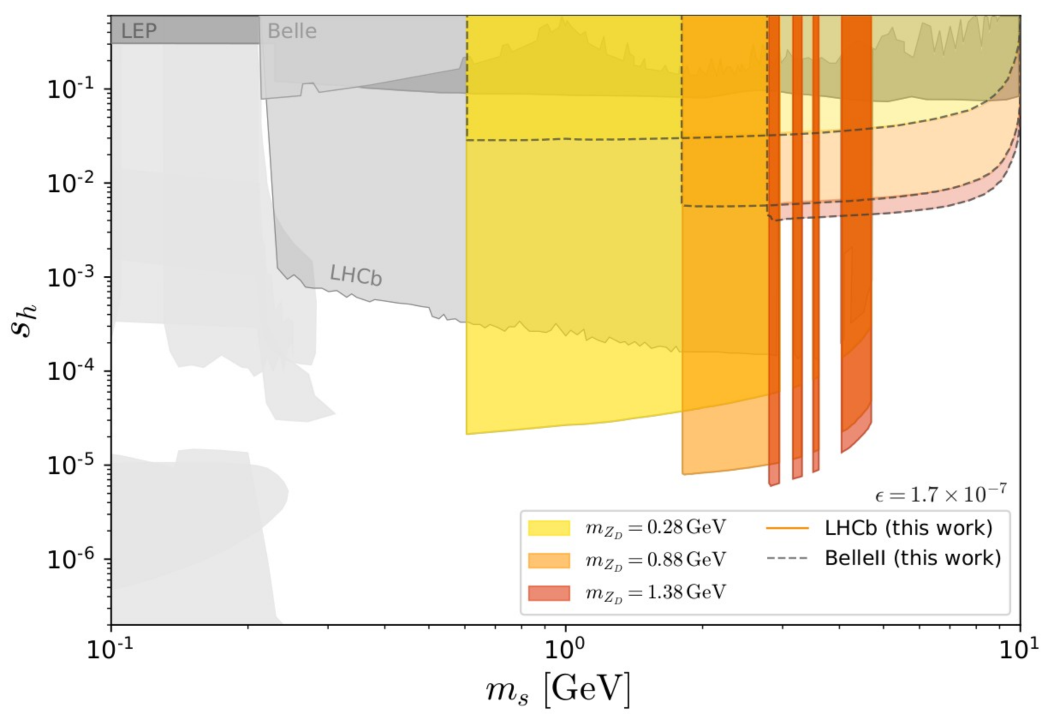
- All final states are measured: SM + 4 leptons

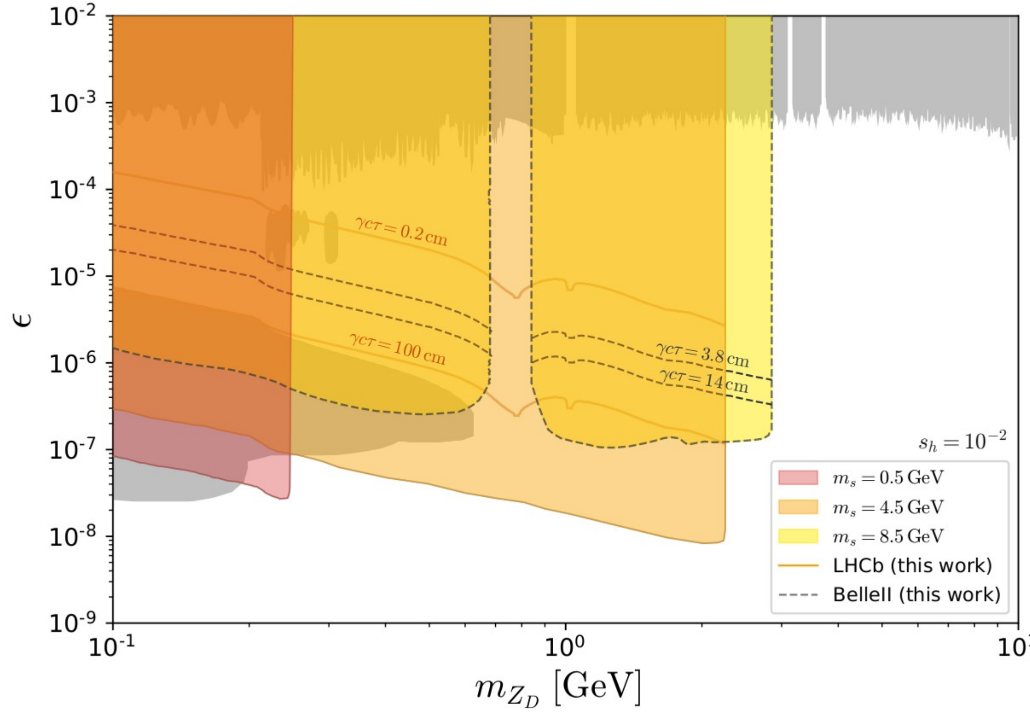
- Number of events

$$N_{\text{evts}} = N_M \, \text{BR}(M \to M' s) \, P_{\text{dec}} \, \text{BR}(Z_D \to \ell^- \ell^+)^2 \, \varepsilon_{\text{eff}}$$

Results – LHCb/Belle II

- Colored: $N_{\text{evts}} \geq 3$
- s_h = scalar mixing angle





Invisible signatures - KOTO

- SM branching ratio: $\mathrm{BR}\left(K_L \to \pi^0 \bar{\nu}\nu\right) = (3.0 \pm 0.3) \cdot 10^{-11}$

- Data puts bounds on

$$\mathrm{BR}(K_L \to \pi^0 X) \lesssim 3.7 \times 10^{-9}, \quad X \text{ invisible}$$

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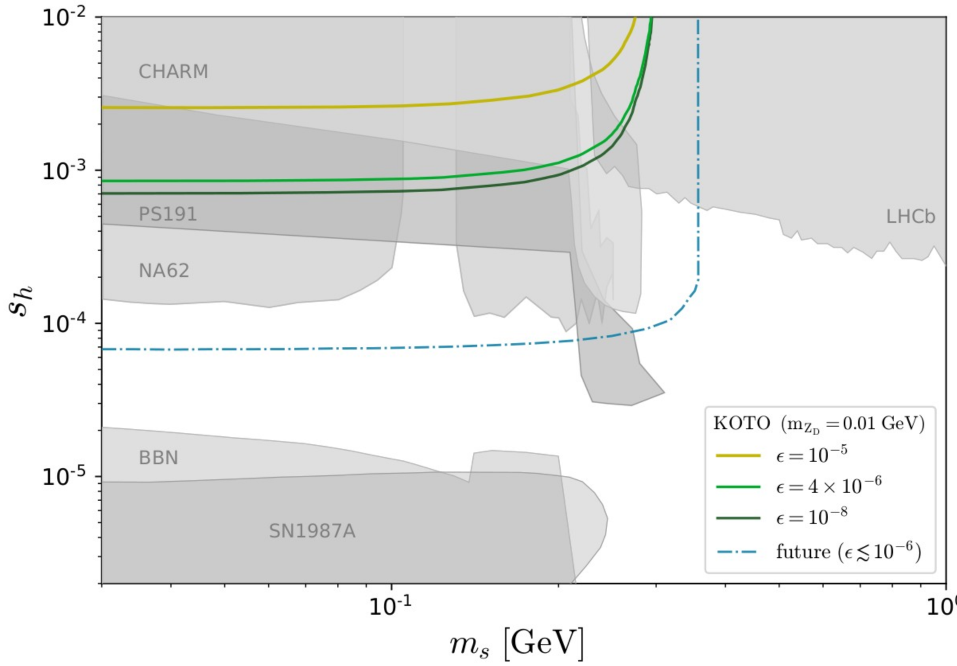
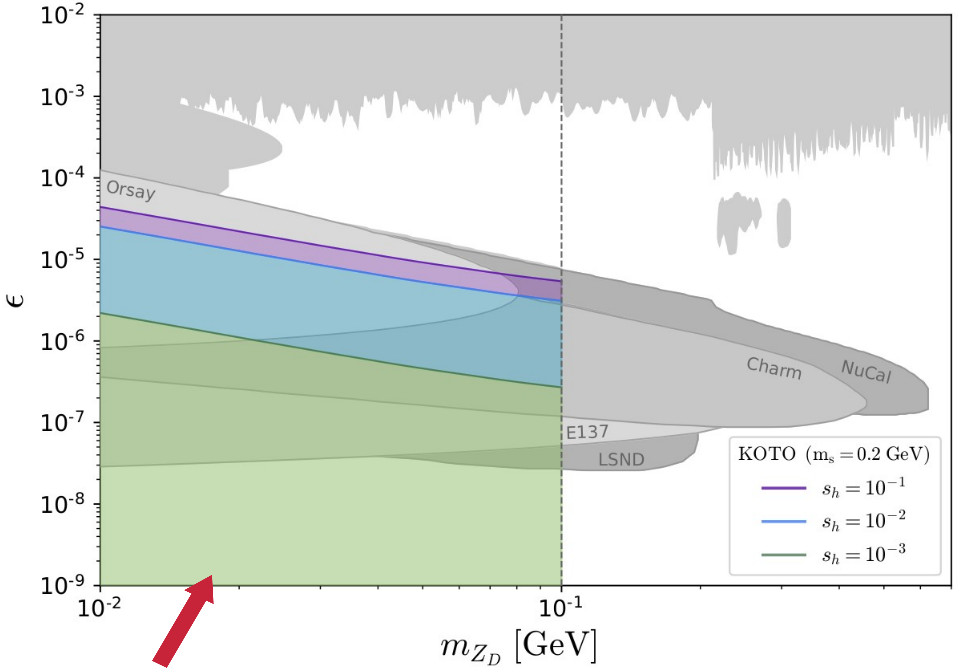
→ Escaping dark particles contribute to the signal!

Results – KOTO





Excluded down to $\epsilon = 0$!

Conclusions

- Future prospects for novel meson decays are promising!

- Dark photon/dark Higgs limits are not robust!

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Thank you for the attention!

Appendix

Phenomenology

- Probe the dark gauge connection

$$\Gamma(s \to Z_D Z_D) \propto \left(\frac{g_D}{m_{Z_D}}\right)^2 \frac{m_s^3}{32\pi}, \quad \text{for } m_s > 2m_{Z_D}$$

- Regime of interest

$$\Gamma(s \to Z_D Z_D) \simeq \Gamma_s(\text{total}), \quad \text{for } \; g_D \gg 7 \cdot 10^{-3} s_h$$

Stuckelberg mechanism

[G. D. Kribs, G. Lee, A. Martin, arXiv: 2204.01755]

- No $U(1)_D$ gauge symmetry
- Operators built out of Z_D^μ

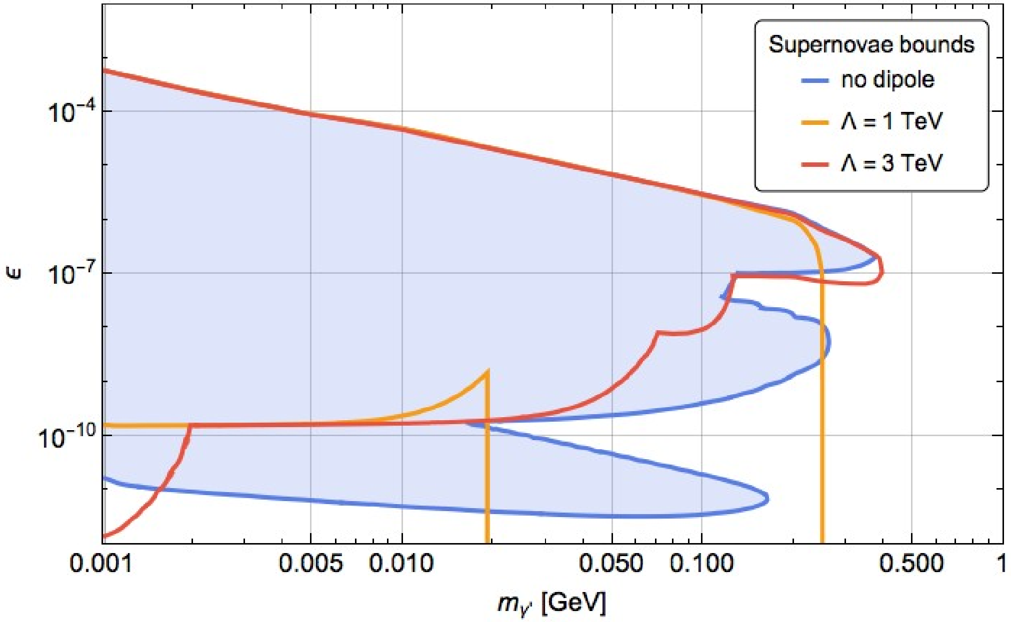
$$\mathscr{L}_{\text{int}} = \frac{m_{Z_D}^2}{2} Z_D^\mu Z_{D\mu} - \frac{\epsilon}{2c_W} Z_D^{\mu\nu} B_{\mu\nu} + \lambda_4 (Z_D^\mu Z_{D\mu})^2 +$$

$$+ \lambda_H (Z_D^\mu Z_{D\mu}) |H|^2 + Z_D^\mu J_\mu$$

$$J^\mu = \sum_f r_f \bar{f} \gamma^\mu f$$

EFT scenario [D. Barducci, E. Bertuzzo, G. G. di Cortona, GMS, JHEP 12(2021)081]

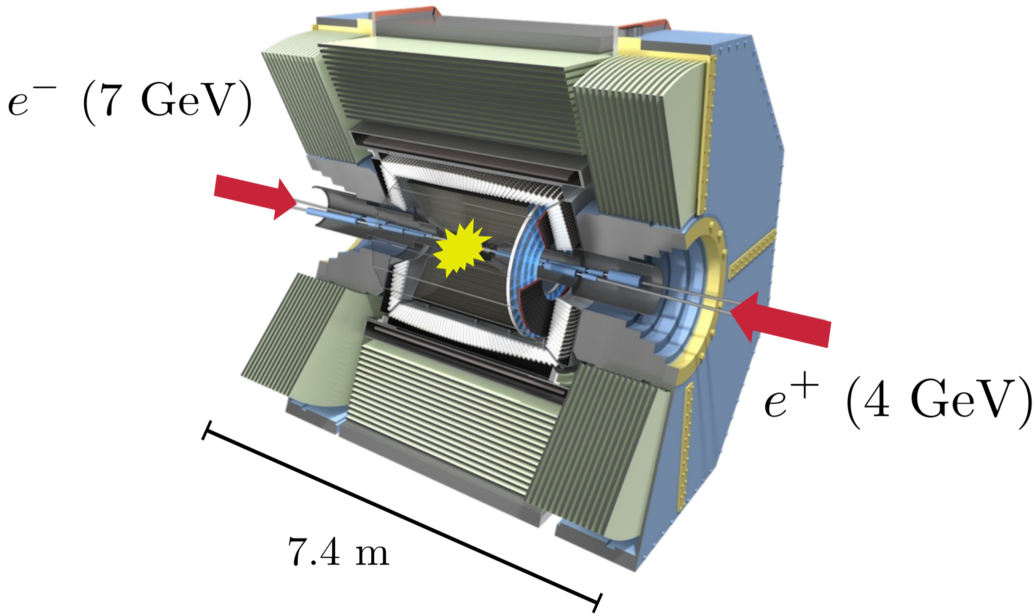
- Addition of a dipole operator $$\mathscr{L}_{\text{dipole}} = \frac{d_e v}{16\pi^2\Lambda^2} Z_{D\mu\nu}\bar{e}\sigma^{\mu\nu}e$$



- Bounds from Supernovae, E137 and LSND
- Modifications to the usual exclusion curves are expected

Belle II

- Asymmetric electron-positron collider



- Angular acceptance

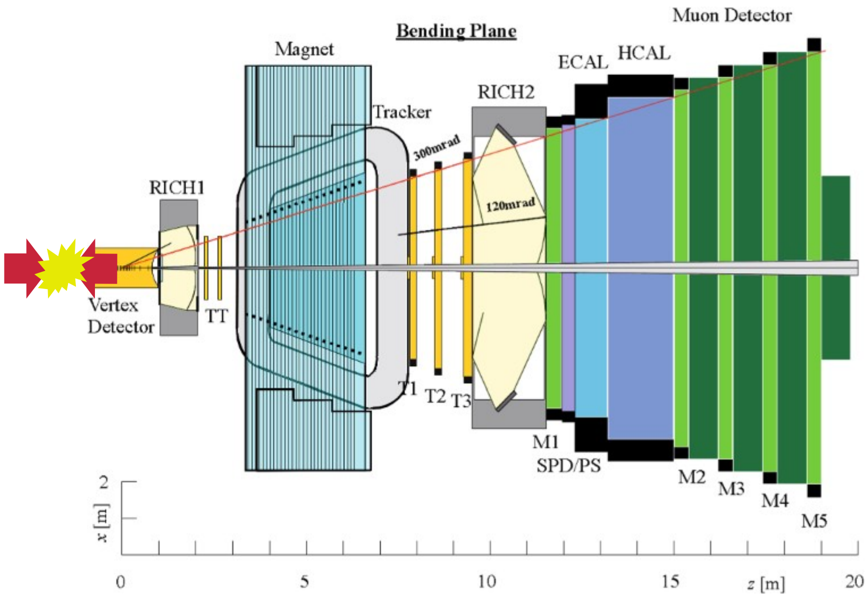
$$17^\circ \leq \theta \leq 150^\circ$$

- Upsilon peak

$$e^- e^+ \to \Upsilon(nS)$$

LHCb

- 13 TeV proton-proton collision



- Angular accepetance

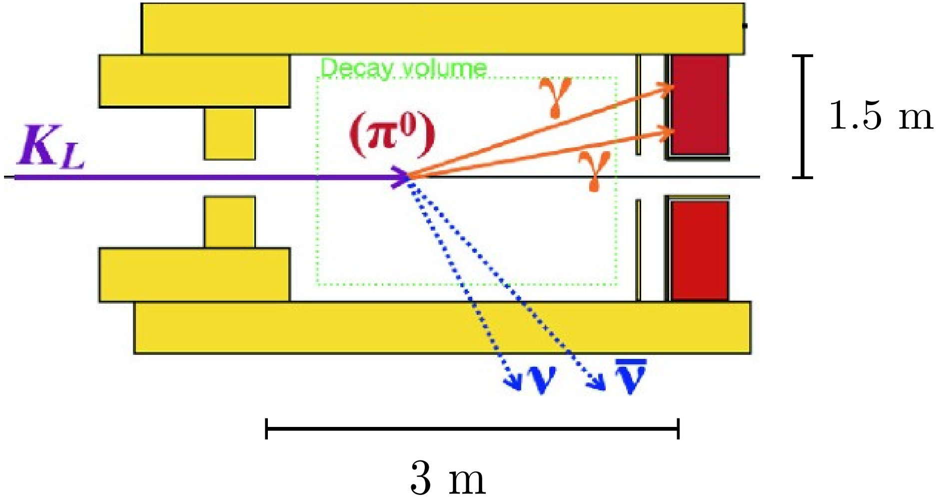
$$\theta \lesssim 275 \text{ mrad}$$

- B-meson production

$$pp \to B, \cdots$$

KOTO

- K_L-beam from 30 GeV proton beam



- SM branching ratio

$$\mathrm{BR}\left(K_L \to \pi^0 \bar{\nu}\nu\right) = (3.0 \pm 0.3) \cdot 10^{-11}$$

- Only photons are measured! (charged particles are vetoed)

Simulation

`Pythia8` → `MadGraph/MadDump` → N_{evts}

(Meson flux) (Decays, decay probability)

- In MadDump interface
  - Detector geometry
  - Kinematical cuts
  - Hadronic decays

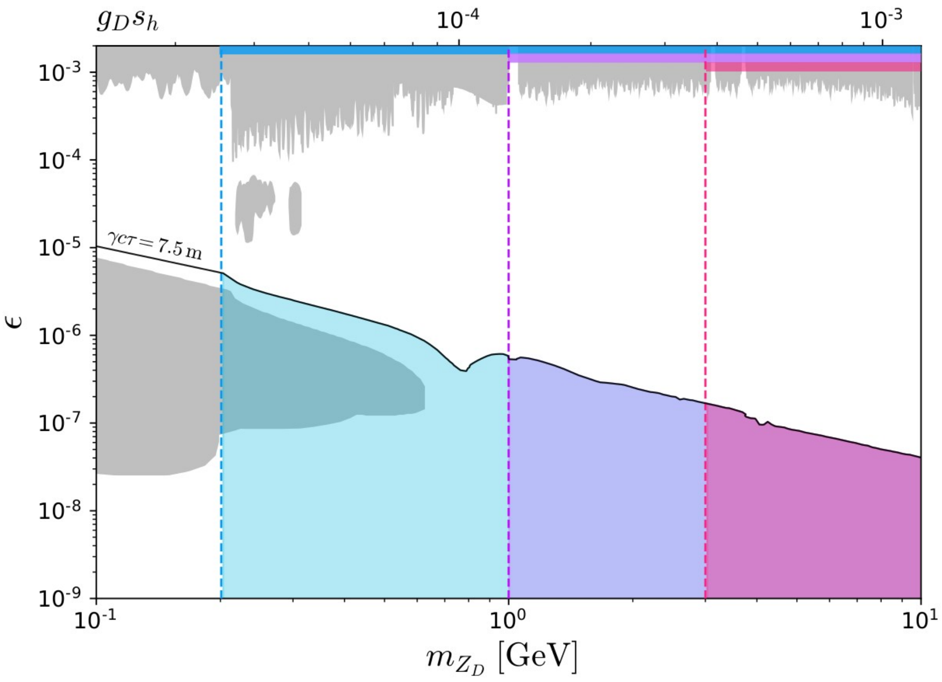
Higgs invisible width

- Invisible channels

$$\Gamma(h \to \text{inv}) = \Gamma(h \to ss) + \Gamma(h \to Z_D Z_D)$$

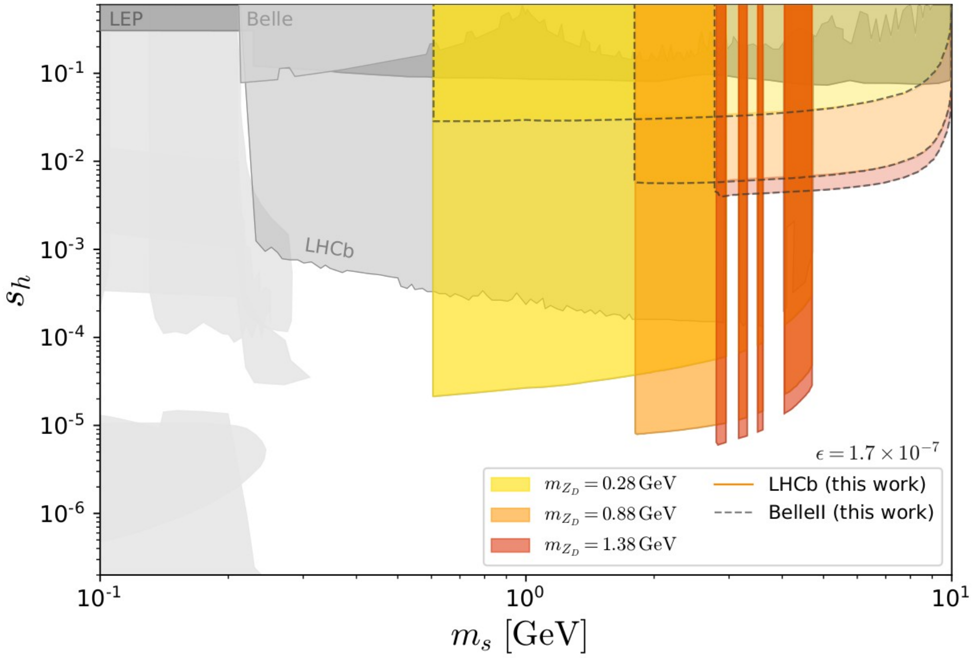
$$\simeq \left(\frac{s_h g_D}{m_{Z_D}}\right)^2 \frac{m_h^3}{32\pi}$$

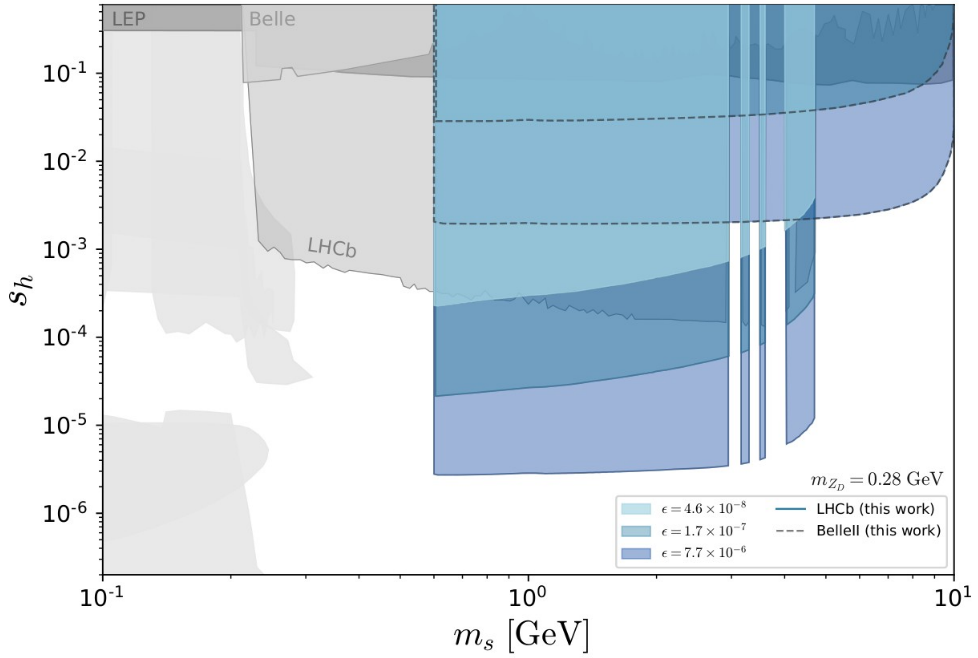
Dark photons
must escape!



LHCb/Belle II exclusion

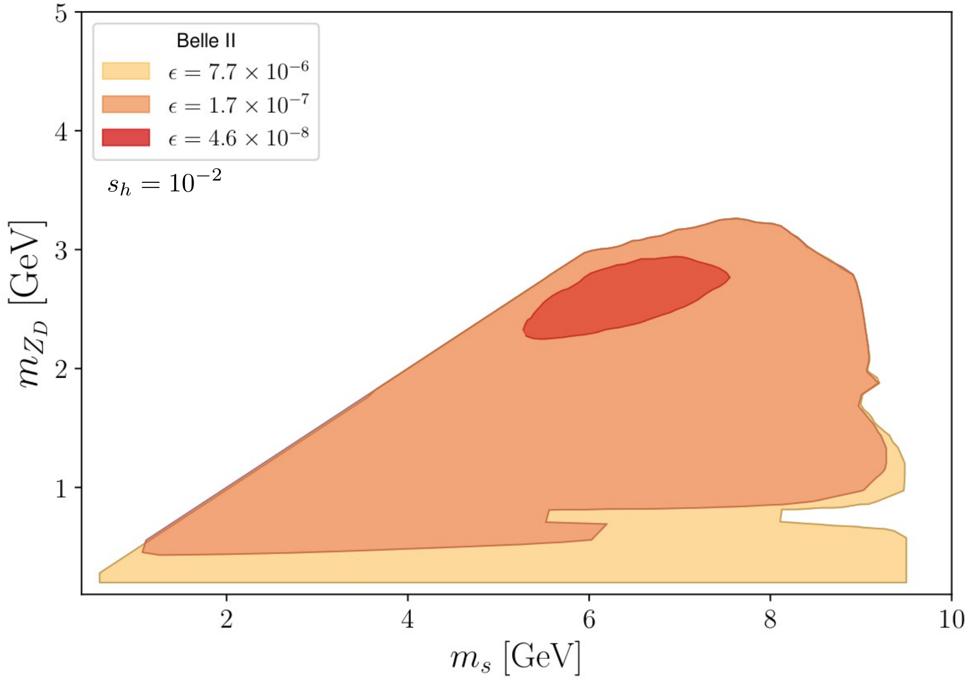
- Varying Kinetic-Mixing parameter

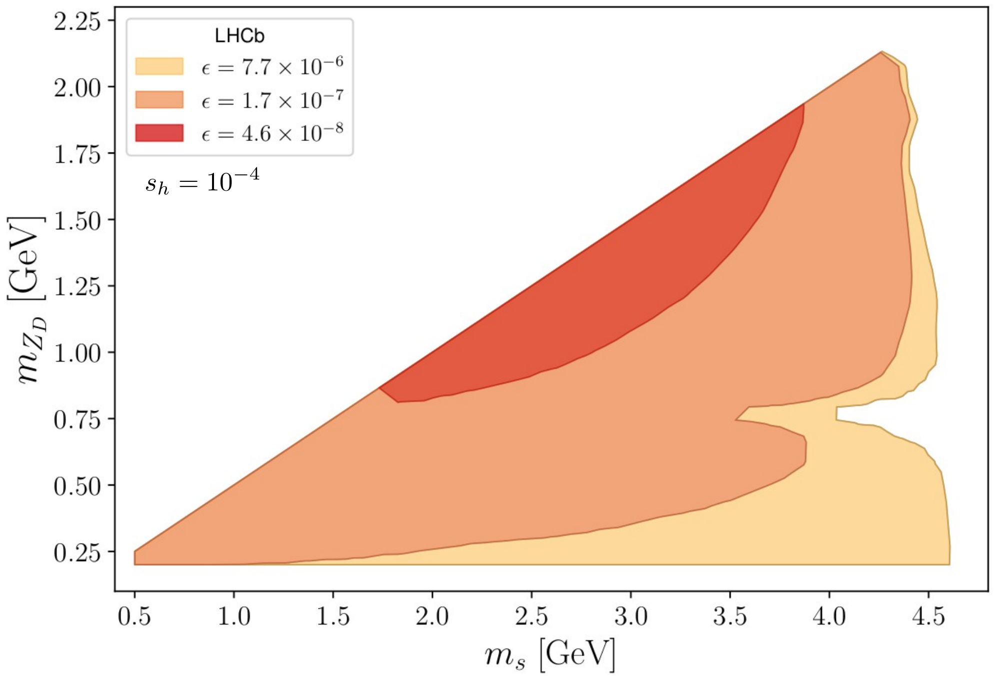




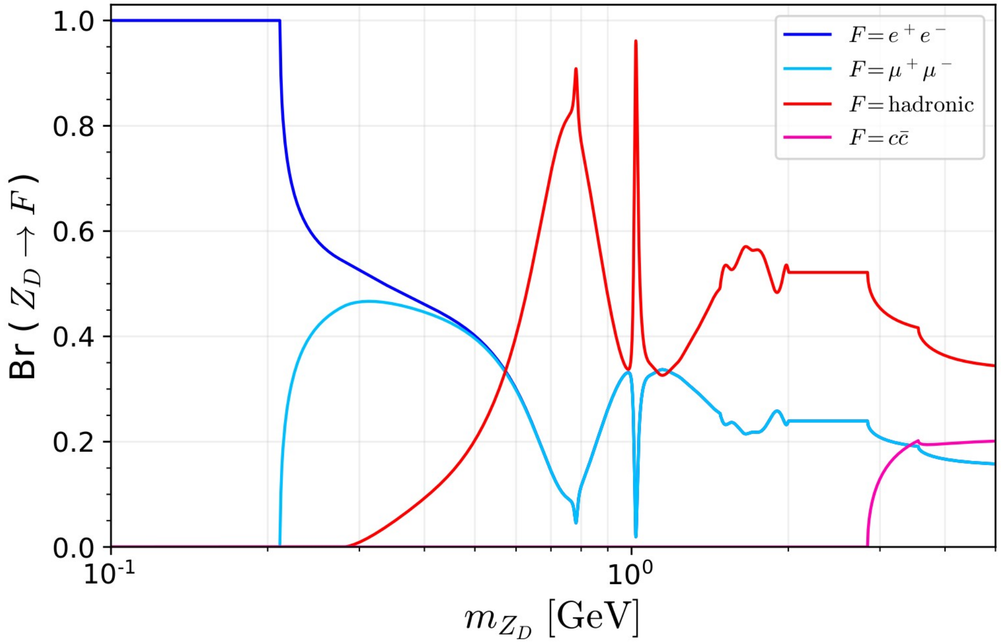
LHCb/Belle II – Mass plots

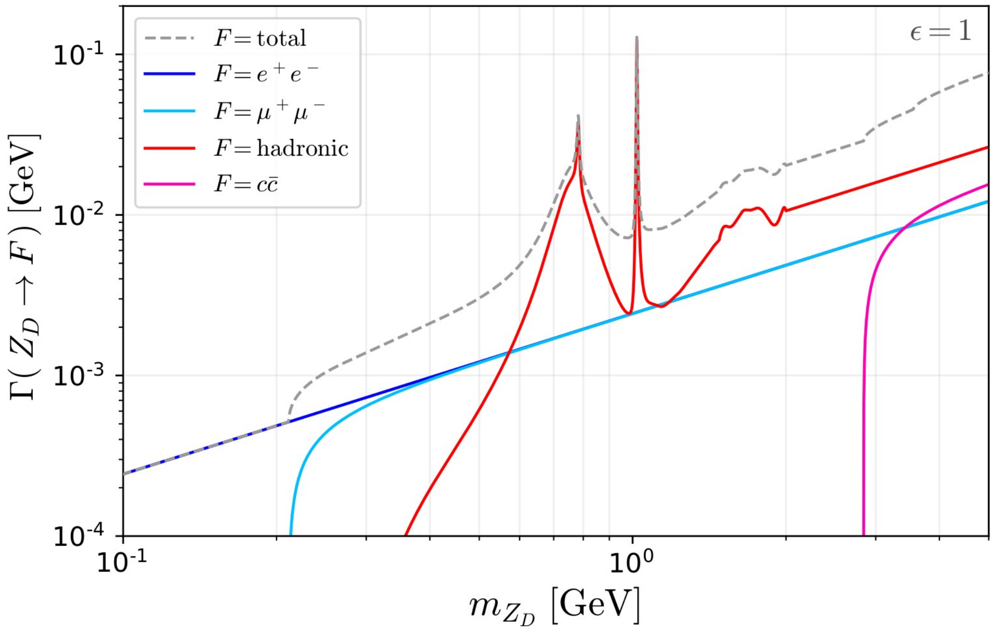
- Regions with $N_{\text{evts}} \geq 3$



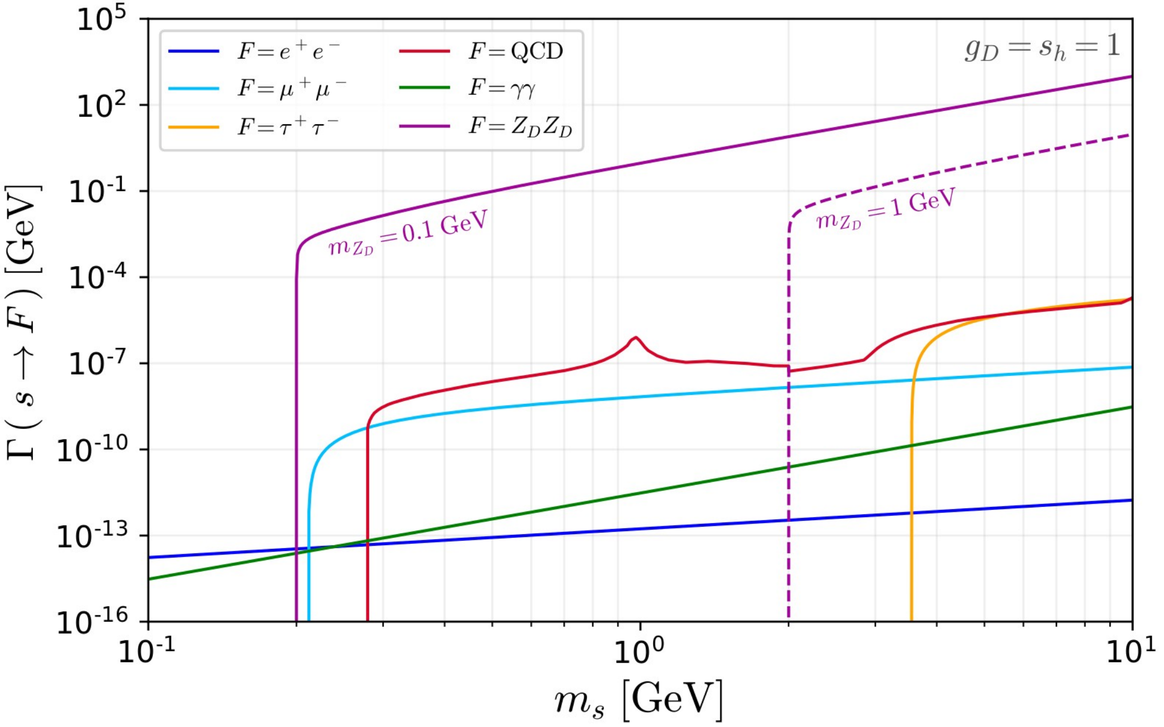


Dark photon widths





Dark Higgs widths



Width to dark photons can dominate the total width!

$$g_D \gg 7 \cdot 10^{-3} s_h$$

Branching ratios

- Upsilon

$$\mathrm{BR}(\Upsilon \to \gamma s) = \frac{s_h^2 G_F m_b^2}{\sqrt{2}\pi\alpha_{\mathrm{EM}}}\left(1 - \frac{m_s^2}{m_\Upsilon^2}\right)$$

Branching ratios

- B-mesons

$$\mathrm{BR}(B^\pm \to K s) = \frac{s_h^2}{\Gamma_B} \frac{\lambda^{1/2}(m_B^2, m_K^2, m_s^2)}{m_B^2} \frac{|\langle K|\bar{s}_L b_R|B^\pm\rangle|^2}{16\pi\, m_B}$$

- Matrix elements depend on the type of kaon considered (pseudo-scalar, scalar, pseudo-vector, vector or tensor)

Branching ratios

- Kaon

$$\mathrm{BR}(K_L \to \pi^0 s) = \frac{s_h^2}{\Gamma_{K_L}} \frac{\lambda^{1/2}(m_K^2, m_\pi^2, m_s^2)}{m_K^2} \frac{|\mathcal{M}_K|^2}{16\pi\, m_K}$$

$$\mathcal{M}_K = -\frac{m_K^2}{v}\left[\frac{7}{18}\gamma_1\left(1-\frac{m_s^2-m_\pi^2}{m_K^2}\right)-\frac{7}{9}\gamma_2+\frac{1}{2}\frac{3\sqrt{2}\,G_F}{16\pi^2}\sum_{i=u,c,t}V_{id}^*\,m_i^2\,V_{is}\right]$$