Dark matter at Belle II

Elias Bernreuther

Fermilab

Belle II Germany Meeting, LMU Munich

September 20, 2022

Light dark matter at accelerators

- **Ordinary matter in our universe is outnumbered by dark matter 5:1 (in mass).**
- All evidence so far relies only on gravity, including our primary measurement:

$$\Omega_\chi h^2 = 0.12$$ Planck, 1807.06209

- **But:** best explanations of relic density require **additional interactions with SM particles**

→ Basis of experimental DM search program

- Due to lack of WIMP observation, **light DM** ($m \lesssim 10\ \mathrm{GeV}$) has become increasingly attractive

→ **Belle II with leading sensitivity for many light dark sectors**

Dark sector mediators

- Focus here on **portal interactions** with DM mediator: $\mathcal{O}_{\mathrm{SM}} \times \mathcal{O}_{\mathrm{DS}}$

Lowest mass dimension

$$\begin{cases} -\frac{\kappa_Y}{2} F'_{\mu\nu} B^{\mu\nu} & \text{Vector portal} \\ (\lambda_3 \phi + \lambda_4 \phi^2) H^\dagger H & \text{Higgs portal} \\ \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu},\ \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi & \text{Axion portal} \\ y_N L H N & \text{Sterile neutrino portal} \end{cases}$$

- Further guidance for light DM in reach of Belle II:

  Residual annihilations $\chi\bar{\chi} \to f\bar{f}$ **have to be suppressed** at late times (low temperatures) to be compatible with cosmo bounds,

  in particular from **CMB** Slatyer, 1506.03811, Planck, 1807.06209

Scalar mediators

- **Scalar mediator + fermionic DM** avoids strong CMB constraints through velocity-suppressed (p-wave) annihilation $\langle \sigma v \rangle \sim v^2$

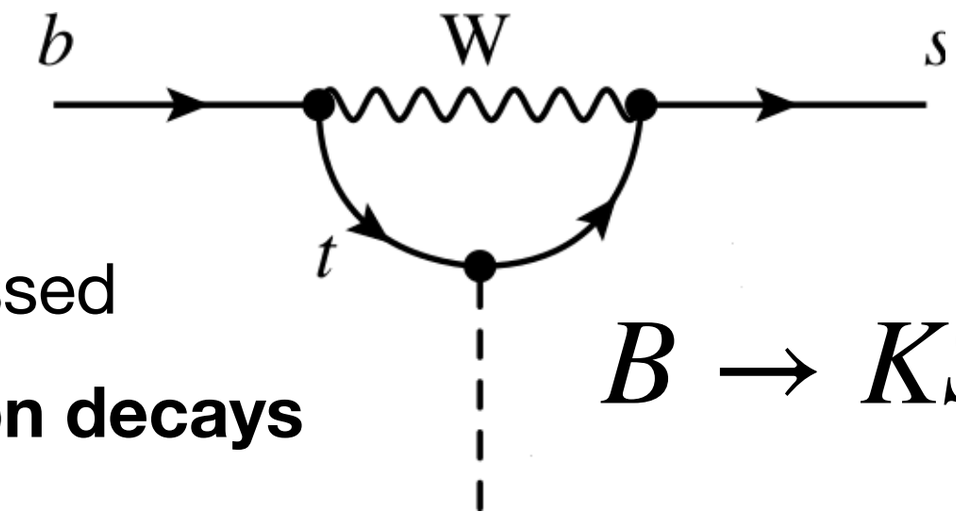
$$\mathscr{L} \supset -\frac{1}{2} m_\phi^2 \phi^2 - m_\chi \bar{\chi}\chi - \lambda_3 \phi H^\dagger H - y_\chi \bar{\chi}\chi\phi$$

- Mixing after EW symmetry breaking: h_{125} and new scalar S

→ $Sf\bar{f}$ **couplings** $\sim \frac{m_f}{v} \sin\theta$

→ Direct production from e^+e^- suppressed

Instead: **heavy quark loops in meson decays**



$B \to KS$

Filimonova et al., 1911.03490, Kachanovich et al., 2003.01788

Scalar mediators

Scalar decay

$\chi\bar{\chi}$

$f\bar{f}$

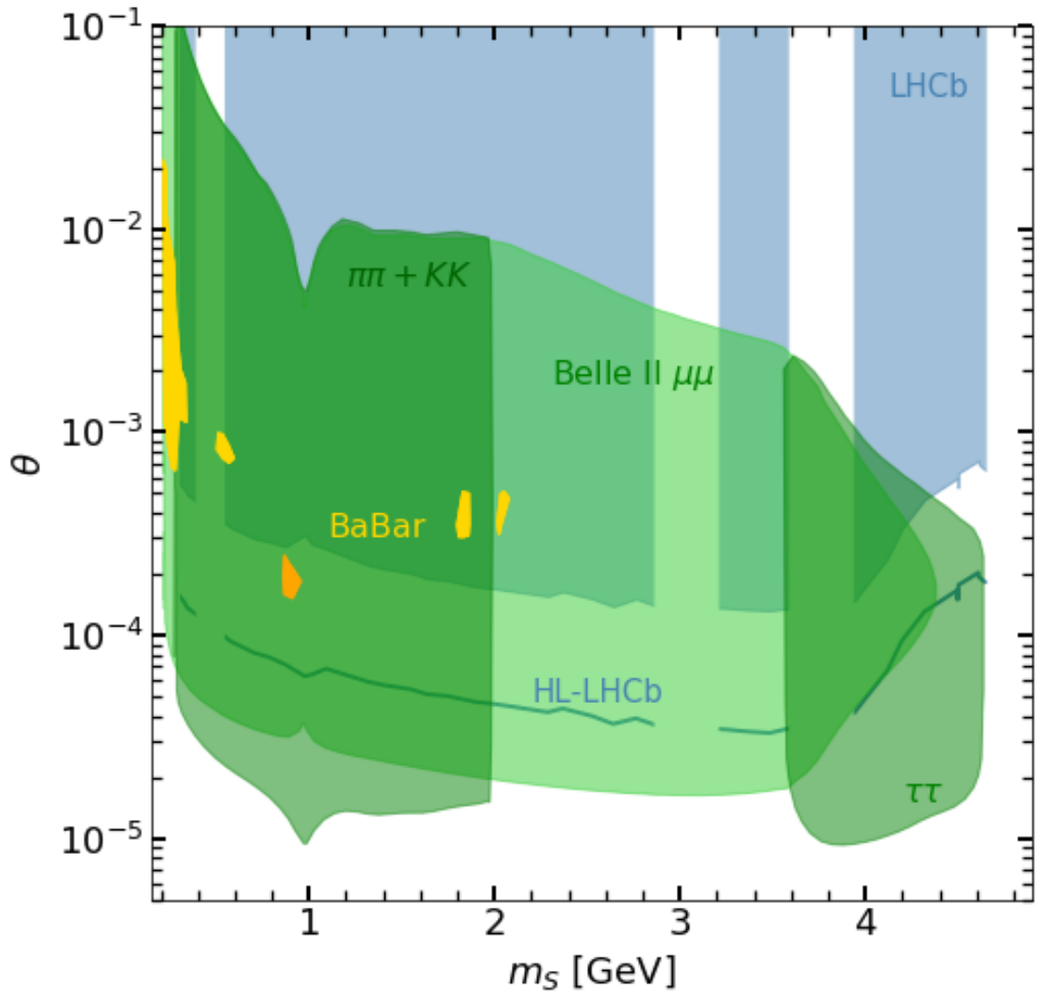
$B \to K +$ two charged tracks

Requires $m_S > 2m_\chi$:

Parameter space with right relic density **ruled out** by direct detection + BaBar

Krnjaic, 1512.04119

Filimonova et al., 1911.03490



Sascha's talk

Pseudoscalar ALPs

- **Pseudoscalar mediator** with fermionic DM avoids direct detection
- Special type of pseudoscalar: **Axion-like particle**
  defined by shift symmetry $a \to a + c$

$$\mathscr{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a}{2}a^2 + \frac{\partial^\mu a}{f_a}\sum_f \frac{c_f}{2}\bar{f}\gamma_\mu\gamma_5 f + \frac{c_\chi}{2}\frac{\partial^\mu a}{f_a}\bar{\chi}\gamma_\mu\gamma_5\chi$$

$$+ c_{GG}\frac{g_s^2}{(4\pi)^2}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{A,\mu\nu} + c_{BB}\frac{g'^2}{(4\pi)^2}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{WW}\frac{g^2}{(4\pi)^2}\frac{a}{f_a}W^A_{\mu\nu}\tilde{W}^{A,\mu\nu}$$

- **Intriguing possibility:** coupling to $W^A_{\mu\nu}\tilde{W}^{A,\mu\nu}$ dominates

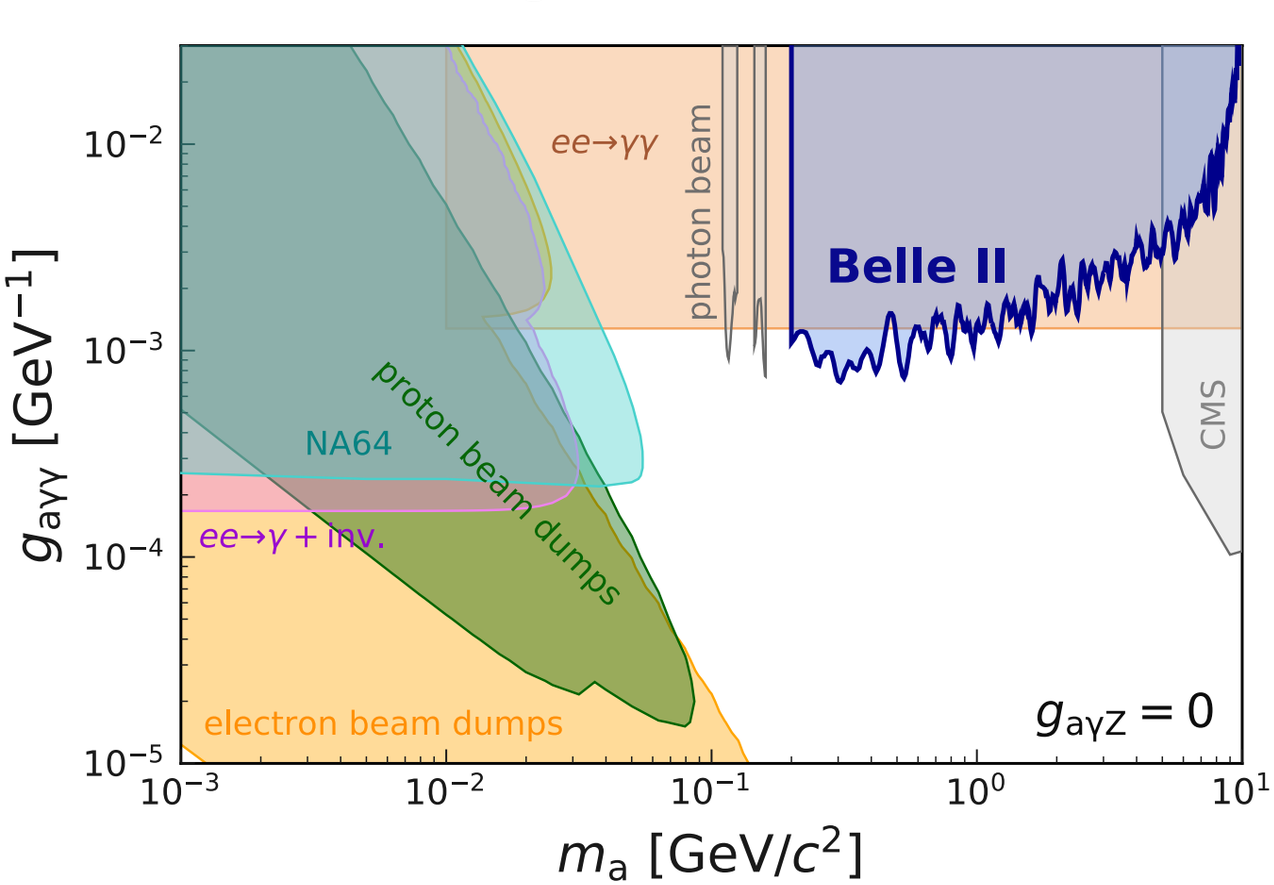
Pseudoscalar ALPs

If ALP coupling to $W^A_{\mu\nu}\tilde{W}^{A,\mu\nu}$ dominates:

Dominant decay mode for light ALP: $a \to \gamma\gamma$

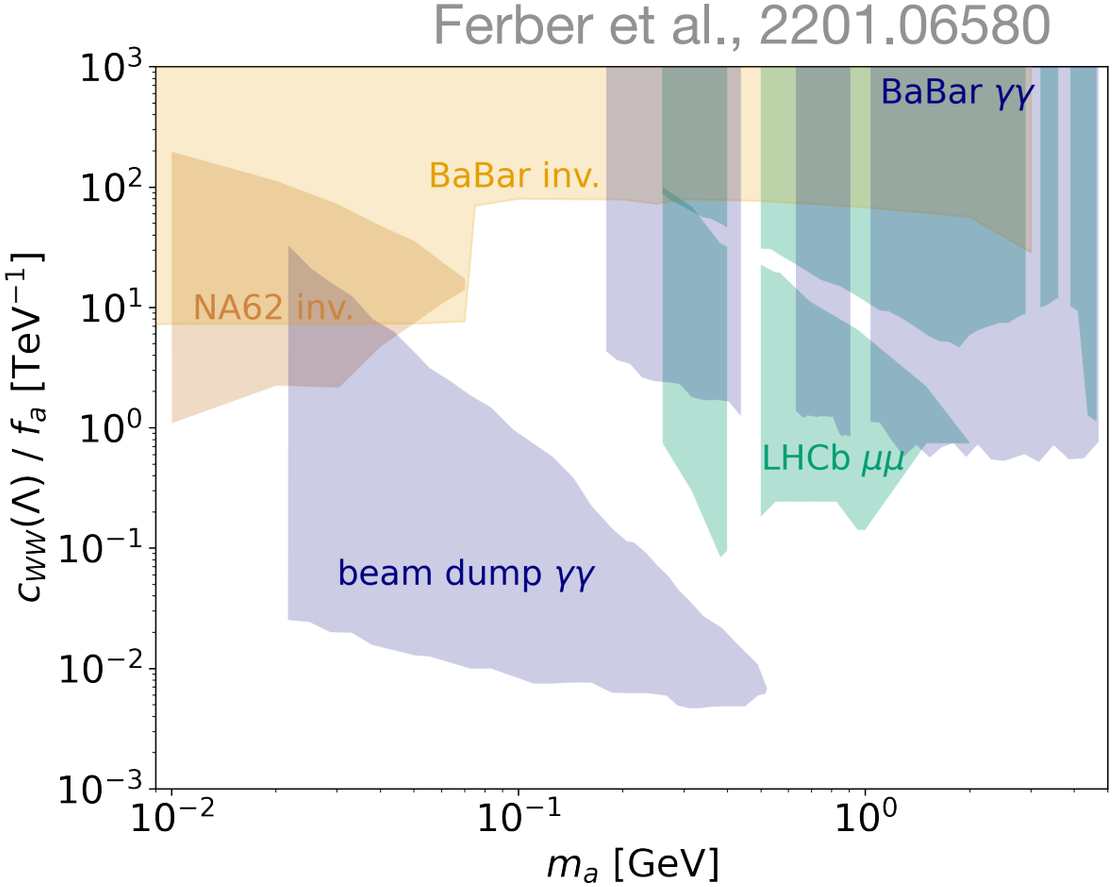
$e^+e^- \to \gamma a\,(a \to \gamma\gamma)$ ⟵ **Production** ⟶ $B \to Ka\,(a \to \gamma\gamma)$

Existing Belle II search:



Belle II, 2007.13071

Ferber et al., 2201.06580



Alexander's talk

Vector mediators

- Massive vector mediator from broken $U(1)'$

$$\mathscr{L} \supset g_\chi A'^{\mu} \bar{\chi} \gamma_\mu \chi + m_{A'}^2 A'_\mu A'^{\mu}$$

- Either direct charges for SM particles by gauging $L_\mu - L_\tau$, $B - L$ …
- Or kinetic mixing $-\epsilon/\cos\theta_W \; F'_{\mu\nu} B^{\mu\nu}$

→ $A' f \bar{f}$ **couplings** $\sim e \epsilon q_f$

- Single-photon search for $A' \to \chi\chi$ in association with ISR γ:

  High sensitivity to on-shell A' production; gap in coverage for $\bar{\chi}\chi$ production via off-shell A' ($m_{A'} \gtrsim 10$ GeV), but Belle II can also be sensitive

  Essig et al., 1309.5084, EB et al., 2203.08824

- Simple setup (A' + light fermionic DM) **in conflict with CMB**

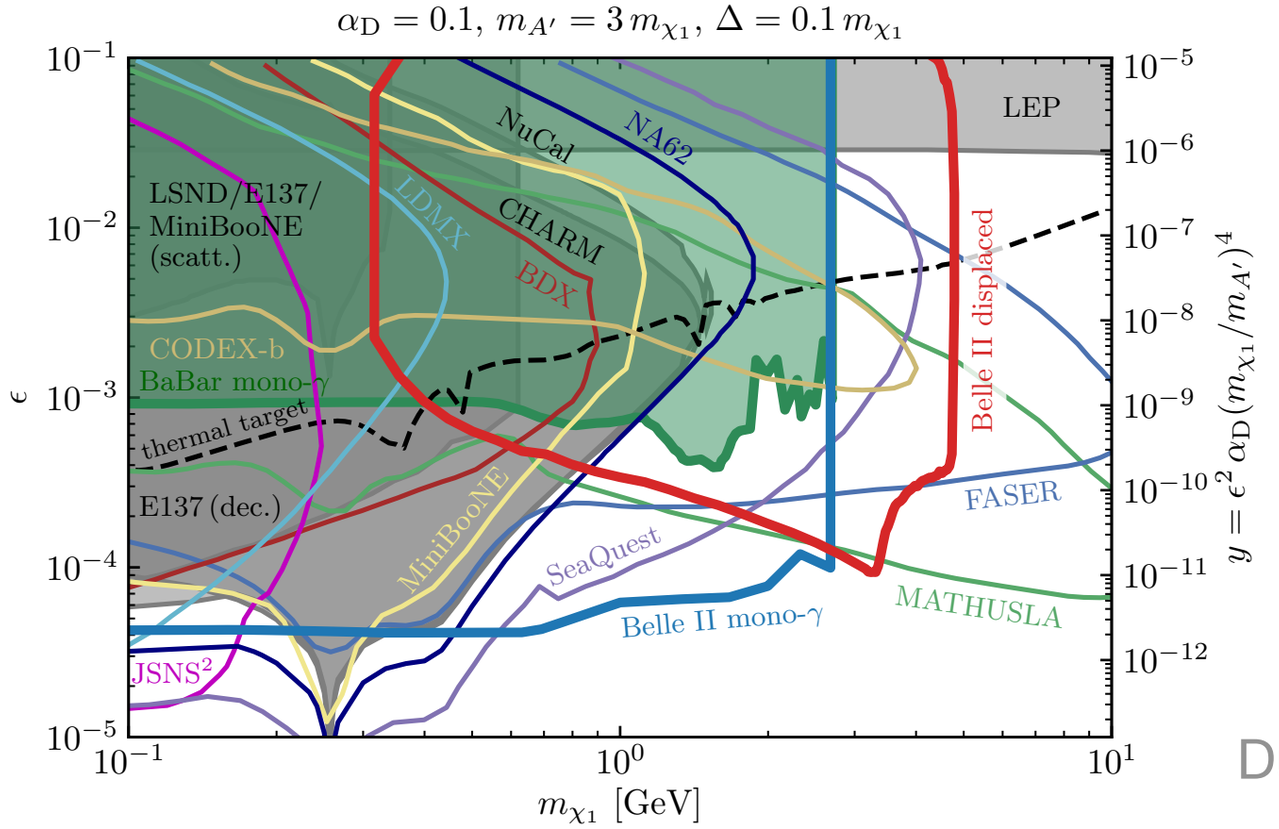
Vector mediator + inelastic DM

- **Inelastic DM avoids CMB** (and direct detection) **constraints:**

$$\chi_1\chi_2 \to A'^{(*)} \to f\bar{f}$$

annihilation strongly suppressed at late time due to low χ_2 abundance

- **Heavier state decays** via $\chi_2 \to \chi_1 A'^{*} \to \chi_1 f\bar{f}$, typically **long-lived**
- **New signature:** $e^+e^- \to \chi_1\chi_2$ followed by displaced decay of χ_2

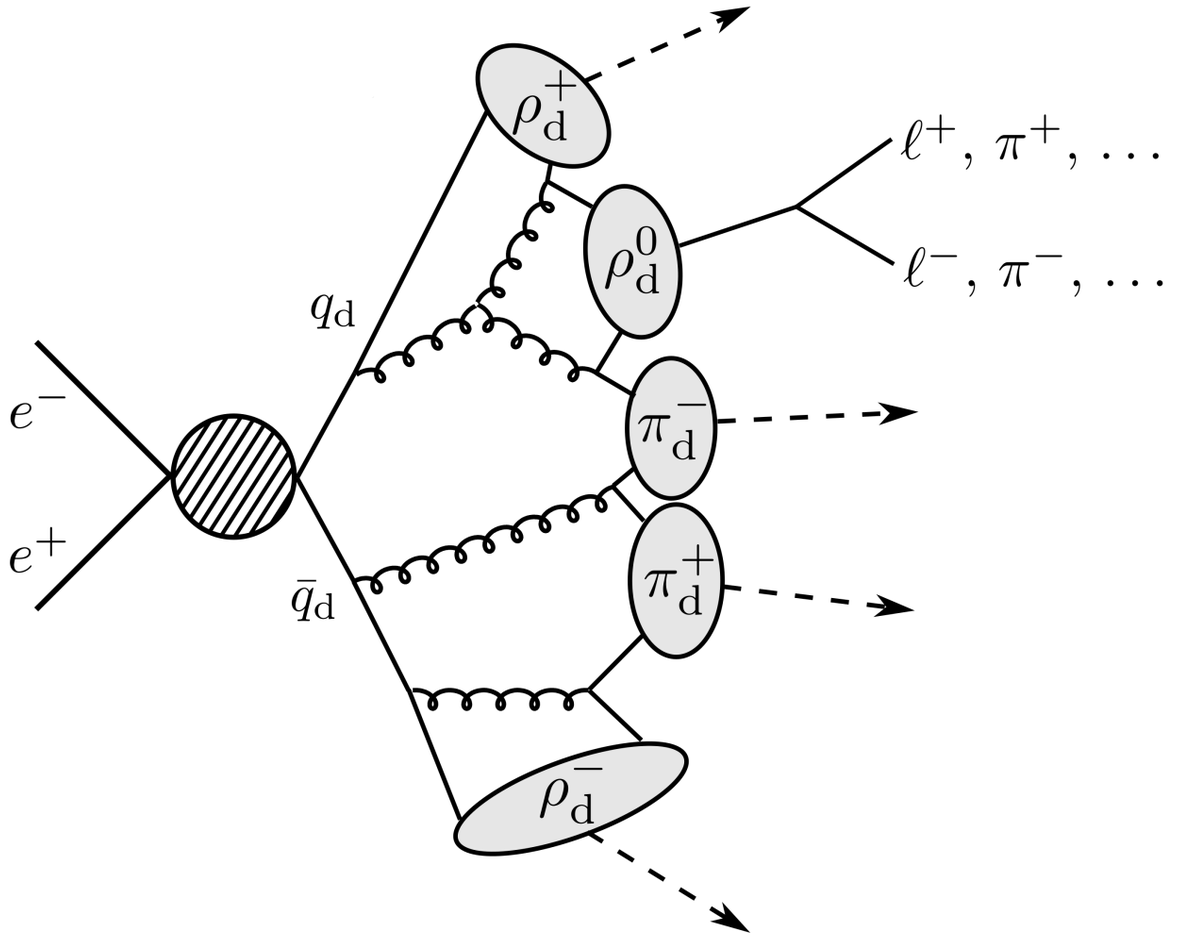


Patrick's talk

Duerr et al., 1911.03176

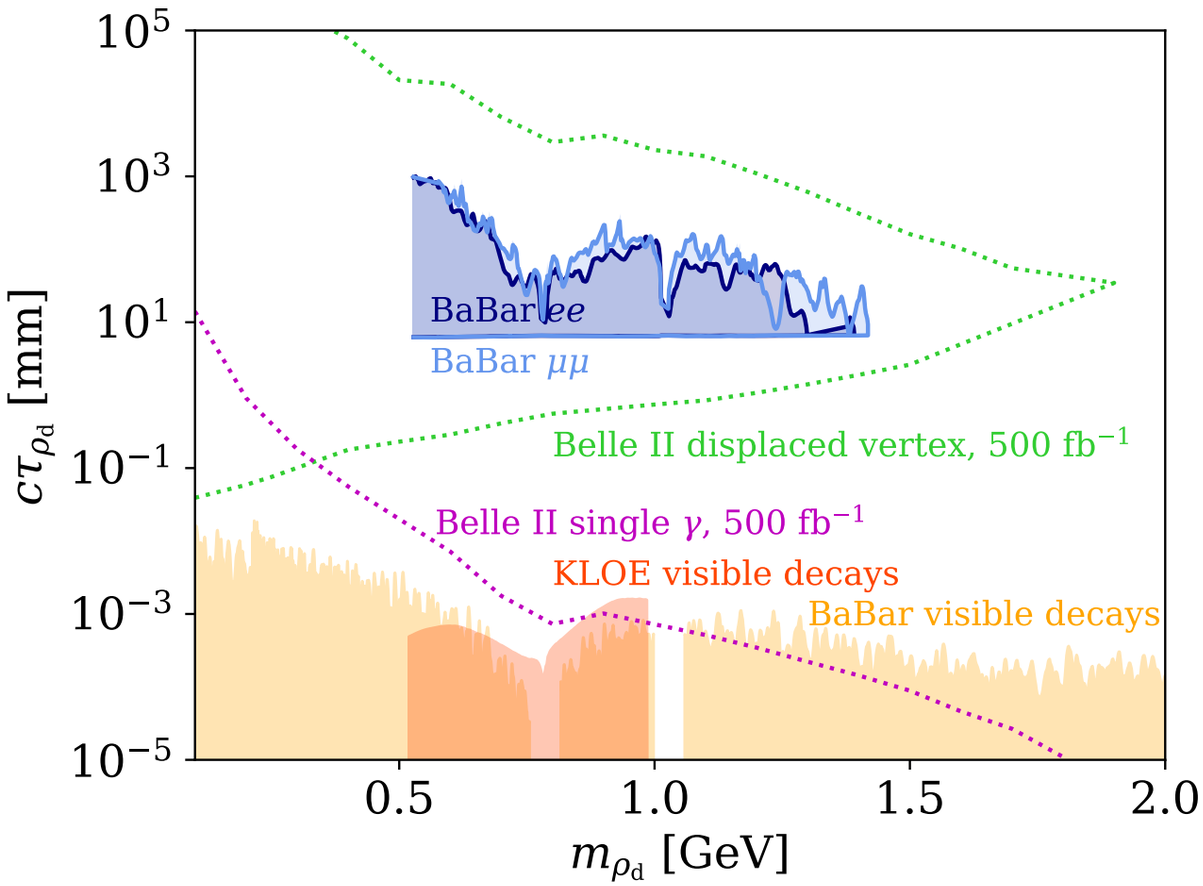
Dark showers

- Entire novel class of signatures featuring light LLPs:
- **Dark showers in strongly interacting dark sectors** resembling SM QCD sector



(multiple) displaced decays number varying from event to event

EB et al., 2203.08824



- Projections for Belle II LLP search improve greatly upon existing bounds from BaBar

Conclusions

- **Light dark sectors are well-motivated**
- **CMB constraints provide model building guidance**
- **Production at Belle II directly or through meson decay**
- **Decay of dark sector mediators in many cases visible and often displaced**
- **Belle II almost uniquely positioned among colliders to have leading sensitivity**

→ **Great examples in upcoming experimental talks**