Forecasting dark showers at Belle II

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# Dark sector searches at the intensity frontier

- **Light dark sectors at the sub-GeV scale** are becoming increasingly attractive due to lack of WIMP observation.

- Among the most sensitive accelerator probes at the **intensity frontier:**

  Belle II experiment at SuperKEKB e^+e^- collider with $\sqrt{s} = 10.58$ GeV

Standard DM search:

single photon recoiling against DM produced via mediator

see e.g. Belle II physics book, arXiv:1808.10567
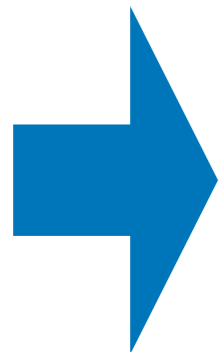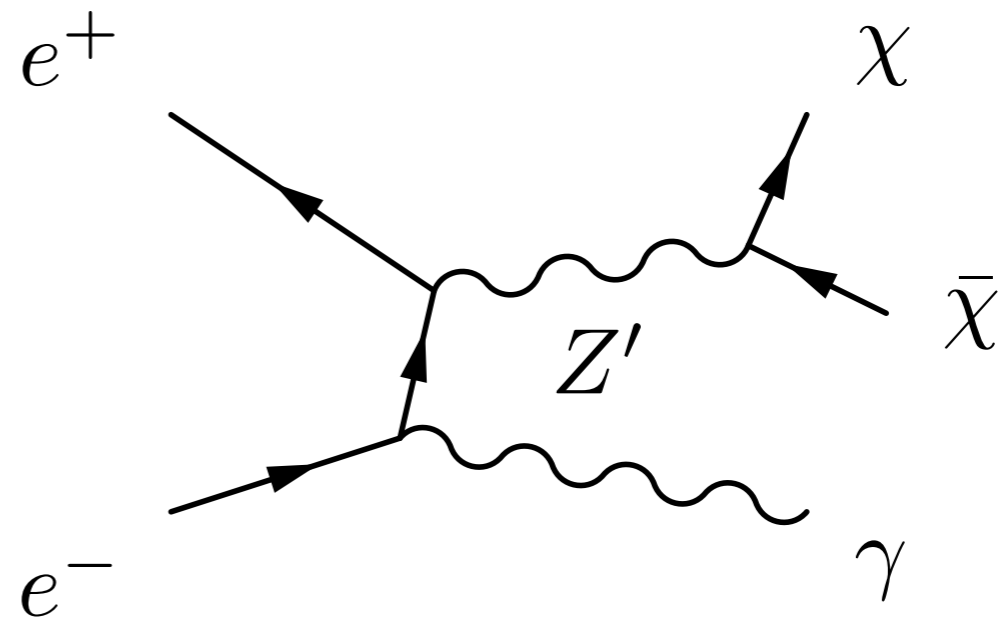
Highly constraining **if** the mediator can be produced directly ($m \lesssim 10$ GeV)

If not, less standard dark sector signatures can be more promising.

Particularly striking example: dark showers

- Dark showers occur in **strongly interacting dark sectors** resembling SM QCD sector:

$$\mathscr{L}_{\text{dark QCD}} \supset -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu,a} + \overline{q_{\text{d}}}i\slashed{D}q_{\text{d}} - \overline{q_{\text{d}}}M_q q_{\text{d}}$$

- **Below the dark confinement scale**:

  Dark pions π_{d} are excellent DM candidates. see e.g. Kribs & Neal arXiv:1604.04627 for review
 Dark vector mesons ρ_{d} are generically unstable and lead to visible signatures.

- Mediator with mass $\gg \sqrt{s}_{\text{Belle II}}$ can be described by an **effective interaction** between dark quarks and SM fermions:

$$\mathscr{L}_{\text{eff}} \supset \frac{1}{\Lambda^2}\sum_f q_f \bar{f}\gamma^\mu f \bar{q}_{\text{d}}\gamma_\mu q_{\text{d}}$$

  $\Lambda :$ **scale of the effective interaction**

- If dark confinement scale $\ll \sqrt{s}$, production of dark quarks via effective interaction leads to **dark shower** and production of dark mesons
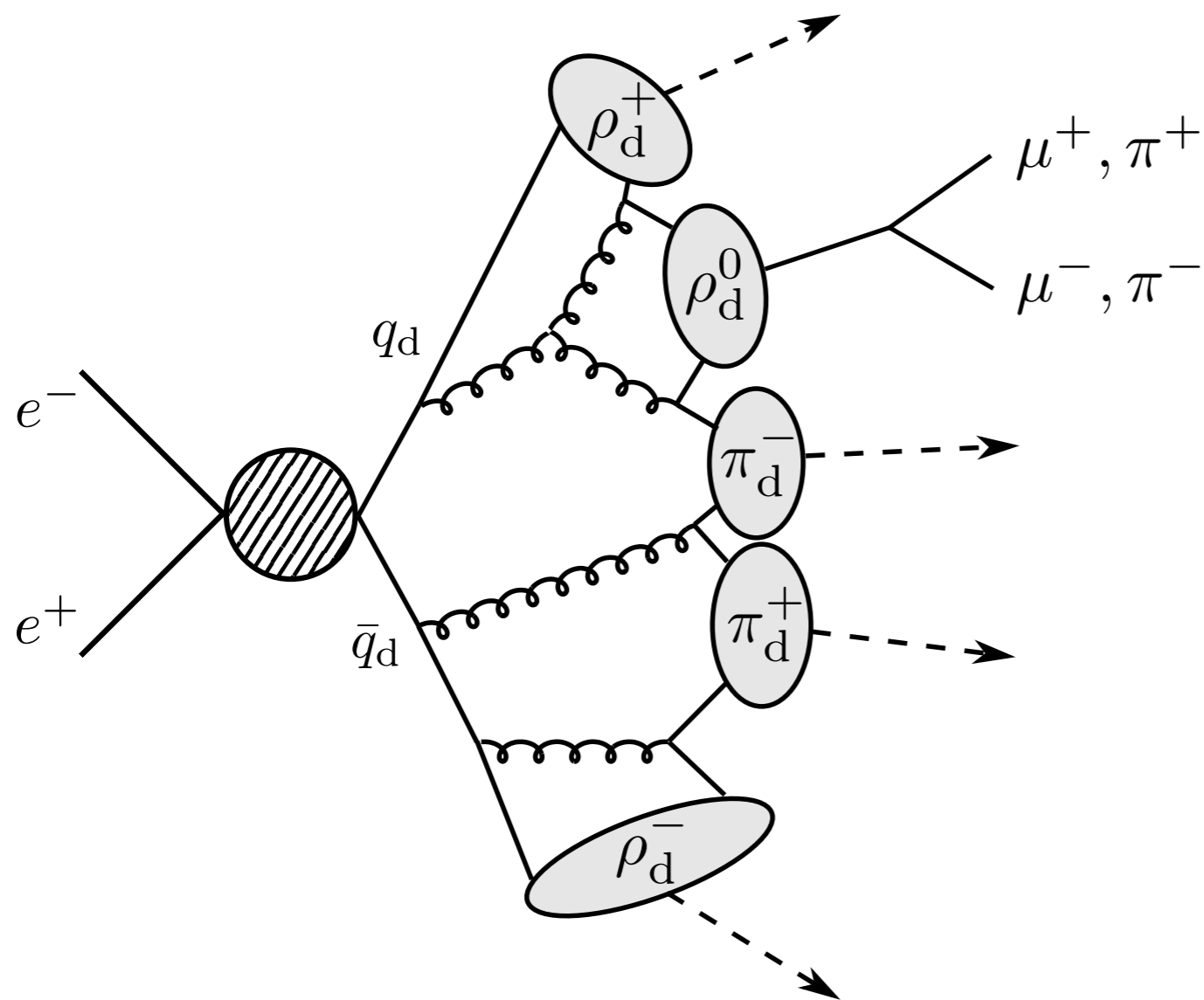
- Rate of dark shower production through effective operator scales as

$$\sigma(e^+ e^- \to q_d \bar{q}_d) \propto \frac{s}{\Lambda^4}$$

- The ρ_d^0 mesons decay to visible SM particles with decay length

$$c\tau_{\rho_d^0} \propto \frac{\Lambda^4}{m_{\rho_d}^5}$$

Parameter space of low-energy effective theory only consists of Λ and m_{ρ_d}.

- **Signature of light dark showers:**

  (multiple) displaced decays number varying from event to event
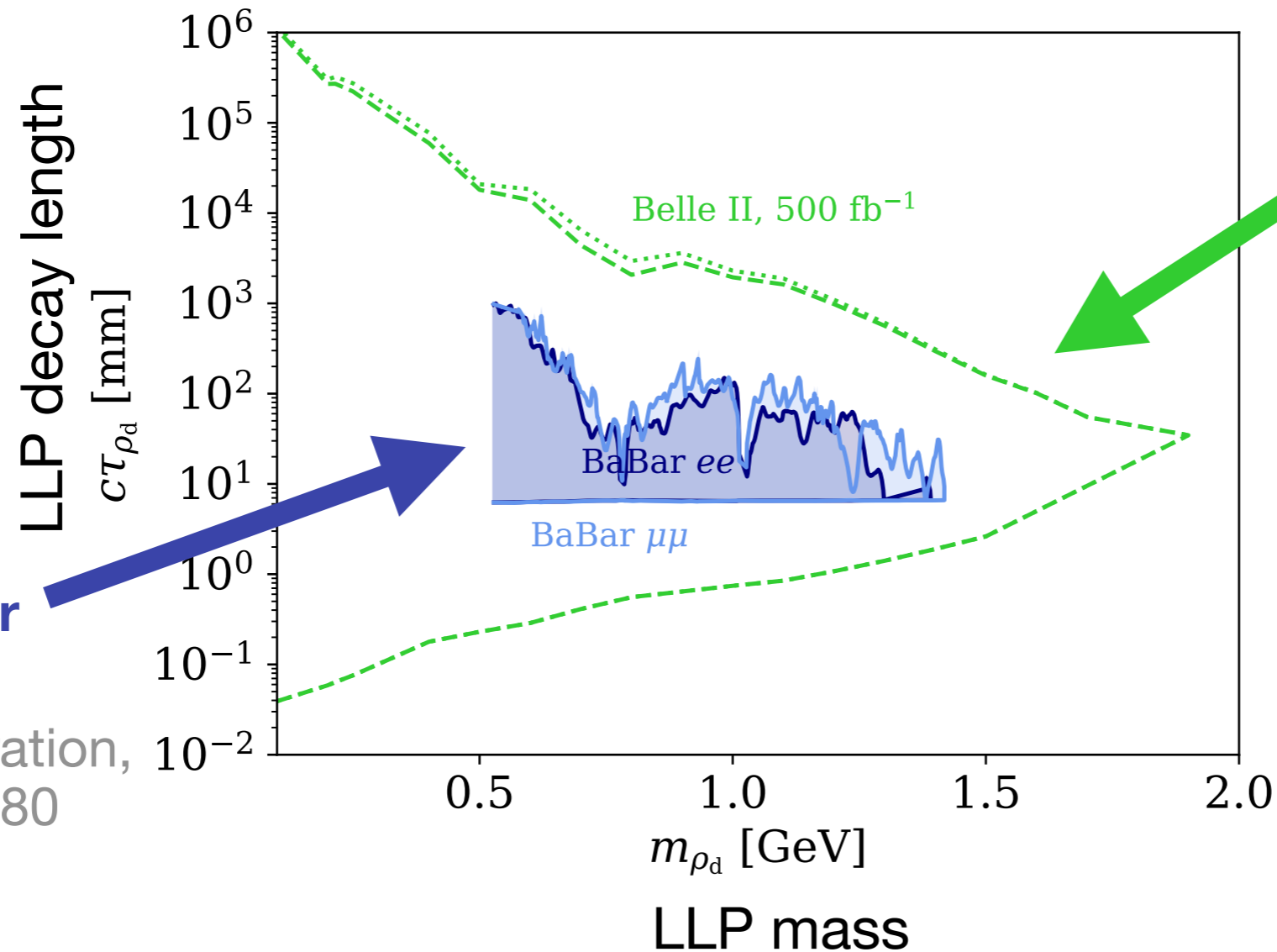
Displaced vertex search at Belle II

- No dedicated search for dark showers at B factories yet, but **model-independent searches for LLPs**

- **Signature:** displaced decays to pairs of oppositely charged tracks (leptons, pions, kaons)

- **Prospective search for displaced vertices at Belle II**
  Duerr et al., arXiv:1911.03176 and arXiv:2012.08595, and EB et al. arXiv:2203.08824

  displaced decays at transverse distance $0.2 \ \mathrm{cm} < R < 60 \ \mathrm{cm}$
  negligible background expected even with only loose selection cuts

| electron pairs	muon pairs
$p(e^+),\, p(e^-) > 0.1 \ \mathrm{GeV}$	$p(\mu^+),\, p(\mu^-) > 0.05 \ \mathrm{GeV}$
$m_{e^+e^-} > 0.03 \ \mathrm{GeV}$	$m_{\mu^+\mu^-} < 0.48 \ \mathrm{GeV} \ or \ m_{\mu^+\mu^-} > 0.52 \ \mathrm{GeV}$
$\alpha(e^+, e^-) > 0.025 \ \mathrm{rad}$	
Displaced vertex position	
$0.2 \ \mathrm{cm} < R < 0.9 \ \mathrm{cm} \ or \ 17 \ \mathrm{cm} < R < 60 \ \mathrm{cm}$	$0.2 \ \mathrm{cm} < R < 60 \ \mathrm{cm}$
$-55 \ \mathrm{cm} \leq z \leq 140 \ \mathrm{cm}$	
$17° \leq \theta_{\mathrm{lab}} \leq 150°$	

Limits on low-energy effective theory from searches for displaced vertices:

Projected limit on dark showers from DV search at Belle II
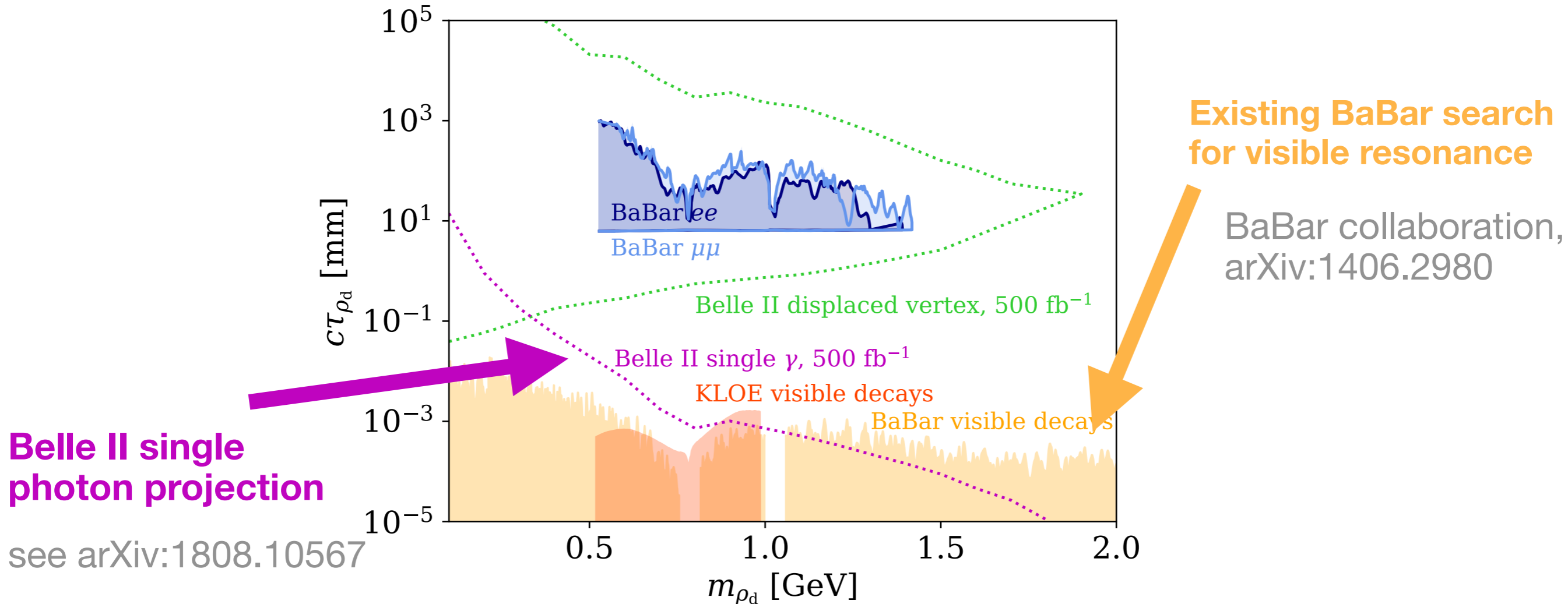
Existing BaBar LLP search

BaBar collaboration, arXiv:1502.02580
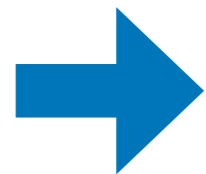
Displaced vertex search at Belle II can greatly improve over BaBar in cosmologically viable parameter space with just 500 fb^{-1} of data.

Additional constraints on the low-energy effective theory:

Existing BaBar search for visible resonance

BaBar collaboration, arXiv:1406.2980

**Belle II single photon projection**

see arXiv:1808.10567

- Existing searches for **visible resonances** at BaBar and KLOE yield complementary constraints on **promptly decaying dark mesons**.

- Events with **invisible dark shower and ISR photon** lead to **single photon signal** with continuous energy spectrum.
 - Projection weaker than for bump hunt but competitive at small LLP mass

Probing the underlying interaction

- At high energies the mediator underlying the effective operator can be produced directly.

- **LHCb search for displaced dimuon resonances** complements Belle II for
  $10 \text{ GeV} < m_{Z'} \lesssim m_Z$ LHCb collaboration, arXiv:2007.03923

- LHCb sensitivity depends on combination of mediator couplings underlying Λ

Belle II favorable scenario
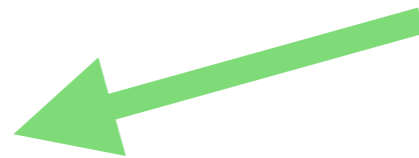
LHCb favorable scenario
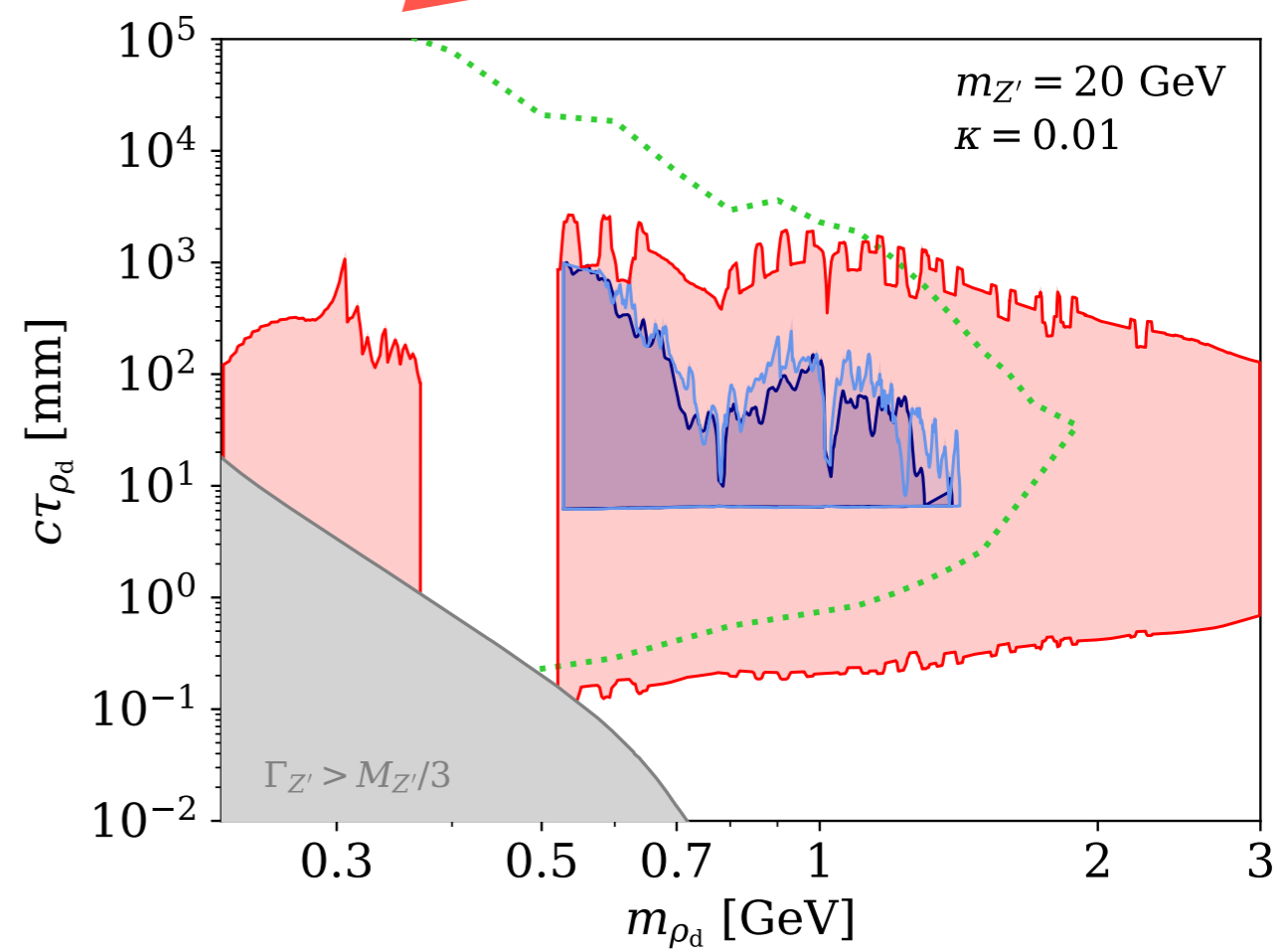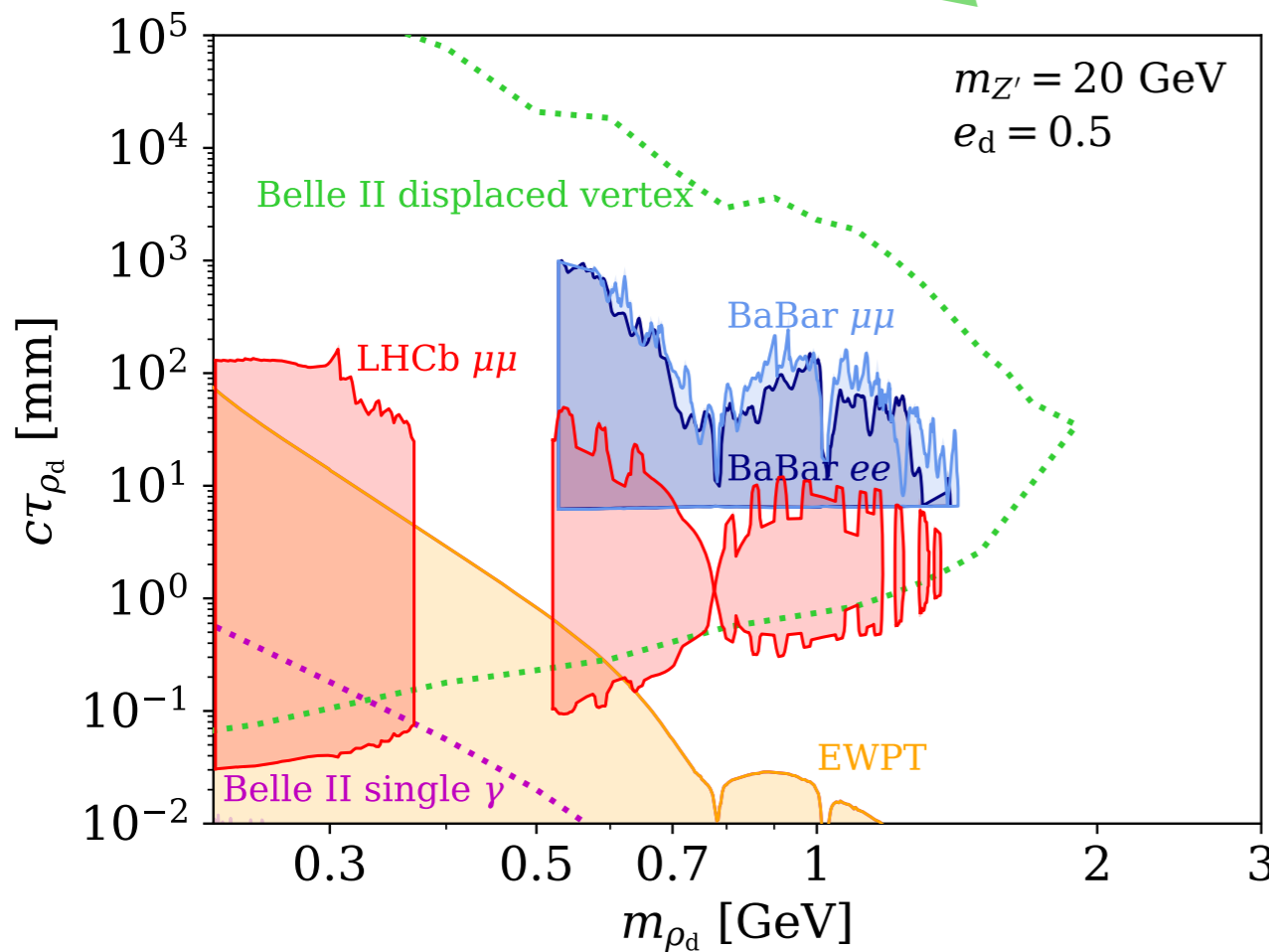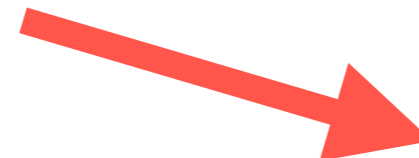
- LHCb most sensitive to $c\tau \approx 1 - 10$ mm, Belle II to $c\tau \approx 10 - 100$ mm

- Strong case for Belle II search even in least favorable scenario

Conclusions

- **Light strongly interacting dark sectors are well-motivated and can give rise to novel dark shower signals at Belle II.**

- **Especially interesting: dark shower production via effective interaction**

- **Displaced vertex search at Belle II improves greatly on BaBar**

- **Additional constraints in prompt regime, in particular single photon search without resonance**

- **High complementarity between intensity frontier experiments and LHC, in particular LHCb**