

Forecasting dark showers at Belle II

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based on [arXiv:2203.08824](https://arxiv.org/abs/2203.08824)

in collaboration with Kai Böse, Torben Ferber, Christopher Hearty, Felix Kahlhoefer, Alessandro Morandini and Kai Schmidt-Hoberg

Dark sector searches at the intensity frontier

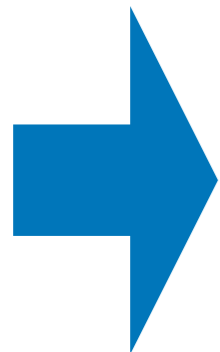
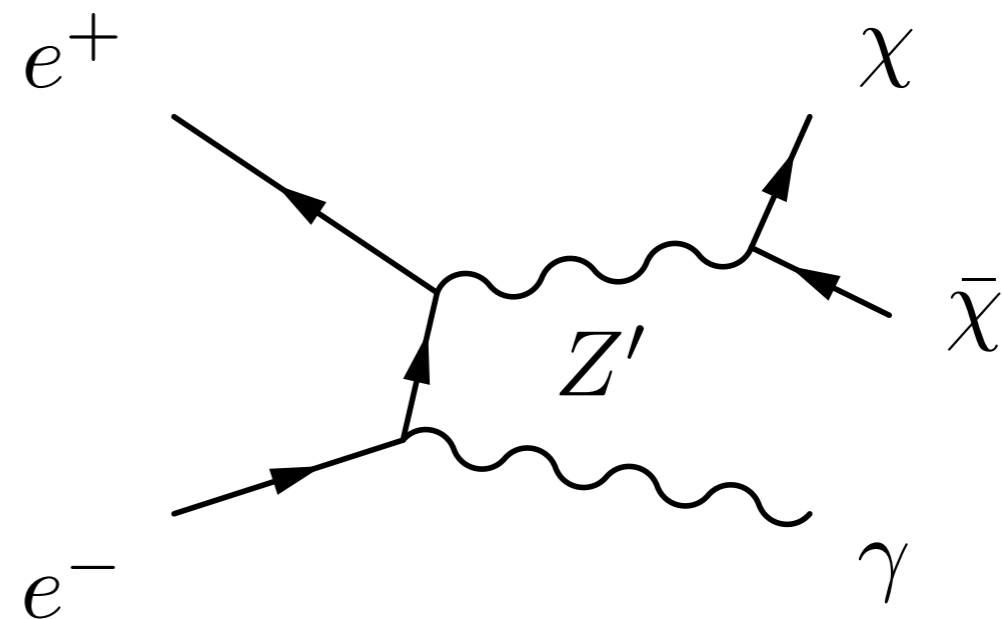
- **Light dark sectors at the sub-GeV scale** are becoming increasingly attractive due to lack of WIMP observation.
- Among the most sensitive accelerator probes at the **intensity frontier**:

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

Strongly interacting dark sector with effective portal

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

$$\mathcal{L}_{\text{dark QCD}} \supset -\frac{1}{4}F_{\mu\nu}^a F^{\mu\nu,a} + \bar{q}_d i \not{D} q_d - \bar{q}_d M_q q_d$$

- **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.

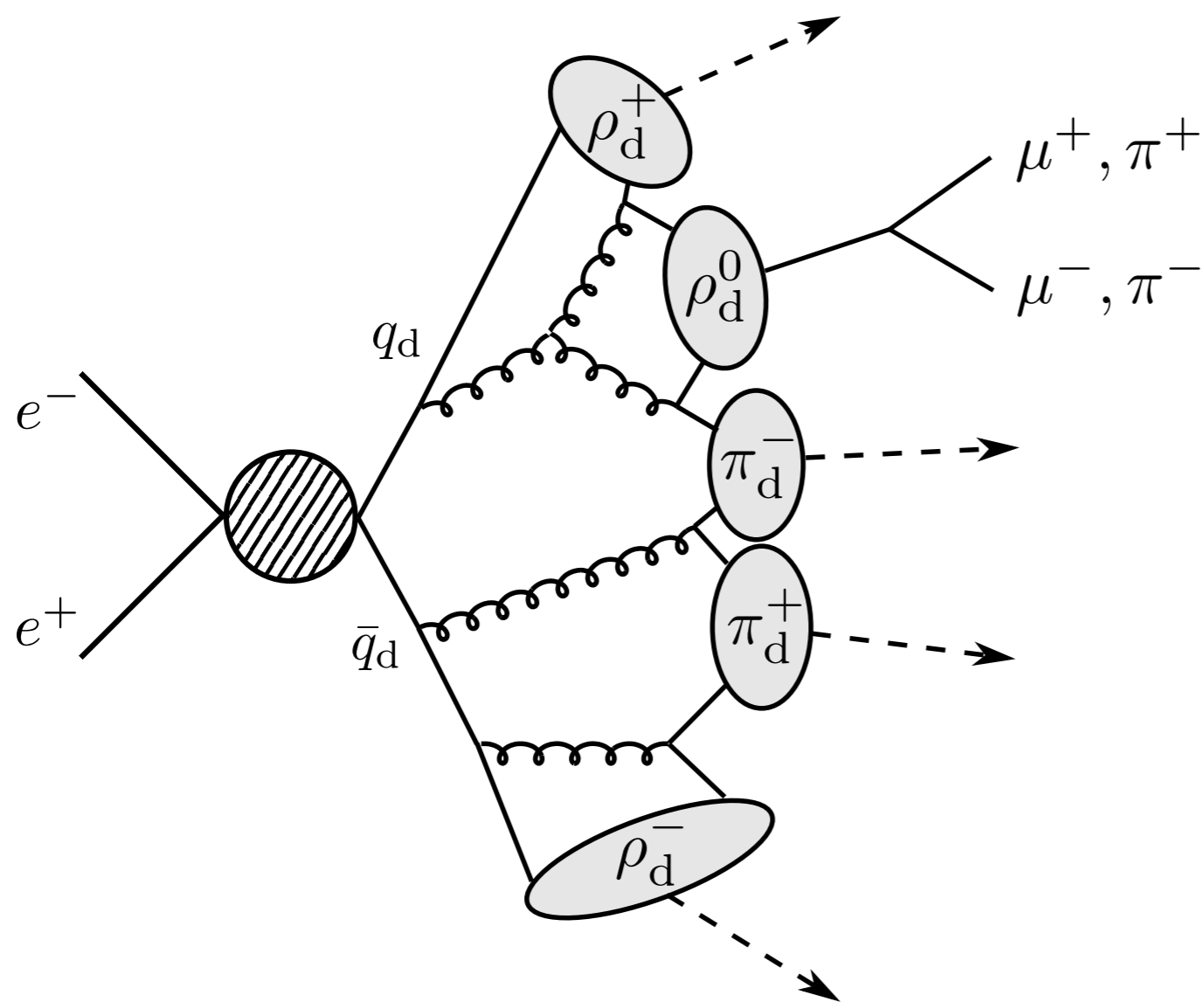
- Mediator with mass $\gg \sqrt{s}_{\text{Belle II}}$ can be described by an **effective interaction** between dark quarks and SM fermions:

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{\Lambda^2} \sum_f q_f \bar{f} \gamma^\mu f \bar{q}_d \gamma_\mu q_d$$

Λ : **scale of the effective interaction**

Dark showers at Belle II

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



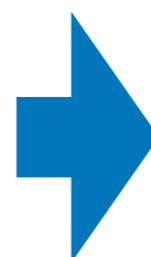
- Rate of dark shower production through effective operator scales as

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

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

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

- Signature of light dark showers:**
(multiple) displaced decays
number varying from event to event



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

Displaced vertex search at Belle II

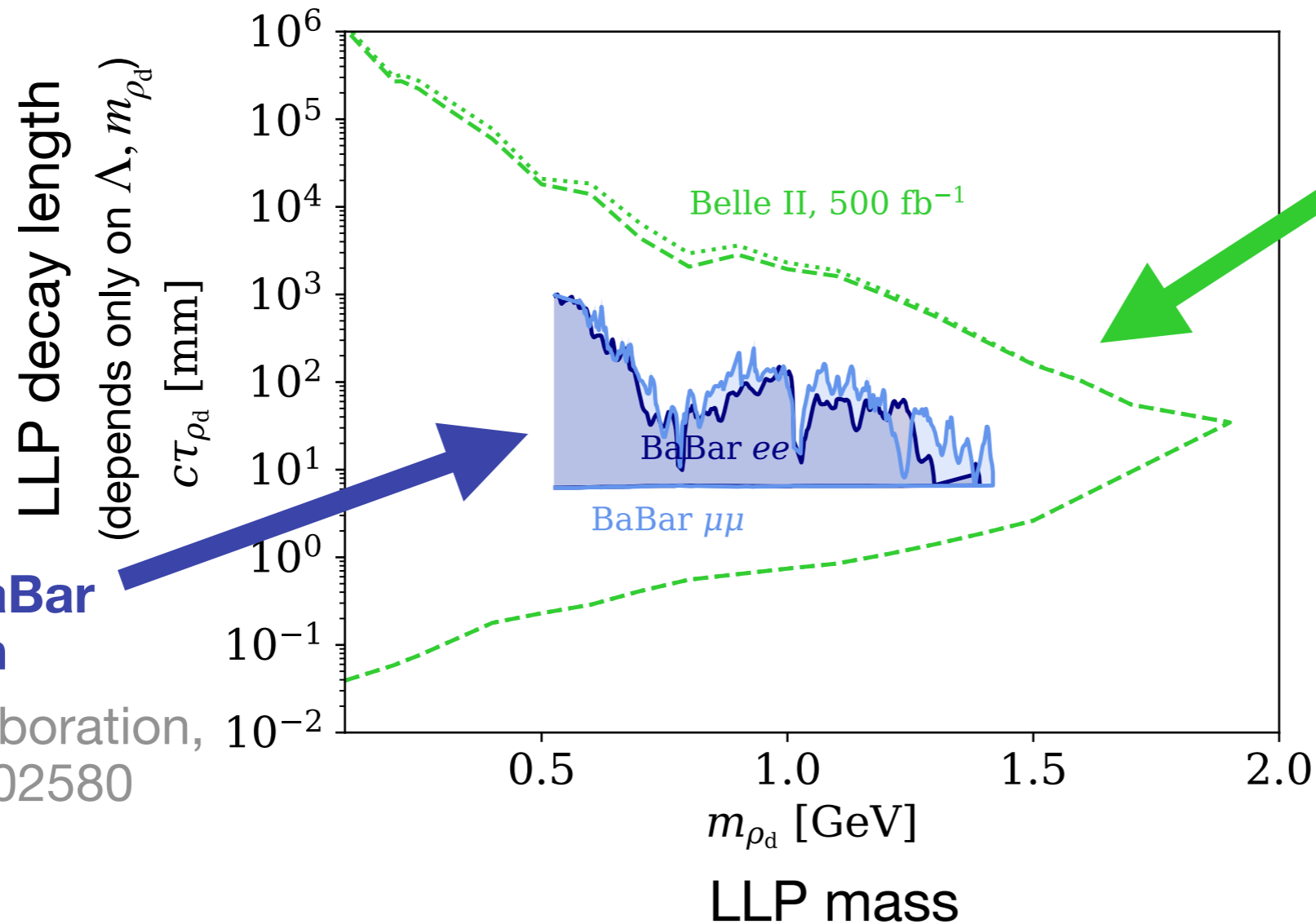
- No dedicated search for dark showers at B factories yet, but **model-independent searches for LLPs**
- **Signature:** displaced decays to pairs of oppositely charged tracks (leptons, pions, kaons)
- **Prospective search for displaced vertices at Belle II**
Duerr et al., arXiv:1911.03176 and arXiv:2012.08595, and EB et al. arXiv:2203.08824

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

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

Belle II LLP sensitivity for dark showers

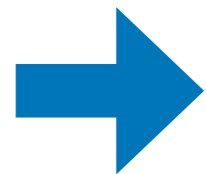
Limits on low-energy effective theory from searches for displaced vertices:



Projected limit on dark showers from DV search at Belle II

Existing BaBar LLP search

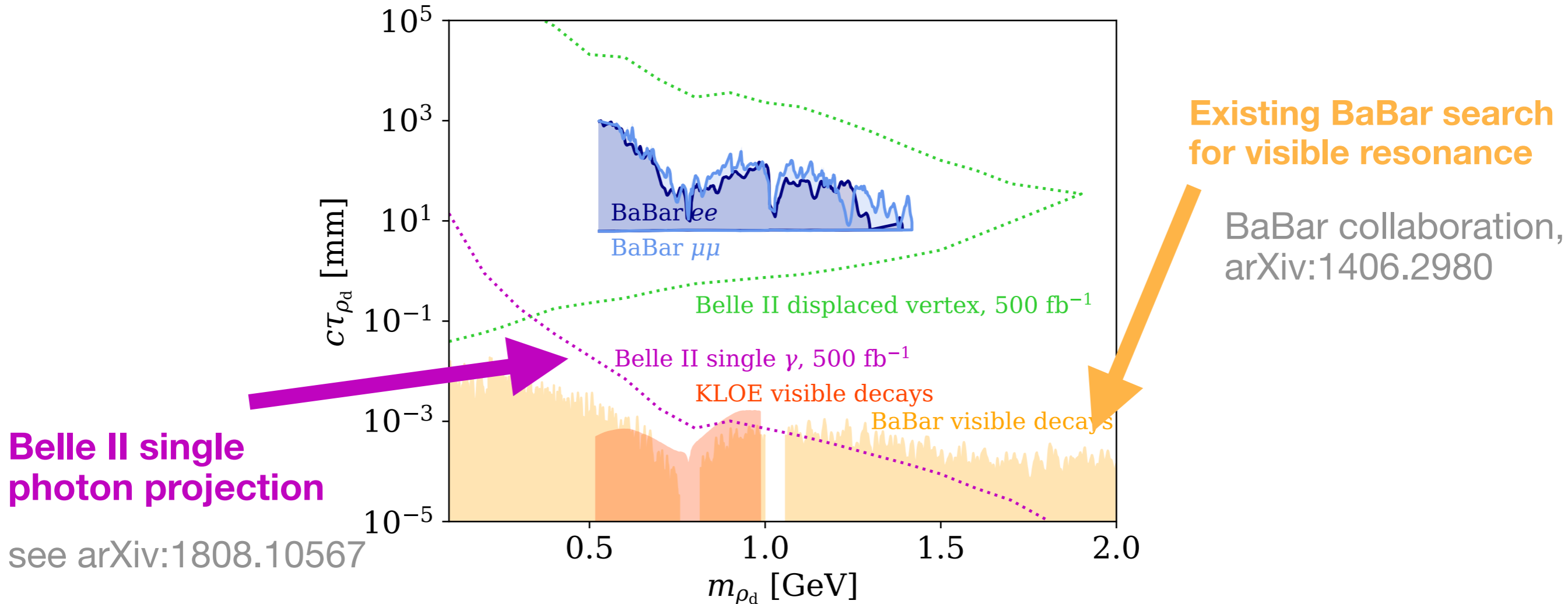
BaBar collaboration,
arXiv:1502.02580



Displaced vertex search at Belle II can greatly improve over BaBar in cosmologically viable parameter space even with just 500 fb⁻¹ of data.

Complementary constraints

Additional constraints on the low-energy effective theory:

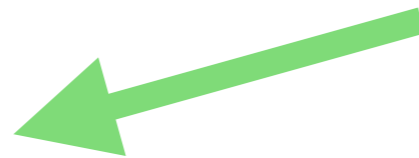


- Existing searches for **visible resonances** at BaBar and KLOE yield complementary constraints on **promptly decaying dark mesons**.
- Events with **invisible dark shower and ISR photon** lead to **single photon signal** with continuous energy spectrum.
 - ➔ Projection weaker than for bump hunt but competitive at small LLP mass

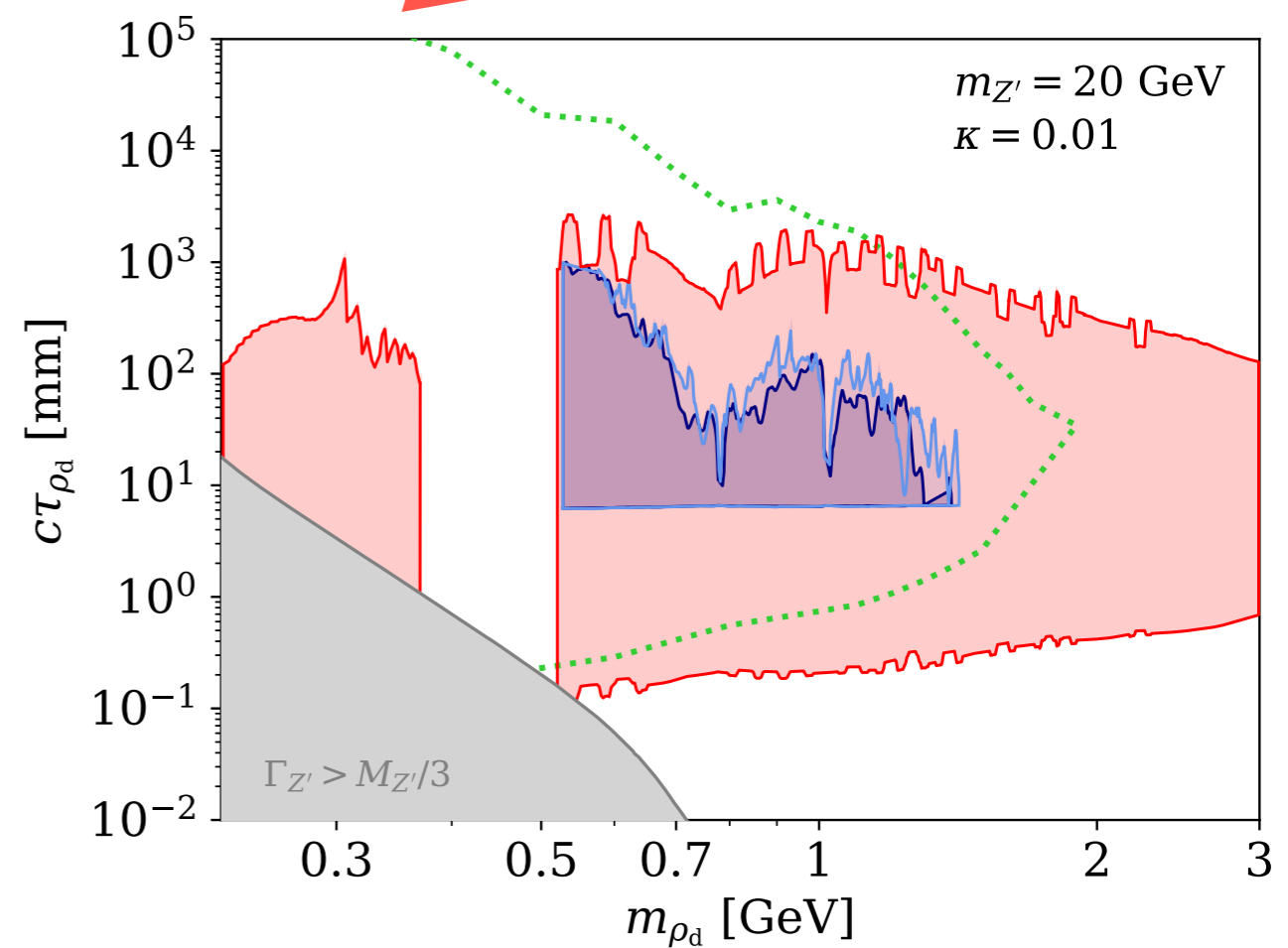
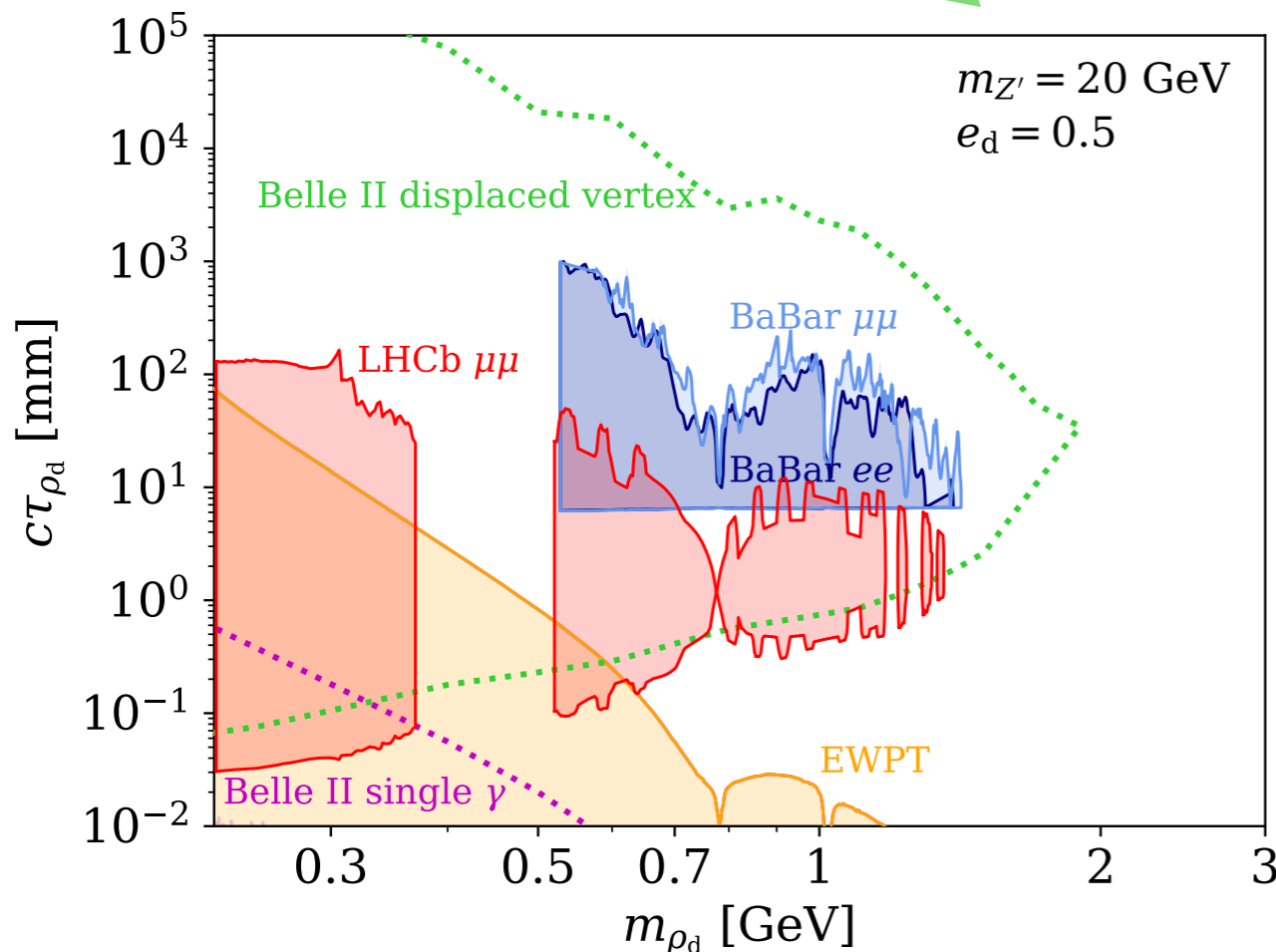
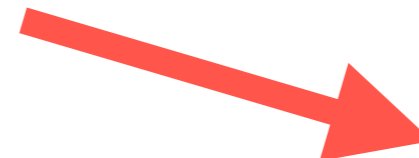
Probing the underlying interaction

- 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 $c\tau \approx 1 - 10 \text{ mm}$, Belle II to $c\tau \approx 10 - 100 \text{ mm}$
- 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**