Dark showers at Belle II

Elias Bernreuther

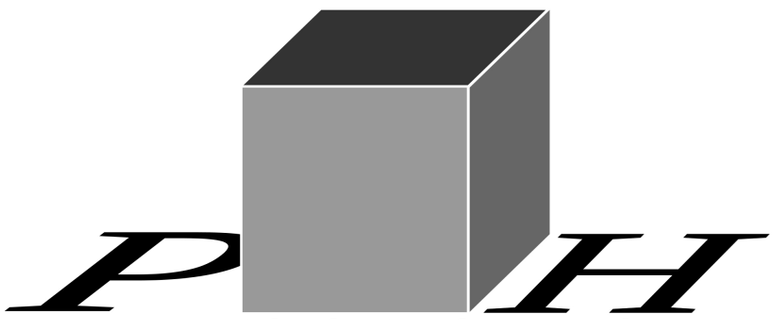
RWTH Aachen University

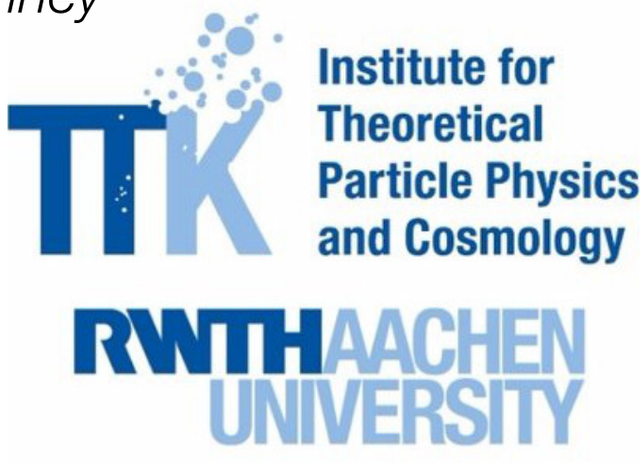
including material from

arXiv:1907.04346 and arXiv:2011.06604

with Felix Kahlhoefer, Michael Krämer and Patrick Tunney

and work in progress
(preliminary)





Strongly interacting dark sectors

- Well-motivated DM scenario: **dark sector may resemble QCD**

$$\mathscr{L} \supset -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a} + \overline{q_\mathrm{d}} i \not{D} q_\mathrm{d} - \overline{q_\mathrm{d}} M_q q_\mathrm{d}$$

with

  - N_f dark quarks q_d in the fundamental representation of a new confining gauge group, e.g. $SU(N_\mathrm{d})$
  - dark gluons $F^a_{\mu\nu}$

- In this talk consider $N_d = 3$ and diagonal mass matrix $M_q = \mathrm{diag}(m_q)$

Dark sector bound states

- Below some scale Λ_d the dark sector confines.
- $N_f^2 - 1$ **dark pions** π_d as (Pseudo-)Goldstone bosons (massive if $m_{q_\mathrm{d}} > 0$)
- If they carry another conserved charge, at least the lightest charged dark mesons ($\pi_\mathrm{d}^+,\ \pi_\mathrm{d}^-$) are stable.
- For $N_f = 2$ and $Q = \mathrm{diag}(1, -1)$ the π_d^0 is stable. Berlin et al., 1801.05805
  (crucial for cosmological viability of dark sector)
- **Dark pions are excellent dark matter candidates.**
- Heavier dark mesons are generically unstable, in particular ρ_d^0, which can mix with other vector bosons, e.g. Z' or dark photon.

$$c\tau_{\rho_\mathrm{d}^0} \propto \frac{\Lambda^4}{m_{\rho_\mathrm{d}}^5} \quad \text{where, e.g. for mixing with B-L } Z' \text{ mediator, } \Lambda = \frac{m_{Z'}}{\sqrt{e_\mathrm{d} g_{B-L}}}$$

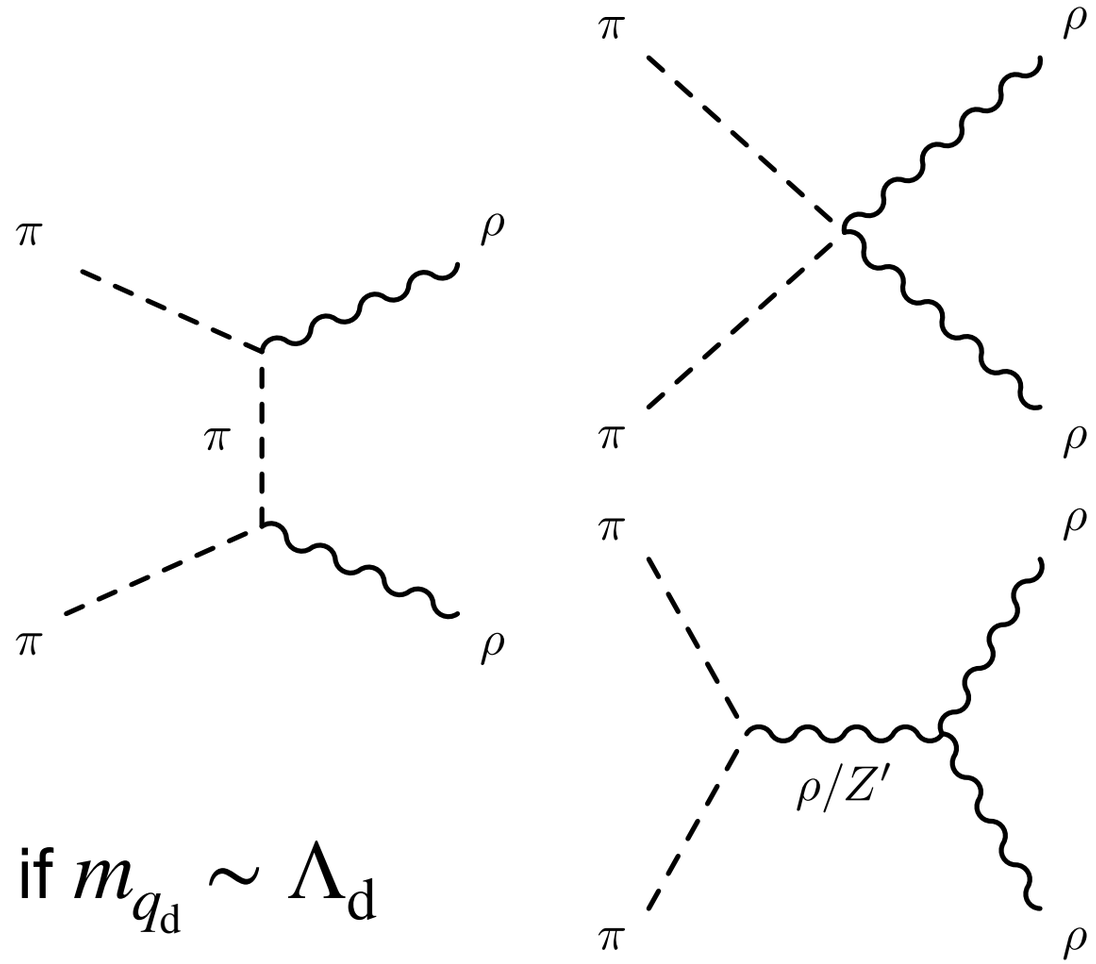
Forbidden annihilations

- (Inverse) decays of ρ_{d}^0 keep it in equilibrium with the SM bath in the early Universe provided that $\Gamma_{\rho_{\mathrm{d}}^0} > H$.
- π_{d}-to-ρ_{d} conversions set the dark pion relic abundance.
- **Dominant freeze-out process:** $\pi_{\mathrm{d}}\ \pi_{\mathrm{d}} \to \rho_{\mathrm{d}}\ \rho_{\mathrm{d}}$
- Annihilation of lighter into heavier state possible at finite temperature, but Boltzmann suppressed

  D'Agnolo, Ruderman, 1505.07107

$$\sigma_{\pi_{\mathrm{d}}\pi_{\mathrm{d}}\to\rho_{\mathrm{d}}\rho_{\mathrm{d}}} \propto \frac{g^2}{m_\pi^2}\, e^{-2\Delta x_f}$$

$$\Delta = (m_\rho - m_\pi)/m_\pi$$



- m_π and m_ρ are expected to be close if $m_{q_{\mathrm{d}}} \sim \Lambda_{\mathrm{d}}$
- **Mechanism works for wide range of masses**

Phenomenology of strongly interacting dark sectors

- Strong interactions in dark sector can induce large self-interactions:

$$\sigma \propto \frac{g^4}{m_{\pi_\mathrm{d}}^2}$$

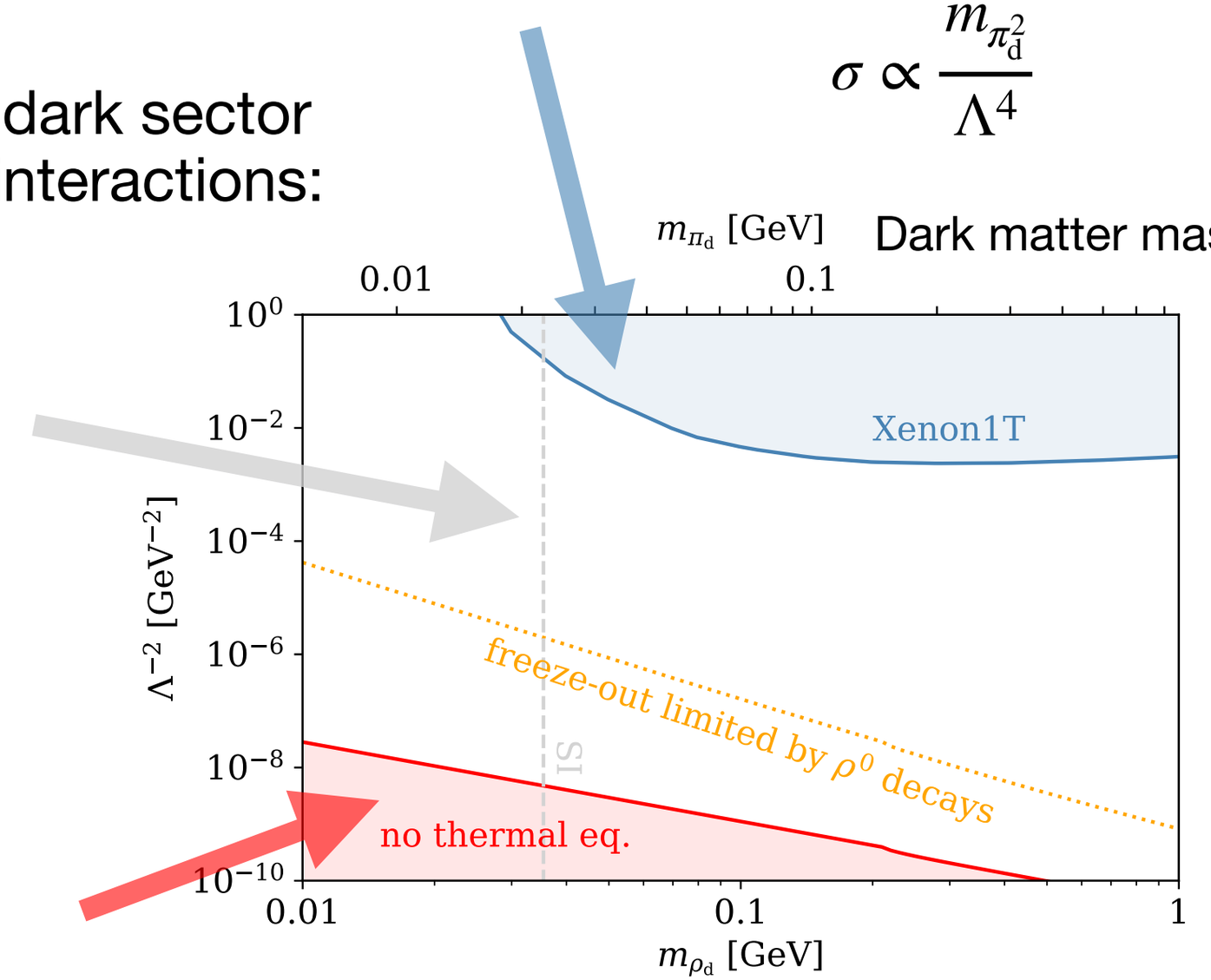
bullet cluster implies

$$m_{\pi_\mathrm{d}} \gtrsim 30 \text{ MeV}$$

$$\Gamma_{\rho_\mathrm{d}^0} < H$$

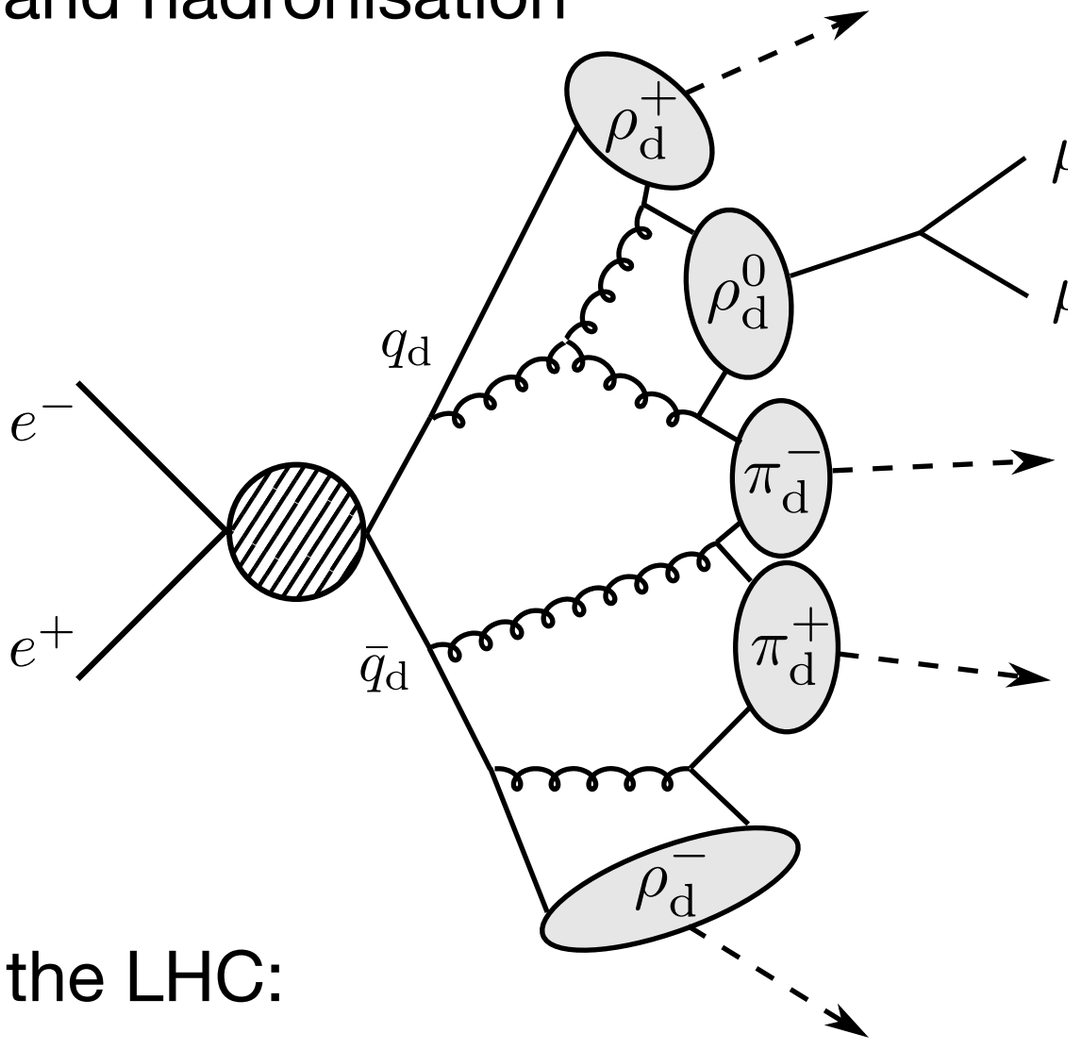
- Dark pions can scatter off electrons via dark rho exchange:

$$\sigma \propto \frac{m_{\pi_\mathrm{d}}^2}{\Lambda^4}$$



Dark showers at colliders

- If $\Lambda_{\mathrm{d}} \ll \sqrt{s}$ → pair production of dark quarks leading to **dark shower** and hadronisation



- Large number of dark mesons in an event, depending on their mass
- Most (75%) escape the detector as $\not{E}_T$
- The ρ_{d}^{0} mesons decay to visible SM particles

→ **Range of novel signatures**

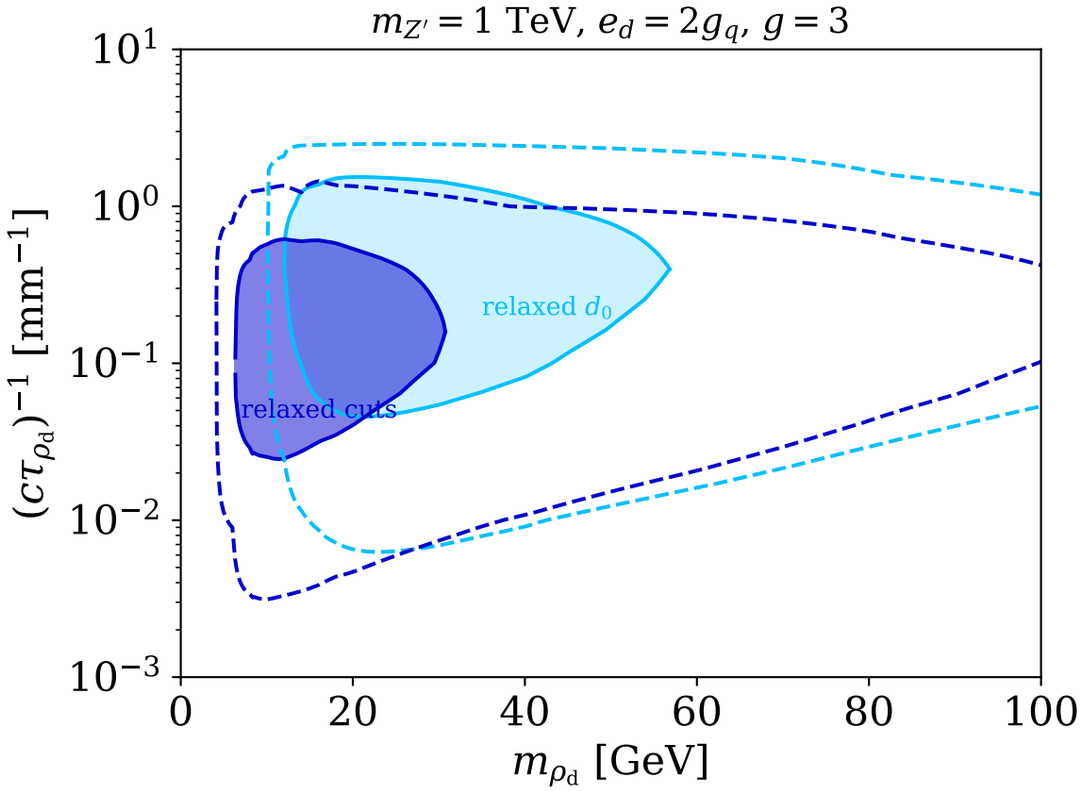
At the LHC:

- prompt decays → semi-visible jets Cohen et al., 1503.00009, 1707.05326
- displaced decays → emerging jets (if mostly visible) Schwaller et al., 1502.05409

  DV+MET (if mostly invisible) EB et al., 2011.06604

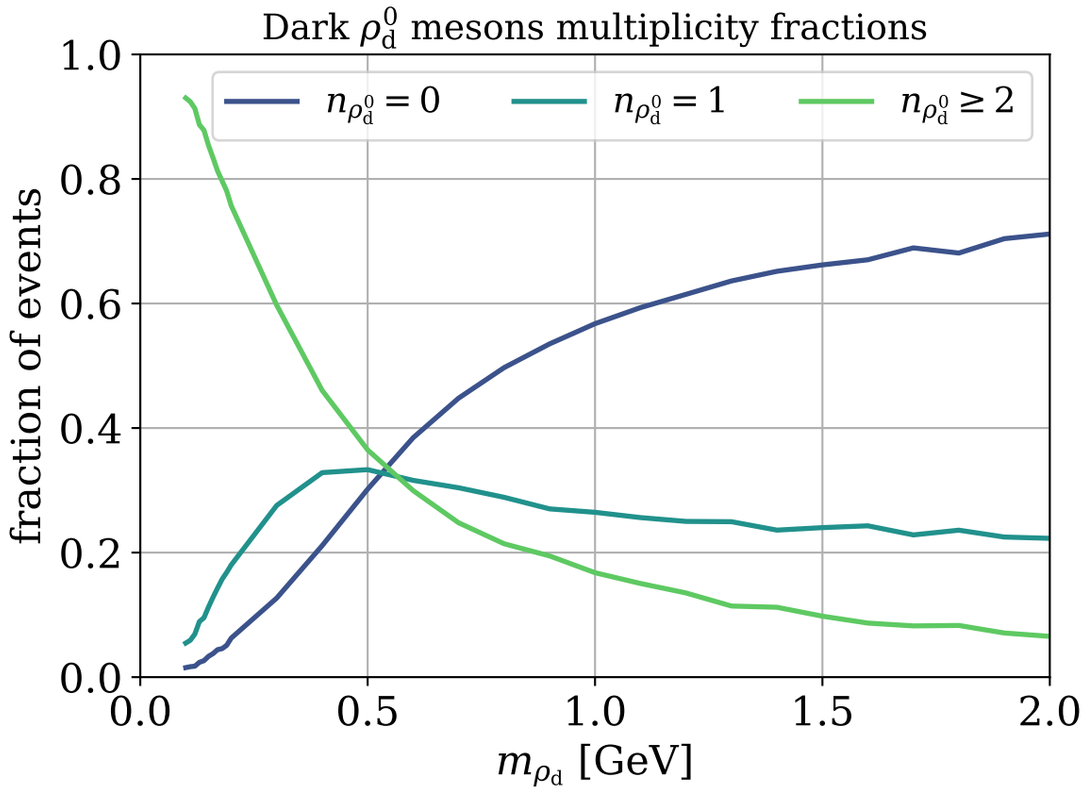
Dark showers at Belle II

- LHC (ATLAS/CMS) searches for displaced vertices and MET are sensitive to $m_{\mathrm{LLP}} \gtrsim 5\ \mathrm{GeV}$.



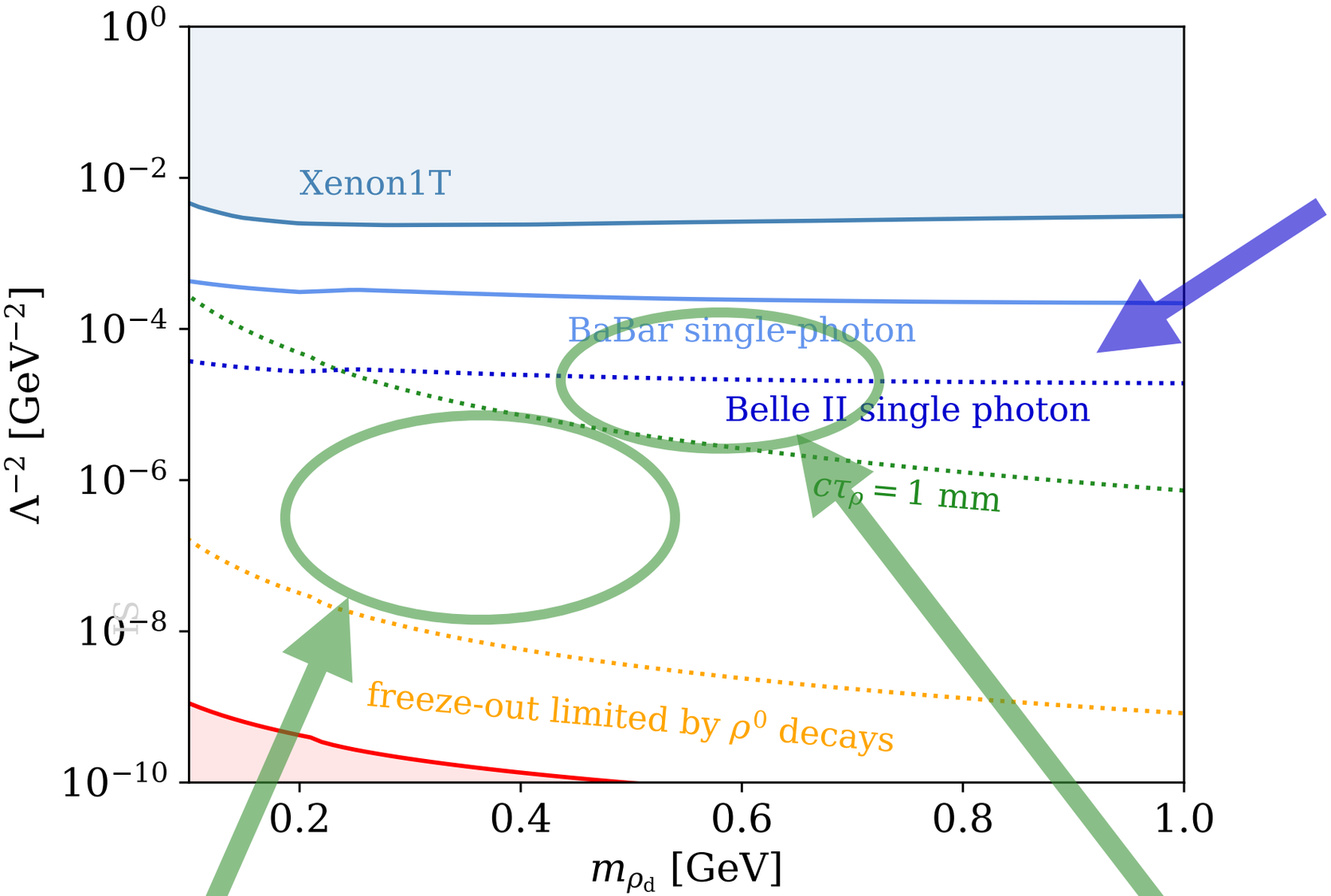
EB et al., 2011.06604

- Opportunity for Belle II on sub-GeV scale
- Typical multiplicity depends on dark meson mass:



- For small masses, typically multiple decaying mesons
- For large masses, no decaying mesons in large fraction of events

Dark showers at Belle II



Single-photon searches are sensitive to events where a fully invisible dark shower is produced together with an ISR photon.

projections from Essig et al. 1309.5084

More interesting:

dark shower becomes partly visible

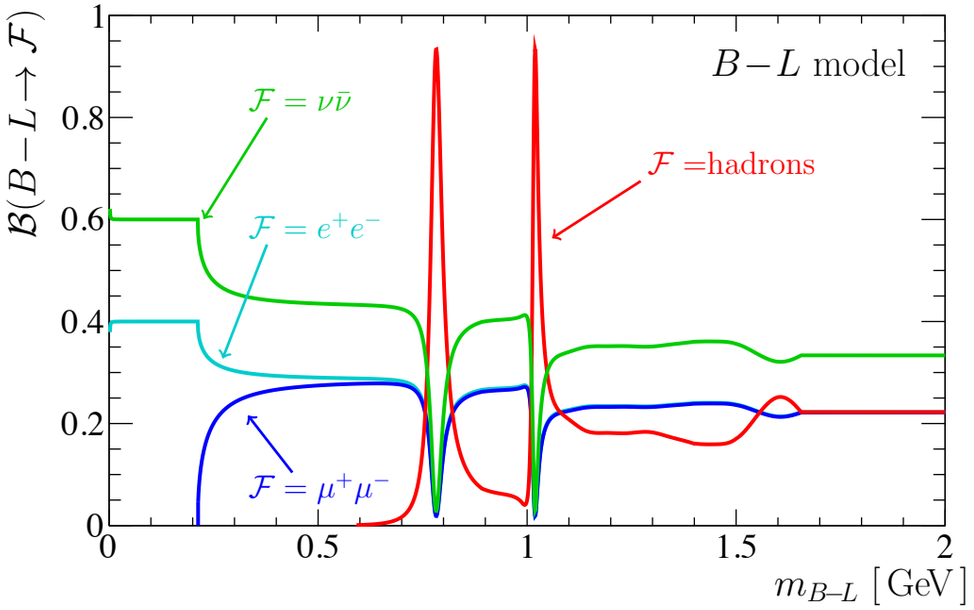
- displaced decays + missing energy
- prompt SM particles + missing energy

Final states

- Branching fractions of dark meson decays depend on portal interaction

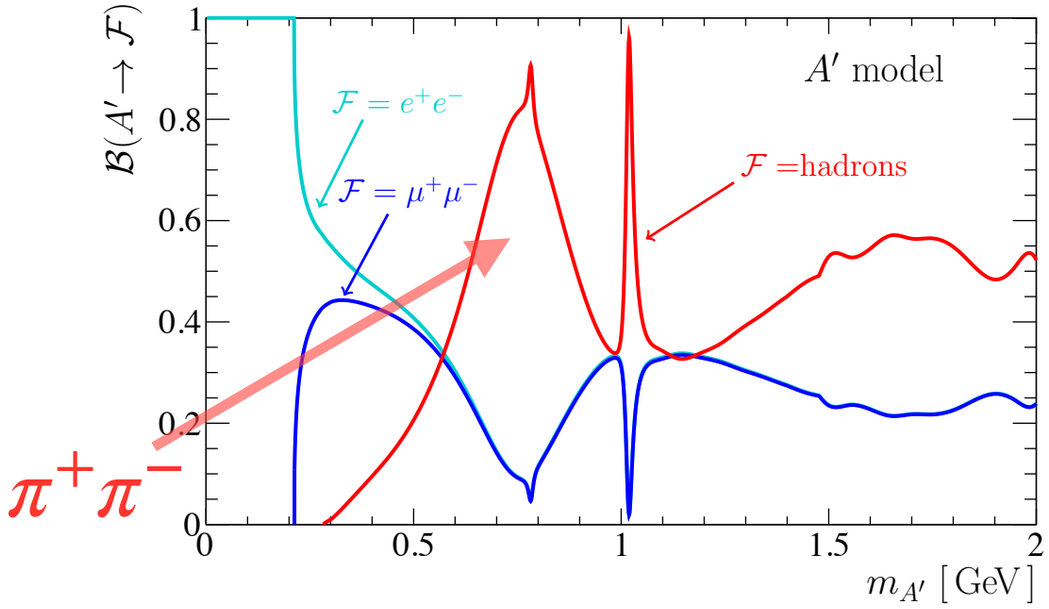
Figures from Ilten et al., 1801.04847

ρ_{d}^0 mixes with B-L Z'



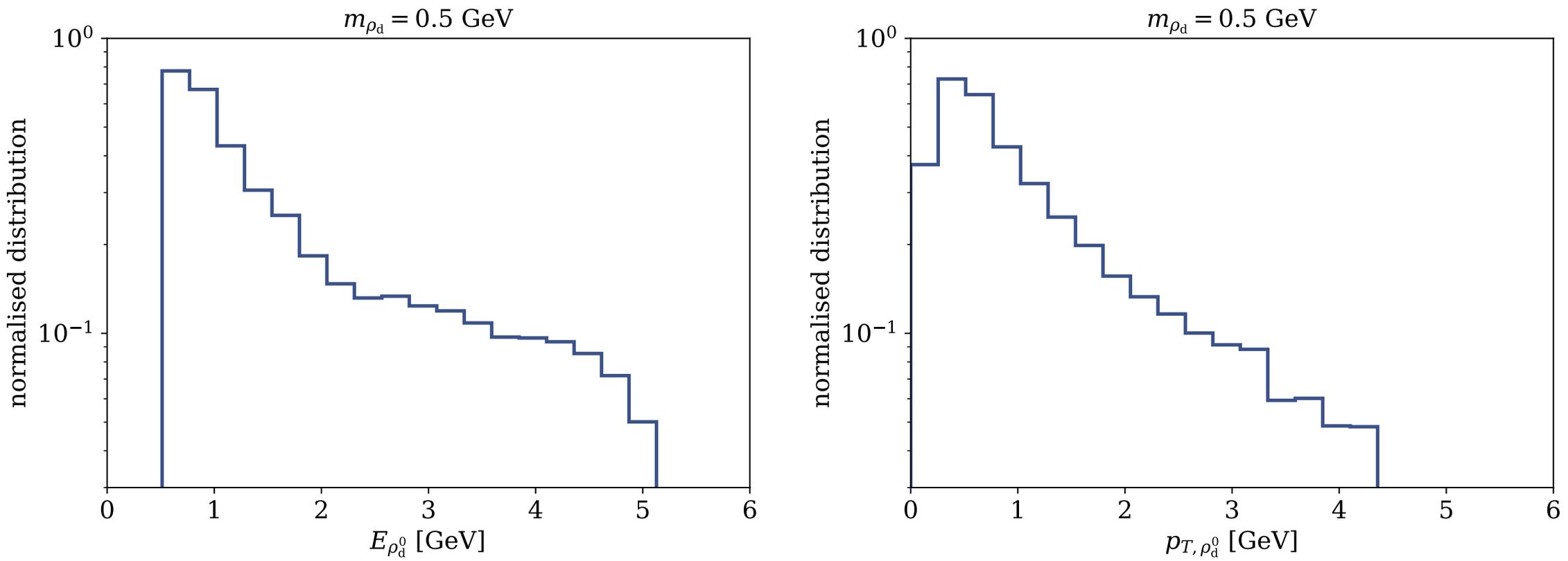
dominantly leptonic decays, in particular $\mu^+\mu^-$
(for $m_{\rho_{\mathrm{d}}} \gtrsim 200$ MeV)

ρ_{d}^0 mixes with dark photon



dominantly hadronic decays
(for $m_{\rho_{\mathrm{d}}} \gtrsim 600$ MeV),
in particular $\pi^+\pi^-$

DV + MET signature



- Displaced dark mesons have sizeable energy and transverse momentum.
- Signature: fully reconstructable two-body decay to $\pi^+\pi^-$ / $\mu^+\mu^-$
  - with invariant mass equal to m_{ρ_d}
  - multiple such vertices in large fraction of events if m_{ρ_d} is small
  - + missing energy

Conclusions

- Dark pions are well-motivated dark matter candidates.
- Strongly interacting dark sectors are cosmologically viable.
- Dark showers give rise to exciting new signatures at the LHC **and at Belle II.**
- Dark showers can be simulated (with caveats).
- Attractive recasting target for standard searches: **single photon.**
- Motivation for **new searches** at Belle II:
  - prompt or displaced decays (with decay lengths of $\mathcal{O}(\mathrm{mm})$)
  - hadronic ($\pi^+\pi^-$) and/or leptonic ($\mu^+\mu^-$) decays, depending on model
  - + missing energy

→ **Lots of exciting future work**