Dark showers at Belle II

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including material from

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**

\[ \mathcal{L} \supset -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a} + \bar{q}_d i\slashed{D} q_d - \bar{q}_d M_q q_d \]

with

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

- In this talk consider \( N_d = 3 \) and diagonal mass matrix \( M_q = \text{diag}(m_q) \)
Dark sector bound states

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

$$c_\tau \rho_d^0 \propto \frac{\Lambda^4}{m_{\rho_d}^5}$$

where, e.g. for mixing with B-L $Z'$ mediator, $\Lambda = \frac{m_{Z'}}{\sqrt{e_{d}\sigma_{B-L}}}$
Forbidden annihilations

• (Inverse) decays of $\rho_d^0$ keep it in equilibrium with the SM bath in the early Universe provided that $\Gamma_{\rho_d^0} > H$.

• $\pi_d$-to-$\rho_d$ conversions set the dark pion relic abundance.

• **Dominant freeze-out process:** $\pi_d \pi_d \rightarrow \rho_d \rho_d$

• Annihilation of lighter into heavier state possible at finite temperature, but Boltzmann suppressed

\[
\Delta = \left( m_{\rho} - m_{\pi} \right) / m_{\pi}
\]

• $m_{\pi}$ and $m_{\rho}$ are expected to be close if $m_{q_d} \sim \Lambda_d$

• **Mechanism works for wide range of masses**

D’Agnolo, Ruderman, 1505.07107
Phenomenology of strongly interacting dark sectors

- Strong interactions in dark sector can induce large self-interactions:
  \[ \sigma \propto \frac{g^4}{m_{\pi_d}^2} \]

bullet cluster implies

\[ m_{\pi_d} \gtrsim 30 \text{ MeV} \]

- Dark pions can scatter off electrons via dark rho exchange:
  \[ \sigma \propto \frac{m_{\pi_d}^2}{\Lambda^4} \]

\[ \Gamma_{\rho_0^d} < H \]

\[ m_{\rho_0^d} \text{ [GeV]} \]

**Dark vector meson mass**

**Dark matter mass**

Xenon1T

**freeze-out limited by \( \rho^0 \) decays**

**no thermal eq.**
Dark showers at colliders

- If $\Lambda_d \ll \sqrt{s}$ → 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 $E_T$
- The $\rho^0_d$ mesons decay to visible SM particles

Range of novel signatures

At the LHC:
- prompt decays → semi-visible jets
- displaced decays → emerging jets (if mostly visible)

$DV+MET$ (if mostly invisible)

Cohen et al., 1503.00009, 1707.05326
Schwaller et al., 1502.05409
EB et al., 2011.06604
Dark showers at Belle II

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

EB et al., 2011.06604
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

$\rho_d^0$ mixes with B-L $Z'$

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

$\rho_d^0$ mixes with dark photon

- dominantly hadronic decays
  (for $m_{\rho_d} \gtrsim 600$ 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 $m_{\rho_d}$
  - multiple such vertices in large fraction of events if $m_{\rho_d}$ 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 \( \mathcal{O}(\text{mm}) \))
  ▶ hadronic \((\pi^+\pi^-)\) and/or leptonic \((\mu^+\mu^-)\) decays, depending on model
  ▶ + missing energy

Lots of exciting future work