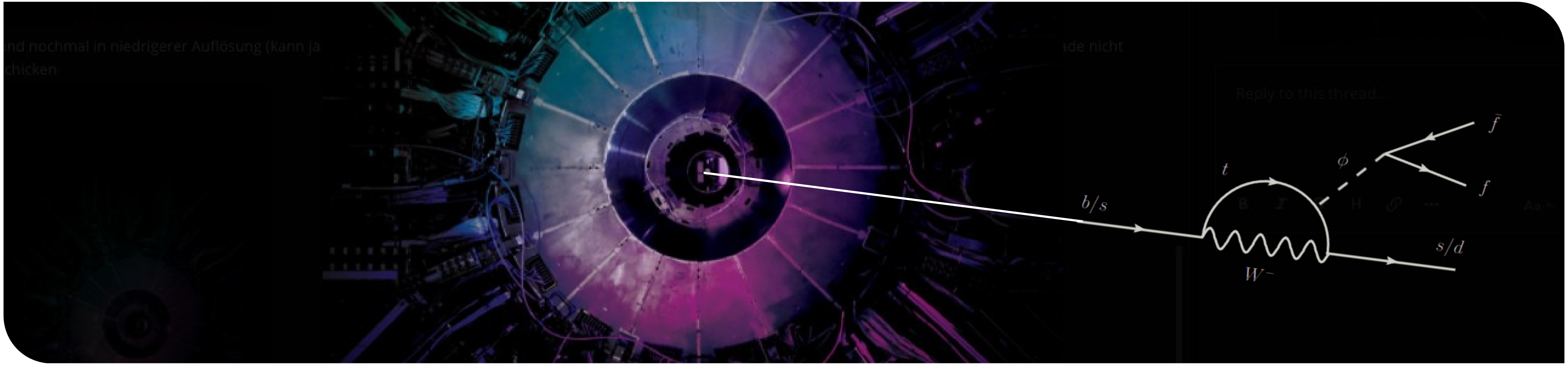
Feebly-interacting particles at the intensity frontier

Felix Kahlhoefer
Third DMLab Meeting, KIT, 16 November 2023



Feebly-interacting particles

- Progress in particle physics guided by paradigm of o(1) dimensionless couplings
  - Any new particle to be discovered must be heavy
  - Need high-energy colliders or look for indirect effects (e.g. rare decays)
- In spite of significant improvements in sensitivity we have no (conclusive) evidence for physics beyond the Standard Model
- Time to question our search strategy and look for places we may have missed
- Light particles could remain to be discovered, if they have very small interactions with Standard Model (SM) particles

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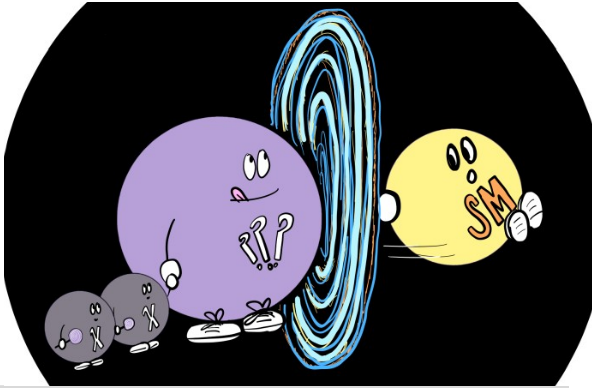
Portal interactions

- Light particles must be gauge singlets

- They can only couple to gauge-invariant combinations of SM fields

  - Only 3 possible combinations with d < 3:

$$
\begin{aligned}
&F^Y_{\mu\nu} \qquad && \text{Vector portal (dim} = 2), \\
&H^\dagger H \qquad && \text{Higgs portal (dim} = 2), \\
&LH \qquad && \text{Neutrino portal (dim} = 5/2)
\end{aligned}
$$



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Portal interactions

- Light particles must be gauge singlets
- They can only couple to gauge-invariant combinations of SM fields
  - Only 3 possible combinations with d < 3:

$F^Y_{\mu\nu} \rightarrow \mathcal{L}_{\text{int}} = \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu}$ Dark photon

$H^\dagger H \rightarrow \mathcal{L}_{\text{int}} = (H^\dagger H)(\lambda S^2 + A S)$ Dark scalar

$LH \rightarrow \mathcal{L}_{\text{int}} = y_{ij} L_i H N_j$ Heavy neutral lepton

Batell et al., arXiv:0906.5614

Axion-like particles

- At d = 3, gauge-invariant combinations of SM fields include the vector and axial-vector fermion currents:

$$\bar{\psi}\gamma_\mu\psi \qquad \bar{\psi}\gamma_\mu\gamma_5\psi$$

- These currents can couple to a new gauge boson (Z')
- Attractive alternative: Derivative coupling to a pseudoscalar boson (d = 5)

$$\mathcal{L}_{\text{int}} = \frac{\partial_\mu a}{f_a}\bar{\psi}\gamma_\mu\gamma_5\psi$$

Axion-like particles

Batell et al., arXiv:0906.5614

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OK, but why?

- Theory:
  - Need new particles to explain puzzling structure of the Standard Model (fine-tuning problems, large hierarchies, accidental symmetries)
- Experiment:
  - Particle-antiparticle asymmetry in the early universe
  - Non-zero neutrino masses
  - Dark matter
  - Experimental anomalies

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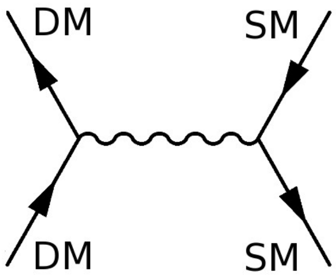
Dark matter mediators

- Predictive models of dark matter require a mechanism to produce DM in the early universe
- Essential ingredient: Non-gravitational interactions between DM and SM particles
- Strong constraints on interactions mediated by SM gauge and Higgs bosons
- Feebly-interacting particles can act as mediator of DM interactions
- Example: Dark fermion charged under U(1)’

  → dark photon mediator



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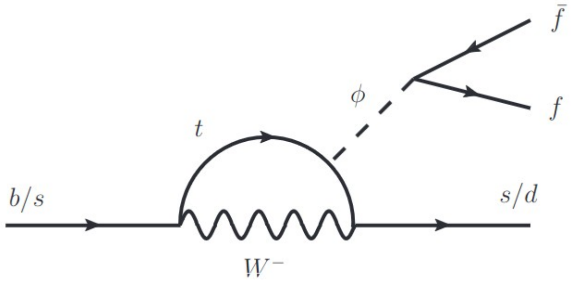
Phenomenology: Production

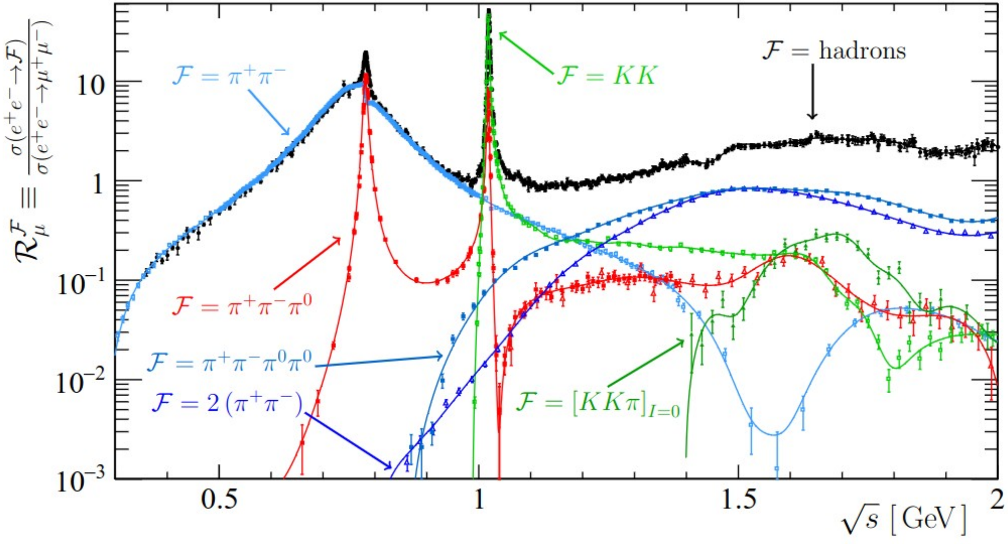
- GeV-scale FIPs can be produced in rare meson decays
- Two main contributions:
  - Loop-induced decays (e.g. penguin diagrams)
    - → Most relevant for (pseudo)scalars with large couplings to top quarks



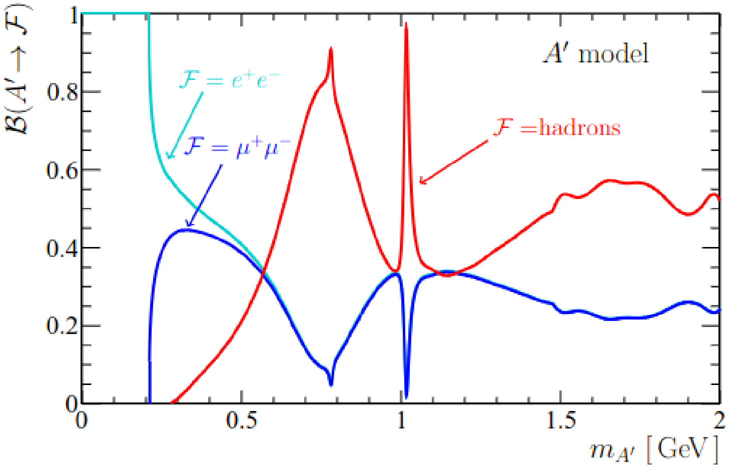
  - Mixing-induced decays (SM particle replaced by FIP)
    - → Heavy neutral lepton: $\nu \to N$ (e.g. $D^+ \to K^0 e^+ N$)
    - → Axion-like particles: $\pi^0 \to a$ (e.g. $K^+ \to \pi^+ a$)
    - → Dark photons: $\gamma \to A'$ (e.g. $\pi^0 \to \gamma A'$)

Phenomenology: Decays

- Calculation of decay modes for GeV-scale FIPs generally hard problem
- Exception: Dark photon decay modes extracted from R ratio



Ilten et al., arXiv:1801.04847



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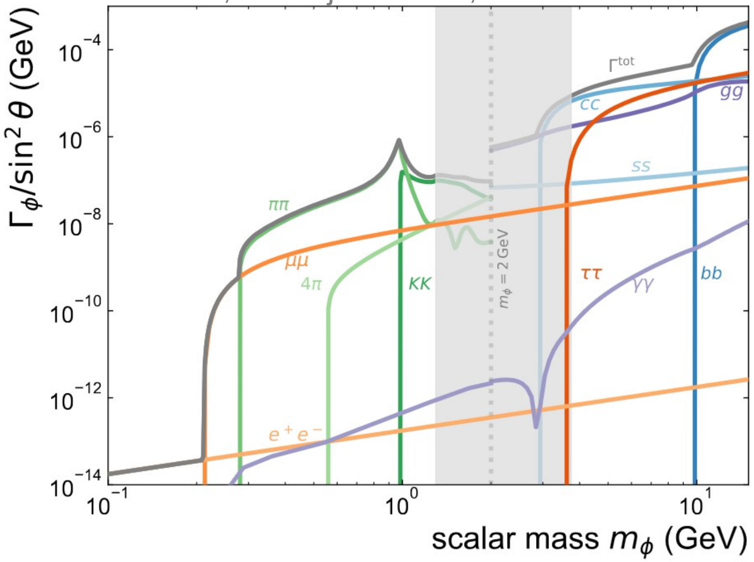
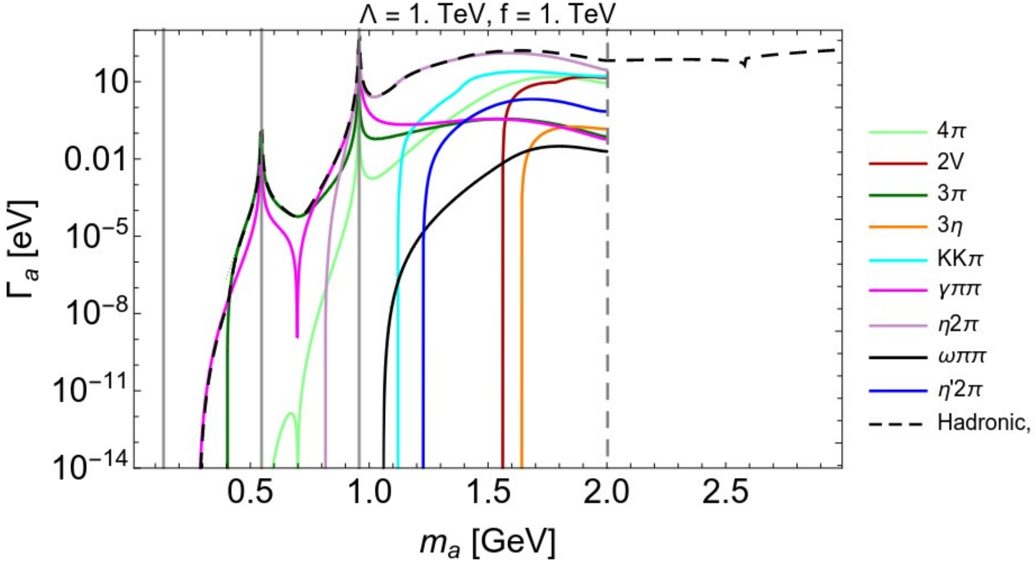
Phenomenology: Decays

- For light (pseudo)scalars: Use dispersion relations and chiral perturbation theory

Ferber, Grohsjean & FK, arXiv:2305.16169



Dalla Valle Garcia, FK et al., arXiv:2310.03524



Phenomenology: Lifetime

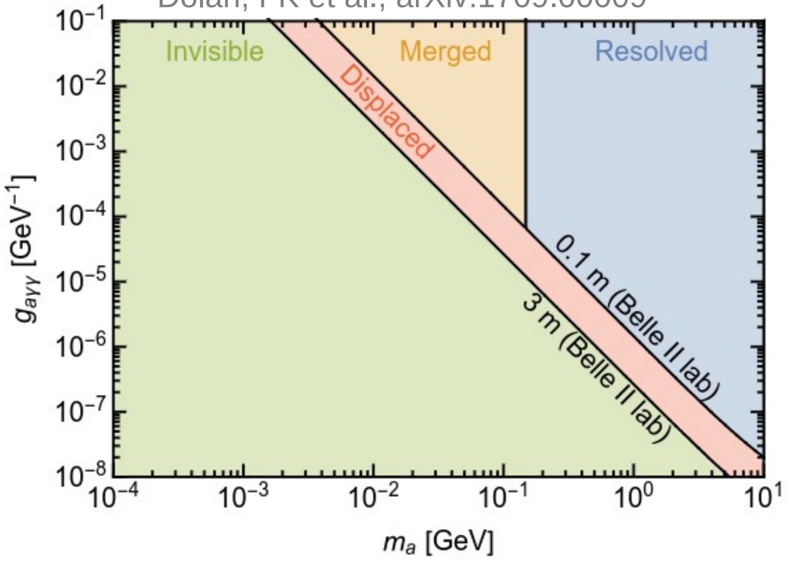
- In addition to the final state, the experimental signature depends decisively on the FIP lifetime

Short lifetime → prompt decay

Intermediate lifetime → displaced decay

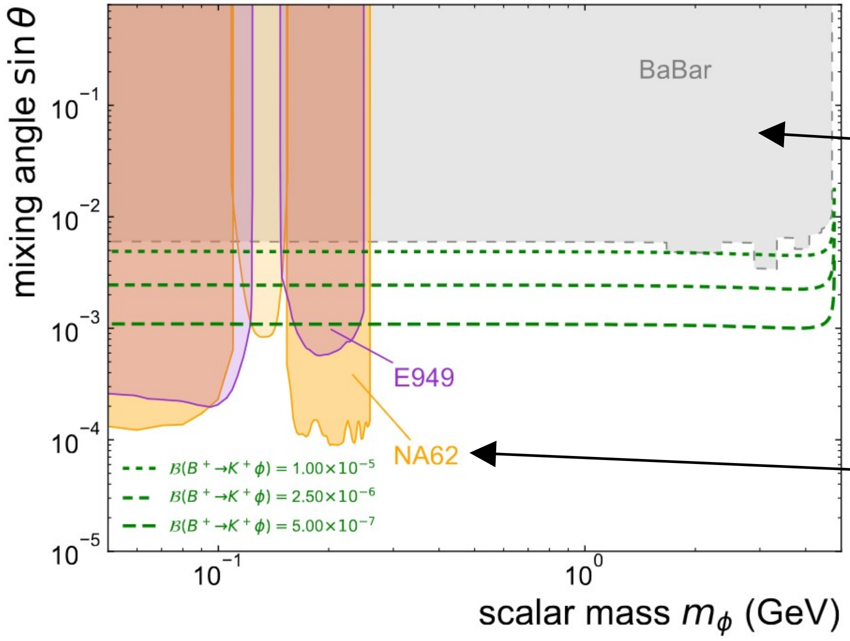
Long lifetime → missing energy

Dolan, FK et al., arXiv:1709.00009



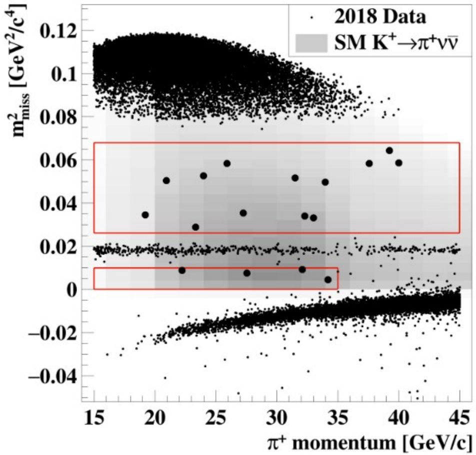
- Note: Missing energy signatures also arise from FIPs decaying into DM

Example 1: Invisibly decaying dark scalars

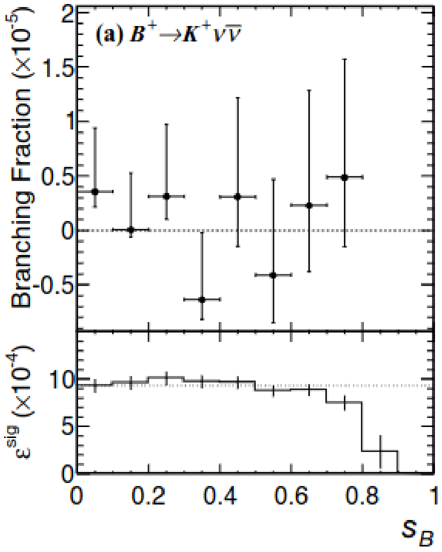


Ferber, Grohsjean & FK, arXiv:2305.16169

NA62, arXiv:2103.15389



BaBar, arXiv:1303.7465



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B → Kνν at Belle II

- Best-fit branching ratio:

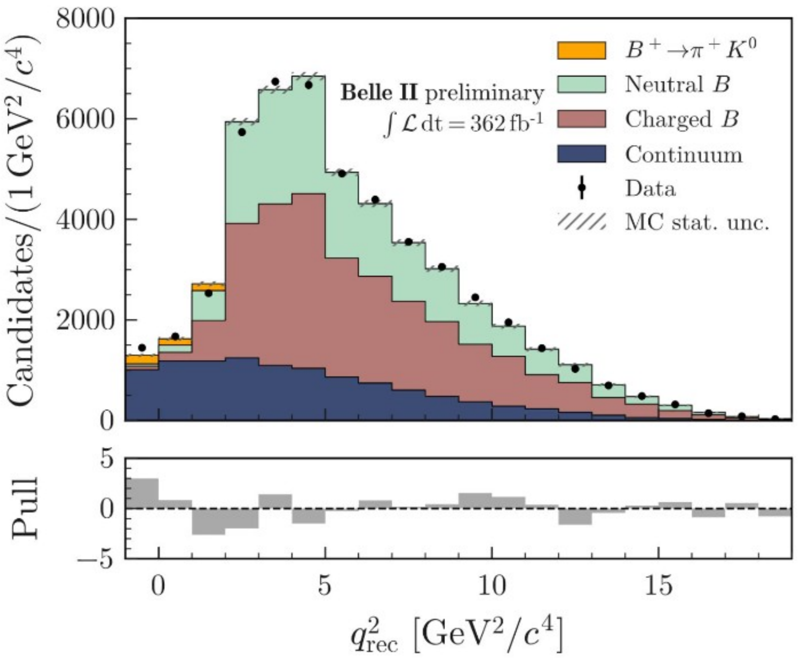
  $(B^+ \to K^+\nu\nu) = (2.4 \pm 0.7) \times 10^{-5}$

  → Somewhat larger than SM prediction

- Could the excess be due to a scalar FIP?

- Resolution of q^2_{rec} for inclusive tag not publicly available

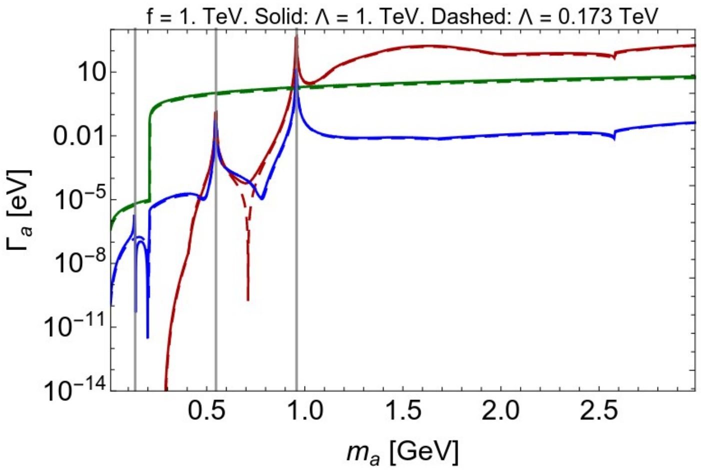
  → Ongoing work with local Belle II group



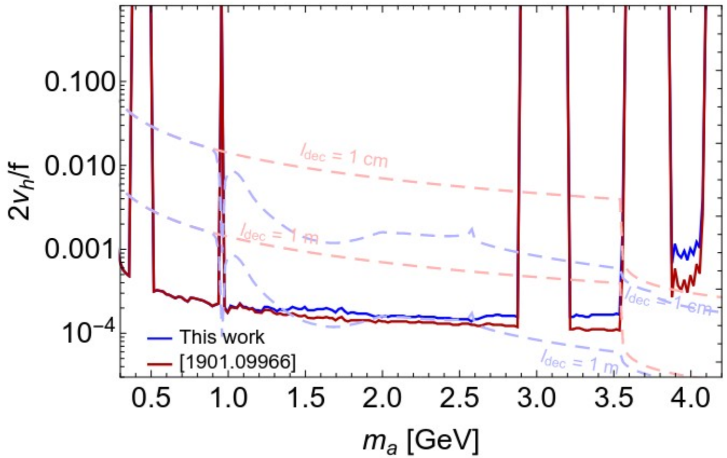
See sensitivity study in Ferber et al., arXiv:2201.06580

Example 2: Long-lived axion-like particles

- CP conservation forbids decay models a → ππ or a → KK
- Common assumption: Leptonic decay modes dominate   Dolan, FK et al., arXiv:1412.5174
- Accurate calculation: Suppressed leptonic branching & weaker LHCb constraints



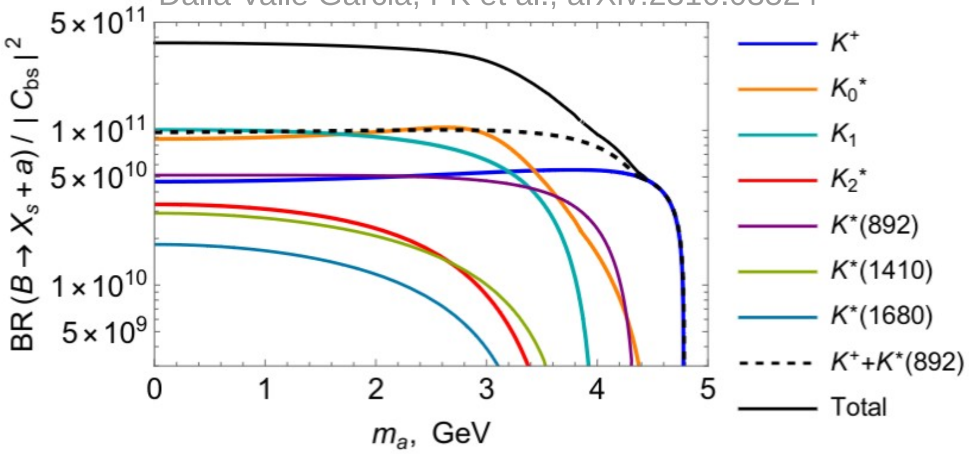
Dalla Valle Garcia, FK et al., arXiv:2310.03524

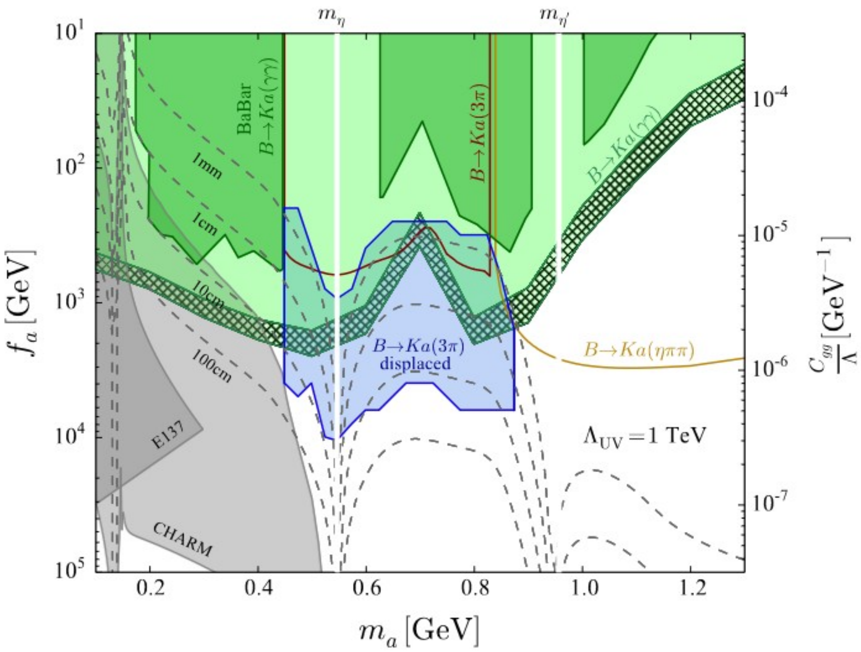


New opportunities

- Look for exclusive B decays and new final states

Dalla Valle Garcia, FK et al., arXiv:2310.03524





Bertholet et al., arXiv:2108.10331

Example 3: Dark photons as DM mediators

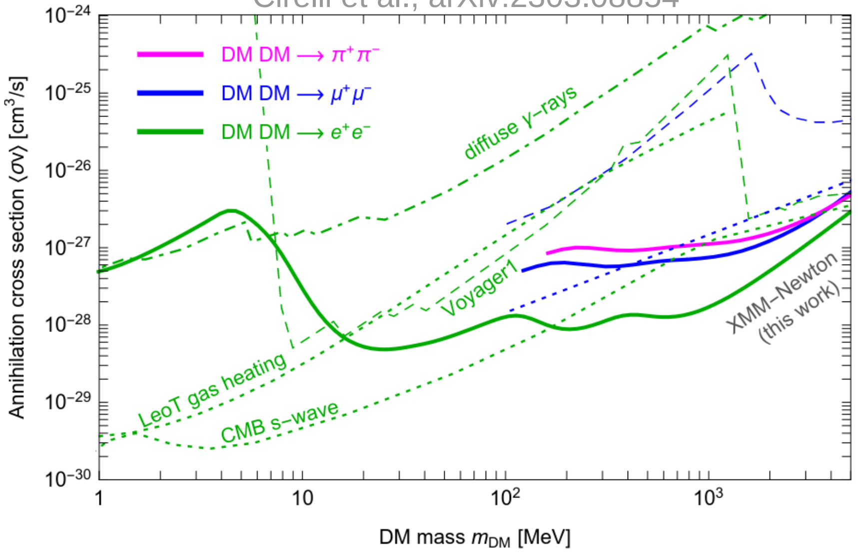
- Thermal freeze-out requires annihilation cross section σv ~ 10^{-26} cm^3/s

- Small fraction of DM particles will continue to annihilate after the end of freeze-out

  → Strong constraints on sub-GeV DM with velocity-independent annihilation cross section

- To evade these constraints, it is necessary to suppress the annihilation rate at small velocities

Cirelli et al., arXiv:2303.08854



Sub-GeV DM: Many possibilities

- Resonant or p-wave annihilations

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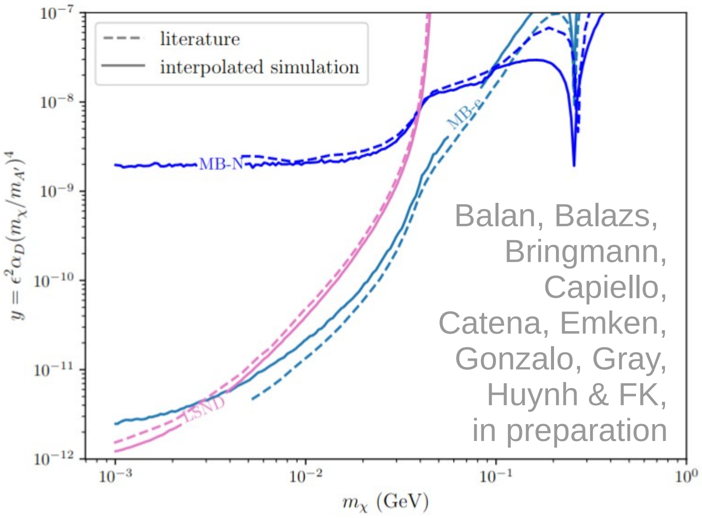
Sub-GeV DM: Many possibilities

- Resonant or p-wave annihilations
- Asymmetric dark matter

  → DM scattering in beam dumps



Balan, Balazs, Bringmann, Capiello, Catena, Emken, Gonzalo, Gray, Huynh & FK, in preparation

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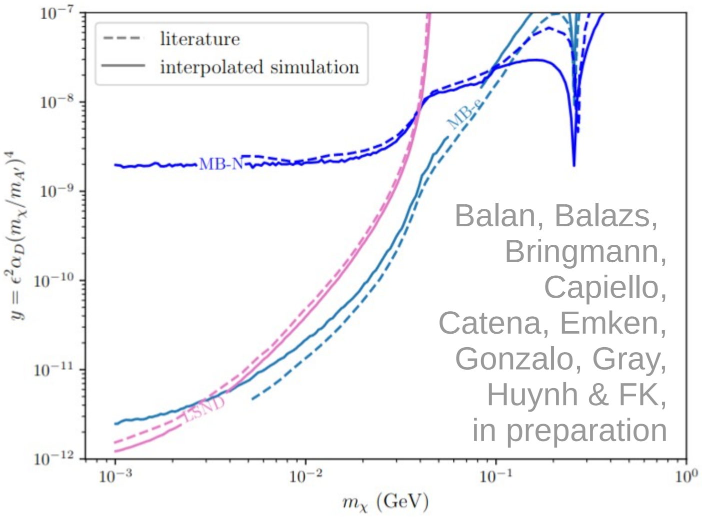
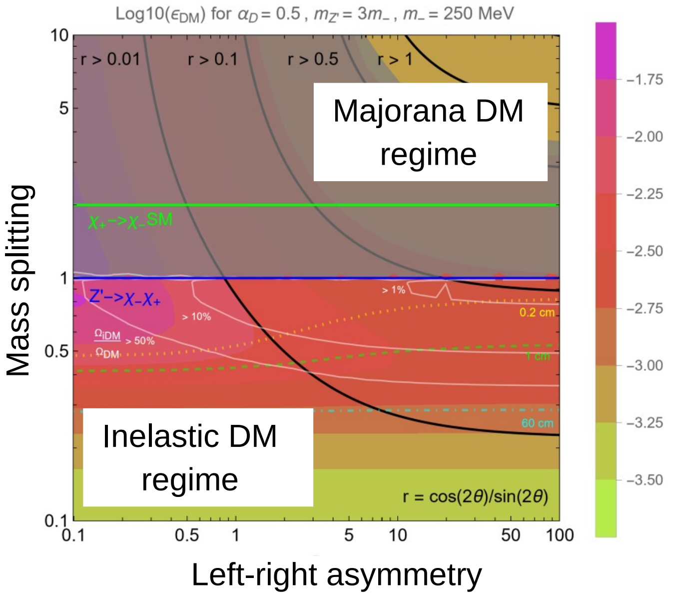
Sub-GeV DM: Many possibilities

- Resonant or p-wave annihilations
- Asymmetric dark matter
  - → DM scattering in beam dumps



- Inelastic dark matter
  - → Displaced vertices in Belle II



Della Valle Garcia, FK, Ovchynnikov, Schwetz, in preparation

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How do GeV-scale FIPs get their mass?

- Attractive possibility: Dark Higgs mechanism
- Complex dark scalar obtains vev & breaks U(1)' gauge symmetry
  - Gauge interactions: Dark photon mass
  - Yukawa interactions: Dark matter mass
- Mixing between dark Higgs boson and SM Higgs boson:

$$h \to \cos\theta \, h + \sin\theta \, \phi$$
$$\phi \to -\sin\theta \, h + \cos\theta \, \phi$$

$$\theta \approx \frac{\lambda_{h\phi} \, v \, w}{m_h^2 - m_\phi^2}$$

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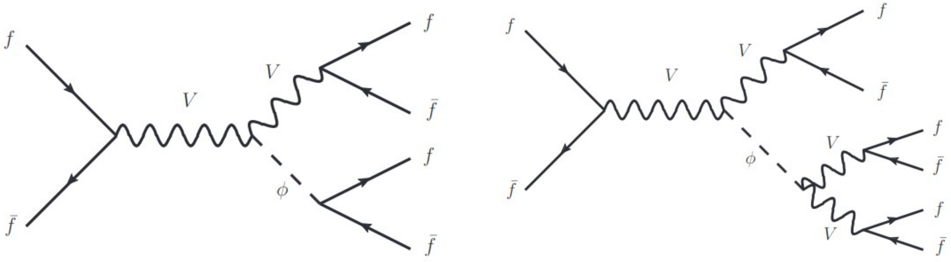
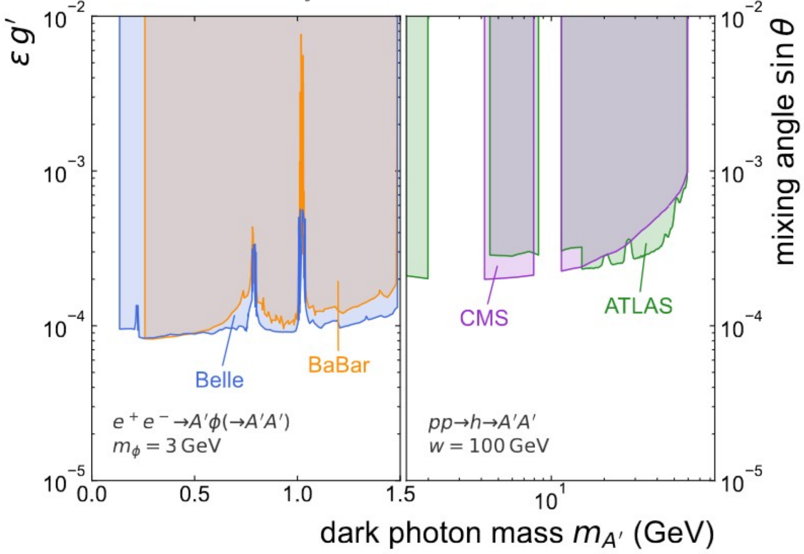
Dark Higgs bosons at colliders

- Consequence 1: New collider signatures



Ferber, Grohsjean & FK, arXiv:2305.16169



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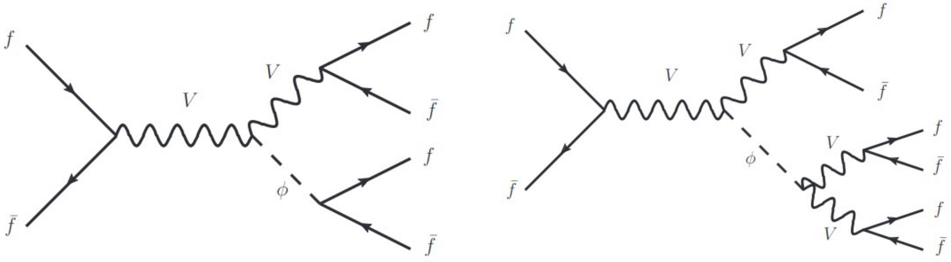
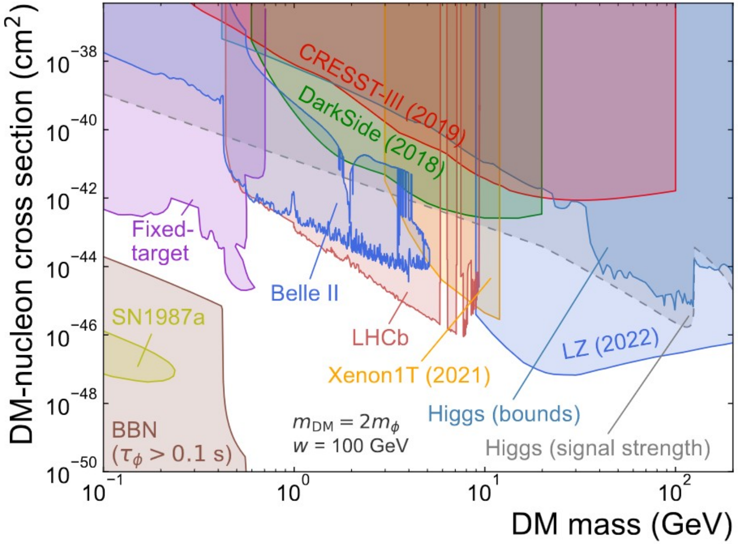


- Consequence 2: New DM interactions
  - Annihilation (DM DM → SM SM)
  - Scattering (DM SM → DM SM)

Ferber, Grohsjean & FK, arXiv:2305.16169



→ Interplay between collider searches and dark matter phenomenology

Conclusions

- Feebly interacting particles
  - have masses at the GeV scale and tiny couplings
  - can have spin 0 (dark scalars, ALPs), ½ (heavy neutral leptons) or 1 (dark photons)
  - may address theoretical fine-tuning problems and experimental evidence for new physics
  - may act as the mediator of dark matter interactions
  - are produced in rare meson decays and decay into variety of final states

- Intensity frontier experiments like Belle II or proton beam dumps offer the ideal environment to search for FIPs and their connection to dark matter