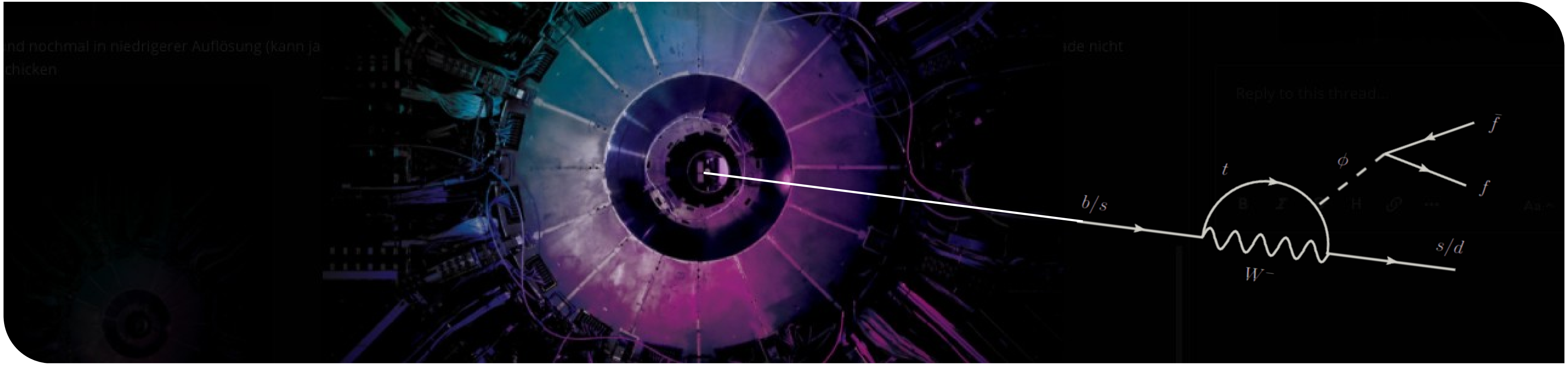
Feebly interacting particles in rare decays

Felix Kahlhoefer
Belle II Germany Meeting 2023, KIT, 25 September 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

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:

$$\begin{array}{rl} F^{Y}_{\mu\nu} & \text{Vector portal } (\text{dim} = 2), \\ H^\dagger H & \text{Higgs portal } (\text{dim} = 2), \\ LH & \text{Neutrino portal } (\text{dim} = 5/2) \end{array}$$

Portal interactions

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

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

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

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

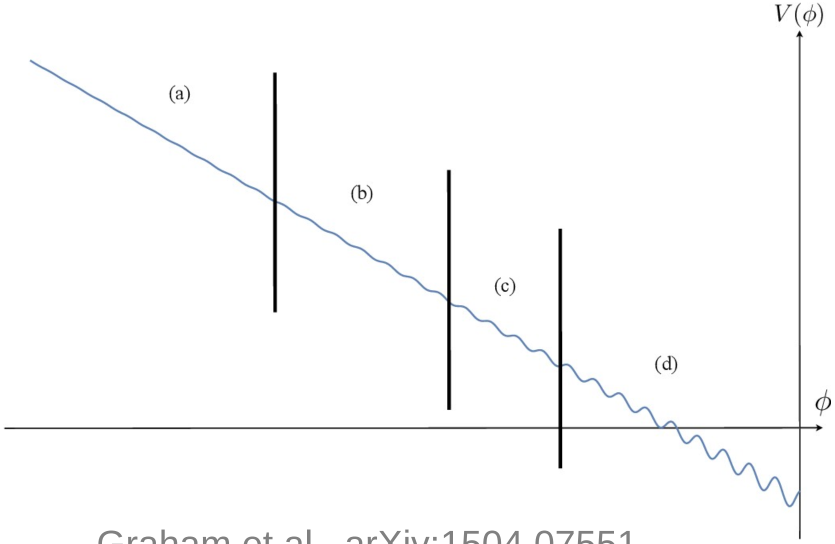
Theory example 1: Hierarchy problem

- The smallness of the electroweak scale (compared to the Planck scale) may be considered a fine-tuning problem

- Possible solution: Relaxion mechanism

  → Dynamical selection of electroweak scale through non-trivial scalar potential

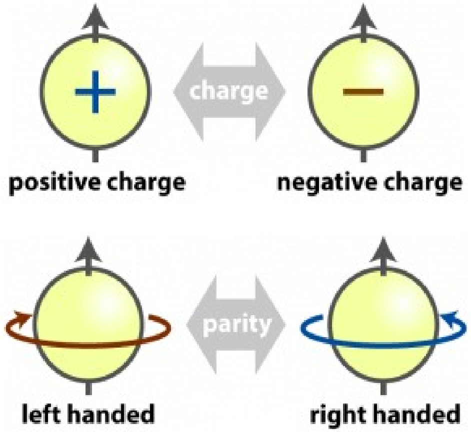
- Implies existence of a light scalar (relaxion) coupled to the Higgs boson

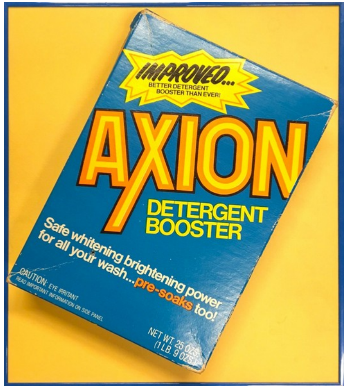


Graham et al., arXiv:1504.07551

Theory example 2: Strong CP problem

- Strong interactions are expected to violate CP symmetry, leading to a neutron electric dipole moment (EDM)
- The fact that no neutron EDM is observed means that CP-violating effects must be extremely small





- This fine-tuning is the strong CP problem
- The Peccei-Quinn solution to this problem assumes a new field with a potential that ensures CP-conservation at the minimum
- Central prediction: The existence of the QCD axion

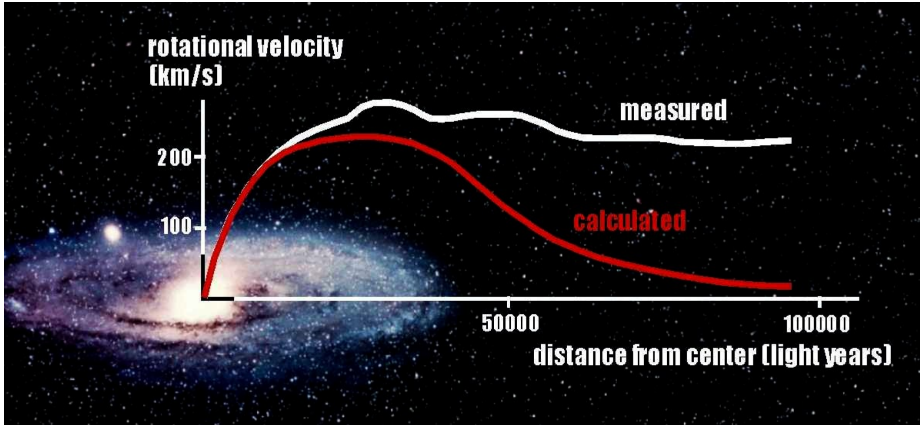
Experiment example 1: Neutrino masses

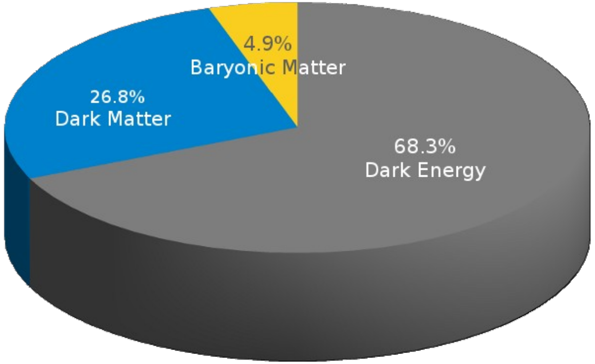
- Neutrino oscillations require the existence of right-handed (sterile) neutrinos
- Right-handed neutrinos could be very heavy (see-saw mechanism), very light (Dirac neutrinos) or anywhere in-between
- Attractive possibility: GeV-scale right-handed neutrinos can explain particle-antiparticle asymmetry of the Universe through decays into SM particles

→ Heavy neutral leptons

Experiment example 2: Dark matter

- Motion of stars and galaxies require an additional gravitational potential from invisible mass



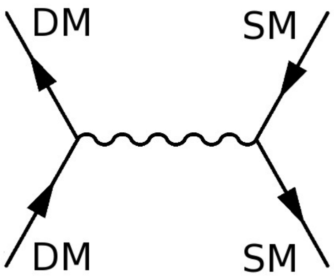


- There must be about 5 times more dark than visible matter to explain observed amounts of structure in the present universe

Dark matter mediators

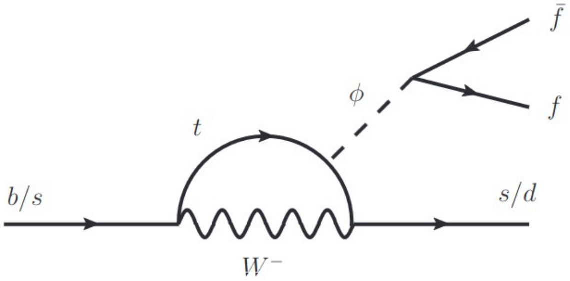
- Predictive models of dark matter require a mechanism to produce DM in the early universe
- Essential ingredient: Non-gravitational interactions between DM and SM particles
- Strong constraints on interactions mediated by SM gauge and Higgs bosons
- Feebly-interacting particles can act as mediator of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

  → dark photon mediator



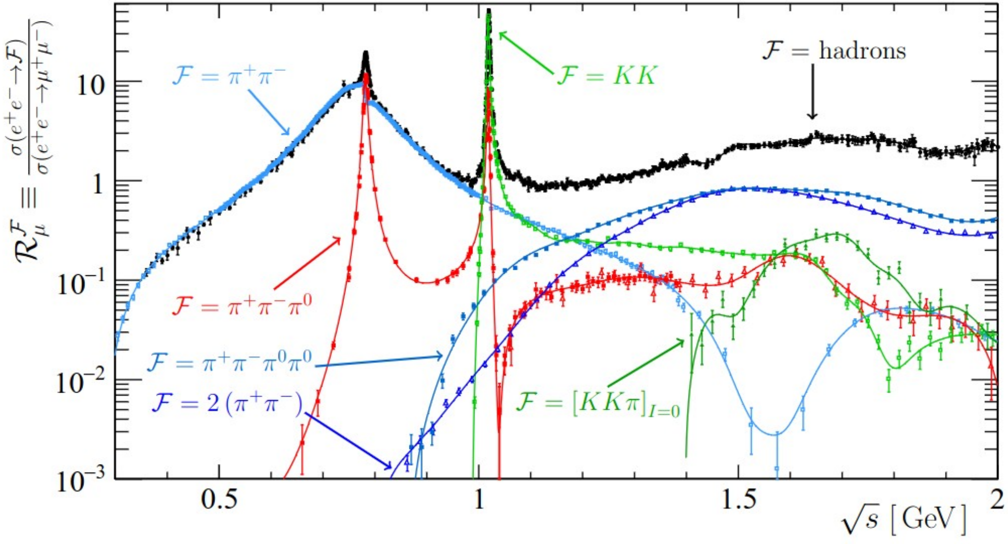
Phenomenology: Production

- 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: $\nu \rightarrow N$ (e.g. $D^+ \rightarrow K^0 e^+ N$)
    - → Axion-like particles: $\pi^0 \rightarrow a$ (e.g. $K^+ \rightarrow \pi^+ a$)
    - → Dark photons: $\gamma \rightarrow A'$ (e.g. $\pi^0 \rightarrow \gamma A'$)

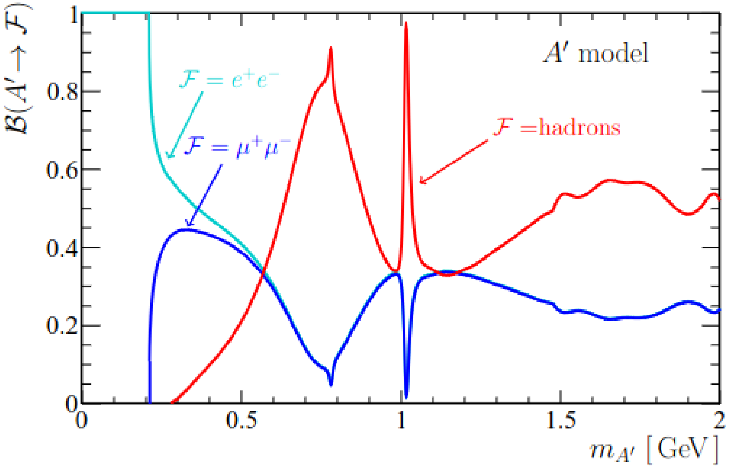


Phenomenology: Decays

- 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



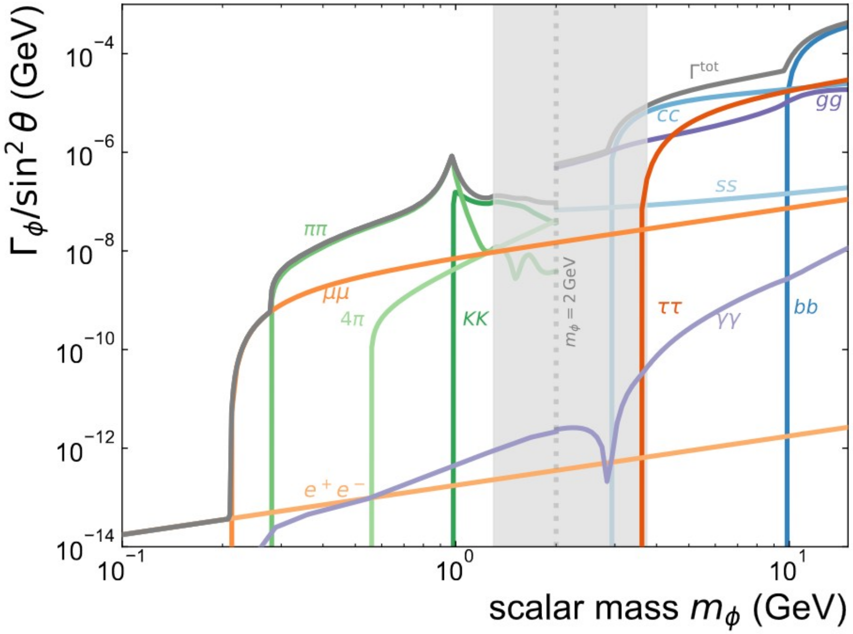
Phenomenology: Decays

- No direct measurements possible for light (pseudo)scalars

  → Substantial theory uncertainties

- Possible solutions:
  - Use dispersion relations with data from scattering (e.g. γγ* → ππ)
  - Use chiral perturbation theory with couplings fitted to meson decays

Ferber, Grohsjean & FK, arXiv:2305.16169

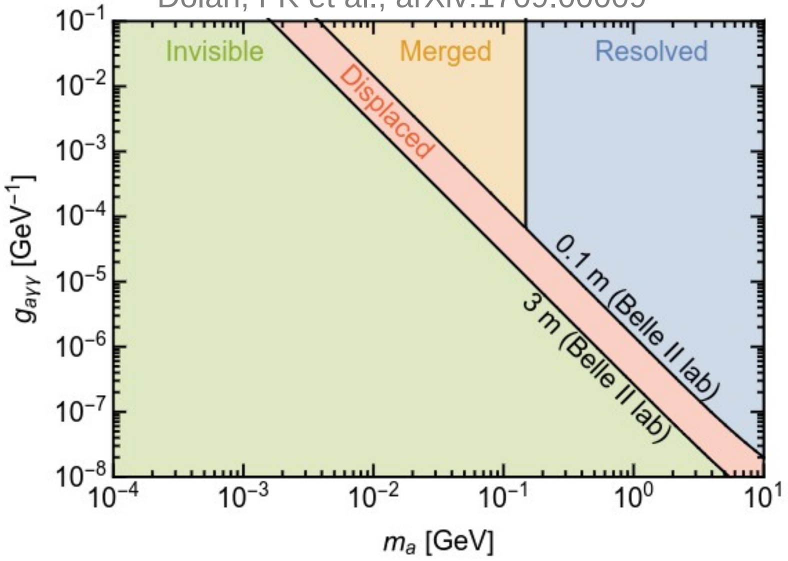


Phenomenology: Lifetime

- 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

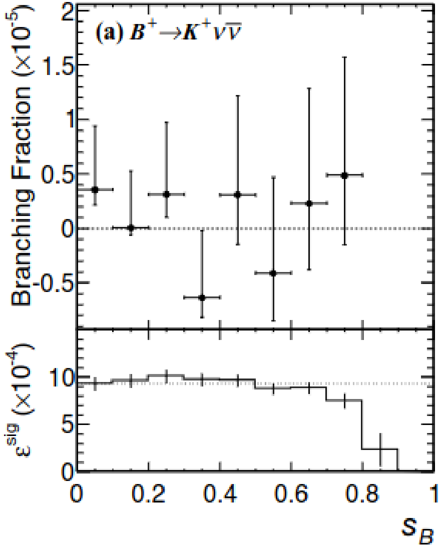
Dolan, FK et al., arXiv:1709.00009



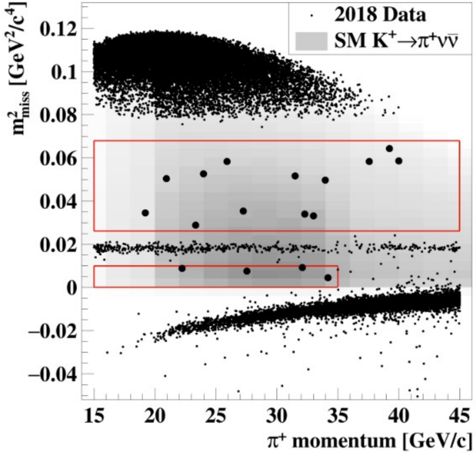
- Note: Missing energy signatures also arise from FIPs decaying into DM

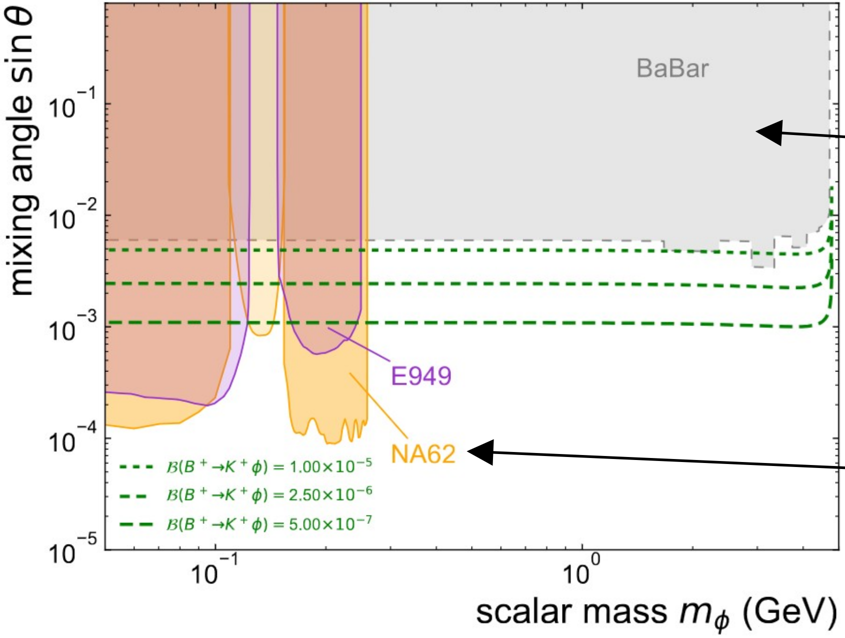
Example 1: Invisibly decaying dark scalars

BaBar, arXiv:1303.7465



NA62, arXiv:2103.15389





Ferber, Grohsjean & FK, arXiv:2305.16169

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?
- Largest pull in narrow range of q^2_{rec}
- Resolution of q^2_{rec} for inclusive tag not publicly available

  → Dedicated analysis highly welcome!

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

B → Kνν at Belle II (notes)

- FIPs may also give rise to broad distribution of q^2
  - Example 1: Dark scalar with large invisible width (i.e. coupling to DM)
  - Example 2: Dark scalar with $m_S > m_B - m_K$

    → Rare B decay through off-shell dark scalar

    → Invariant momentum distribution similar (but not identical) to B → Kνν

Bird et al., arXiv:hep-ph/0601090

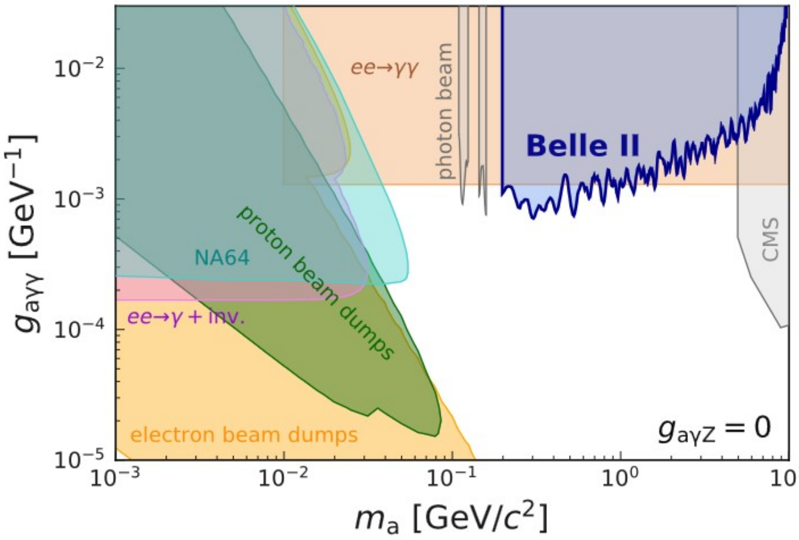
- Model-independent analysis (or details for recasting) required

Example 2: Long-lived axion-like particles

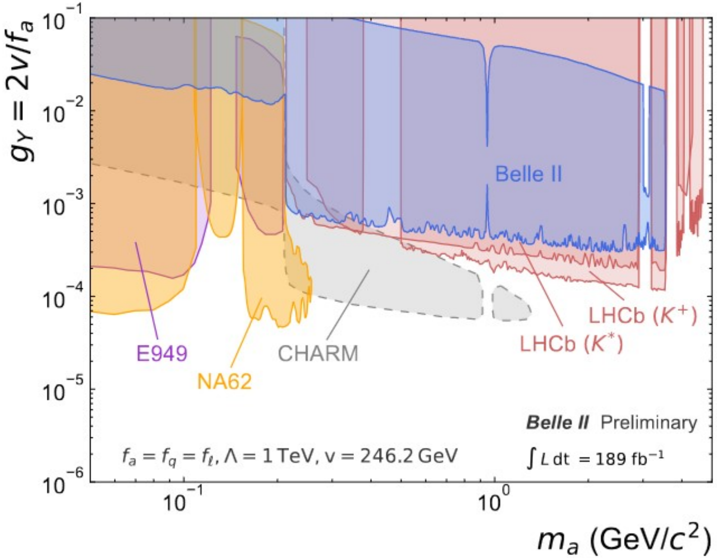
- Two scenarios:

Photon dominance (direct production)

Fermion dominance (B decays)



Belle II, arXiv:2007.13071

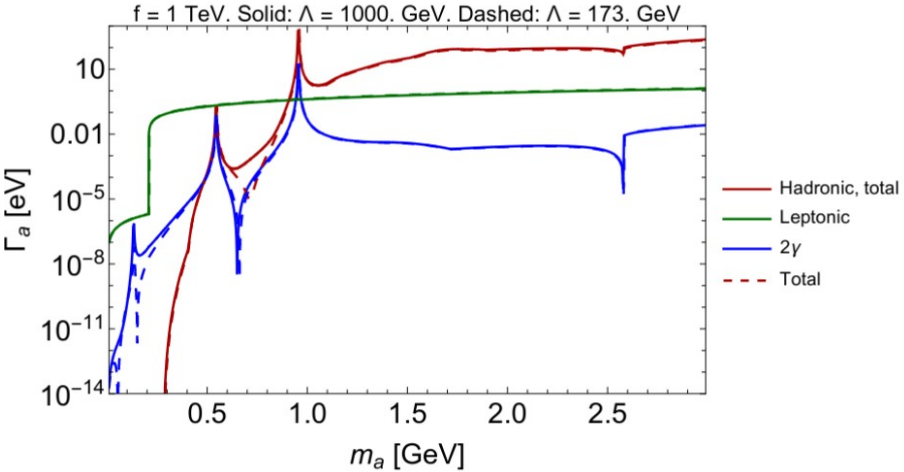


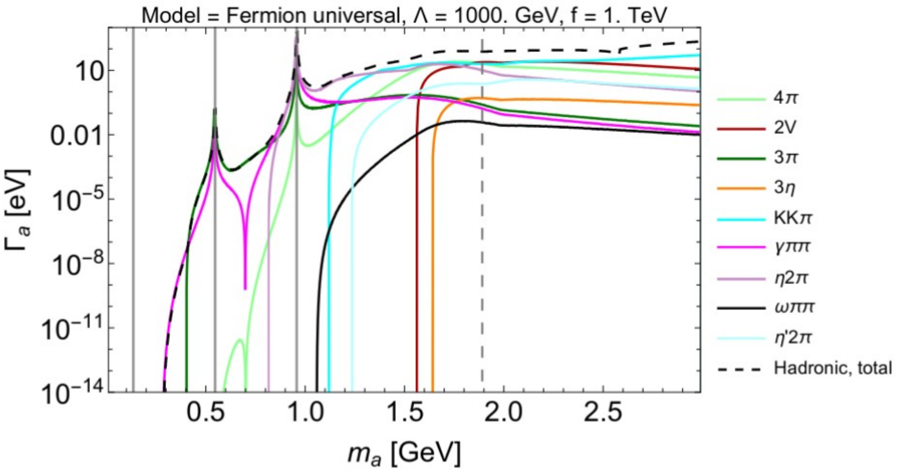
Belle II, arXiv:2306.02830

Axion-like particle decays modes

- CP conservation forbids decay models a → ππ or a → KK
- Common assumption: Leptonic decay modes dominate Dolan, FK et al., arXiv:1412.5174
- Only true below 1 GeV

FK, Garcia, Ovchynnikov and Zaporozhchenko (in preparation)

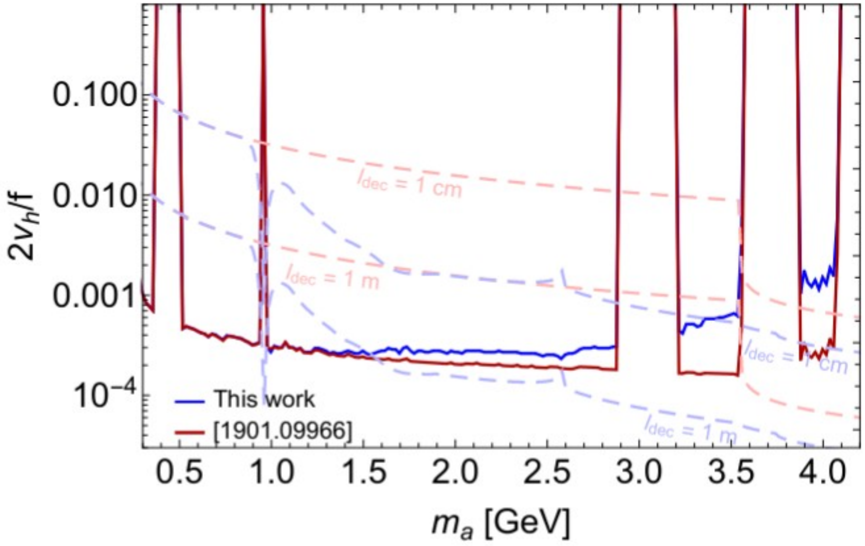




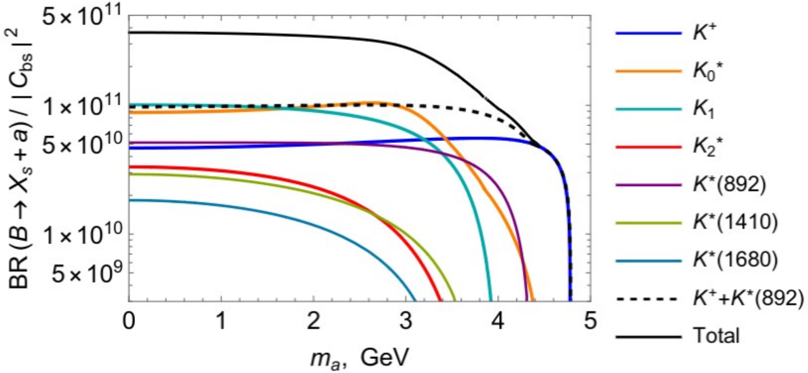
Improved constraints

- Accurate calculation leads to suppressed branching into leptons
- Constraints from LHCb weakened significantly.

FK, Garcia, Ovchynnikov and Zaporozhchenko (in preparation)

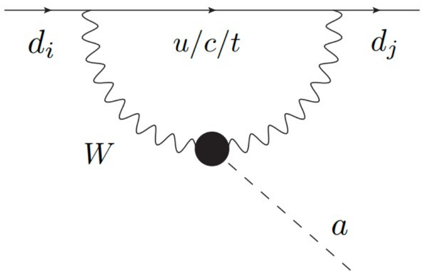


- What about Belle II?
- Opportunity: Look for exclusive B decays and new final states



Gluon and W boson dominance

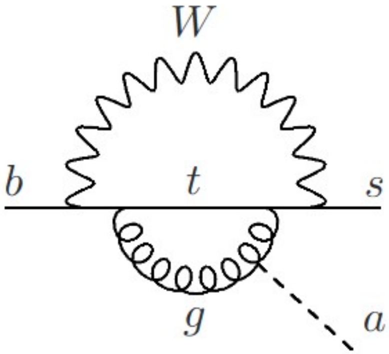
- ALPs coupled to gluons or *W* bosons can also be produced in *B* meson decays



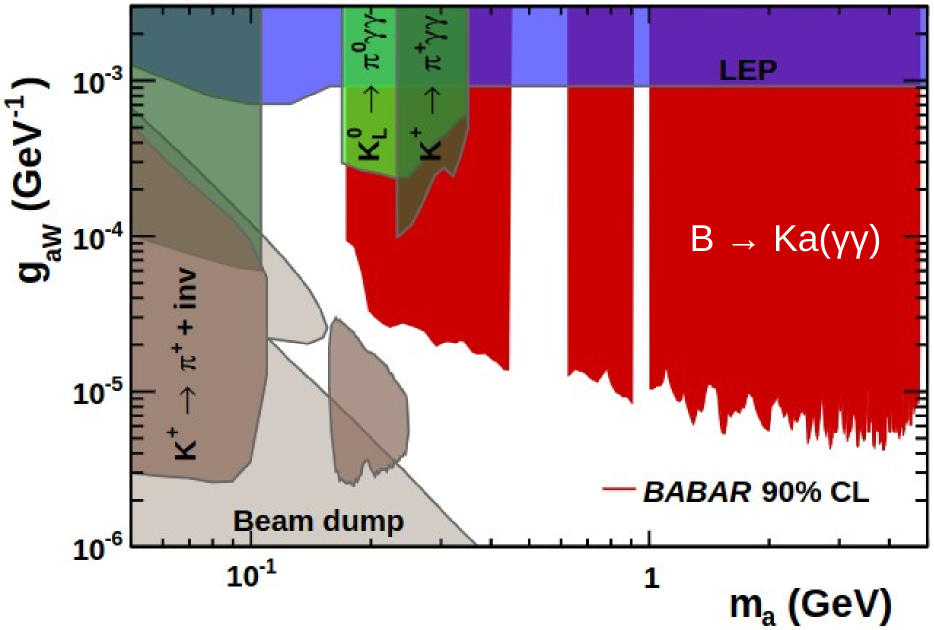
- However, they do not decay into leptons at all!

- W boson coupling: Dominant decay into photons

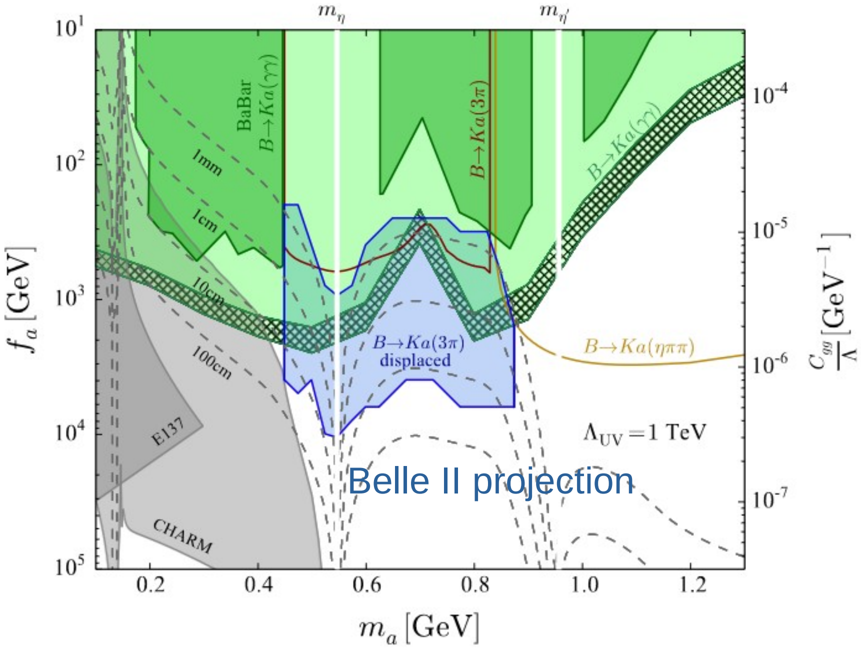
- Gluon coupling: Dominant decay into hadrons



New final states in rare B decays



BaBar, arXiv:2111.01800



Bertholet et al., arXiv:2108.10331

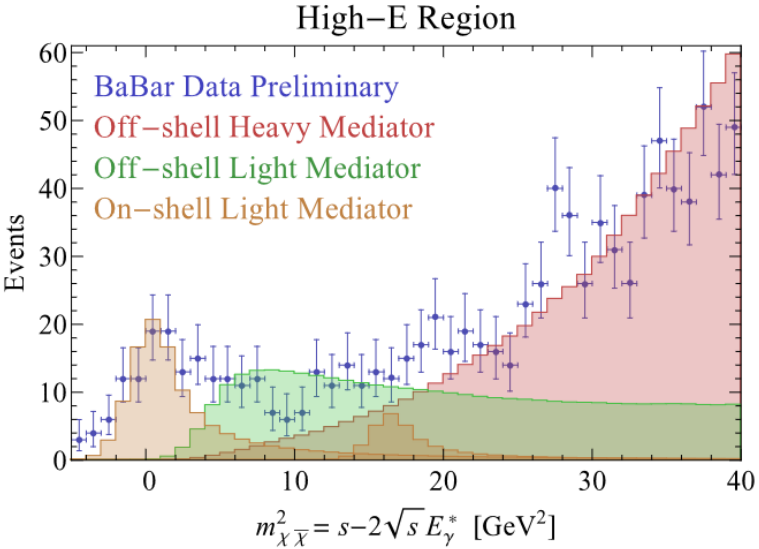
Example 3: Dark photons in rare decays

- Sensitivity to GeV-scale dark photons dominated by couplings to leptons (e.g. $e^+ e^- \rightarrow A' \gamma$)

- What if the dark photon is too heavy to be produced on-shell?

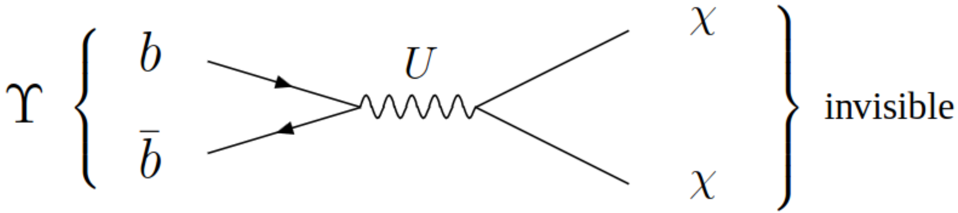
  → Substantial loss in sensitivity

Belle II projections studied in
Bernreuther et al., arXiv:2203.08824



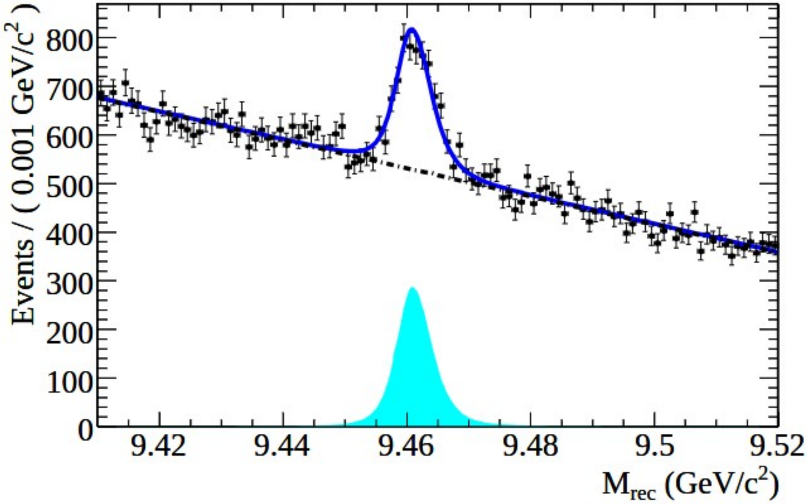
Essig et al., arXiv:1309.5084

Radiative Y decays



Fayet, arXiv:0910.2587

BaBar: arXiv:0908.2840



- Production of Y(1S) identified through pions produced in decay of heavier Y resonances
- Current bound: B(Y(1S) → inv) $< 3.0 \times 10^{-4}$
- Standard Model: B(Y(1S) → inv) $\approx 1 \times 10^{-5}$

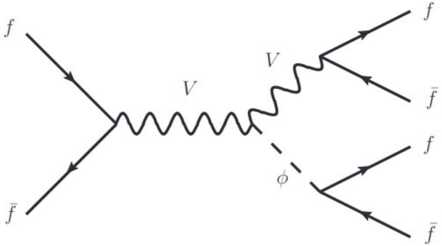
How do GeV-scale FIPs get their mass?

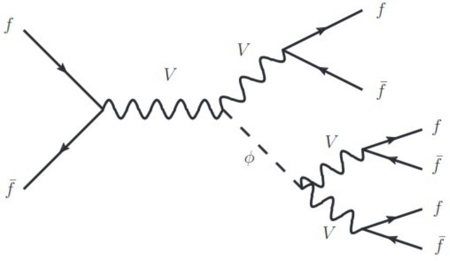
- Attractive possibility: Dark Higgs mechanism
- Complex dark scalar obtains vev & breaks U(1)’ gauge symmetry
  - Gauge interactions: Dark photon mass
  - Yukawa interactions: Dark matter mass
- Mixing between dark Higgs boson and SM Higgs boson:

$$\begin{aligned} h &\to \cos\theta\, h + \sin\theta\, \phi \\ \phi &\to -\sin\theta\, h + \cos\theta\, \phi \end{aligned} \qquad \theta \approx \frac{\lambda_{h\phi}\, v\, w}{m_h^2 - m_\phi^2}$$

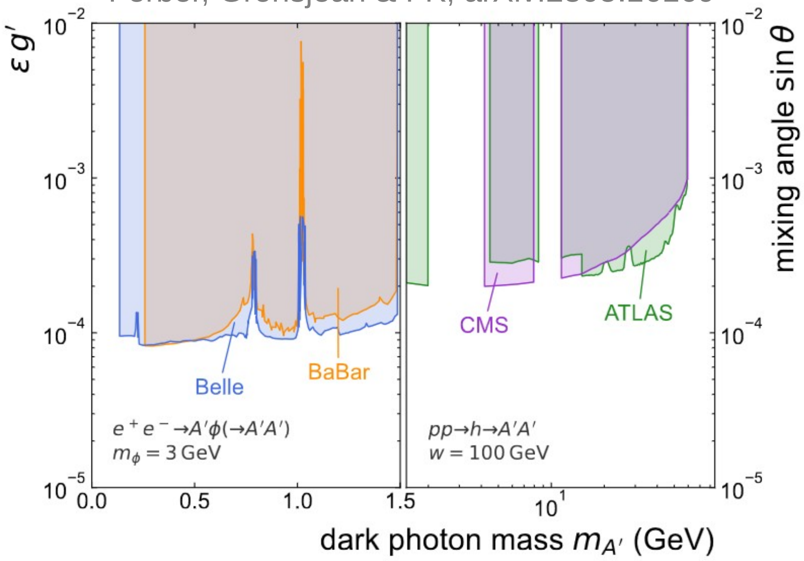
Dark Higgs bosons at colliders

- Consequence 1: New collider signatures





Ferber, Grohsjean & FK, arXiv:2305.16169



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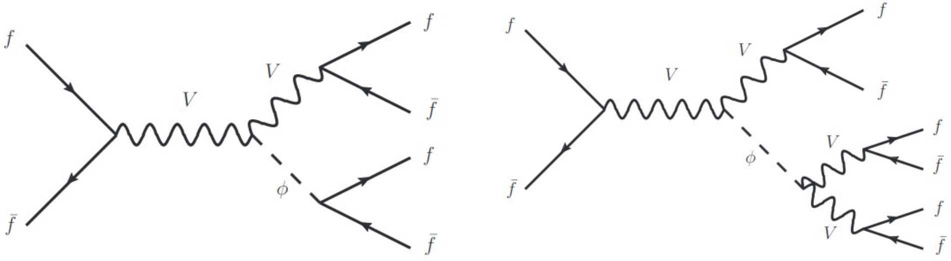
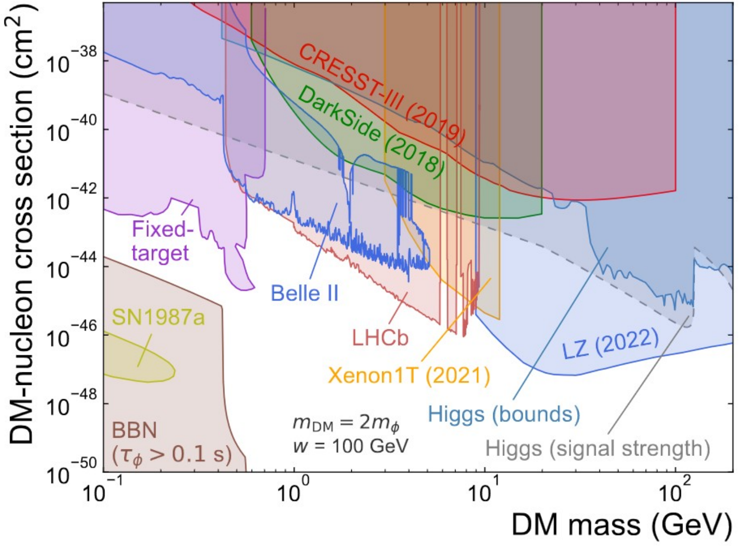


- Consequence 2: New DM interactions
  - Annihilation (DM DM → SM SM)
  - Scattering (DM SM → DM SM)

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
  - are produced in rare meson decays and decay into variety of final states

- Belle II offers the ideal environment to perform a broad range of searches for FIPs and provide model-independent constraints