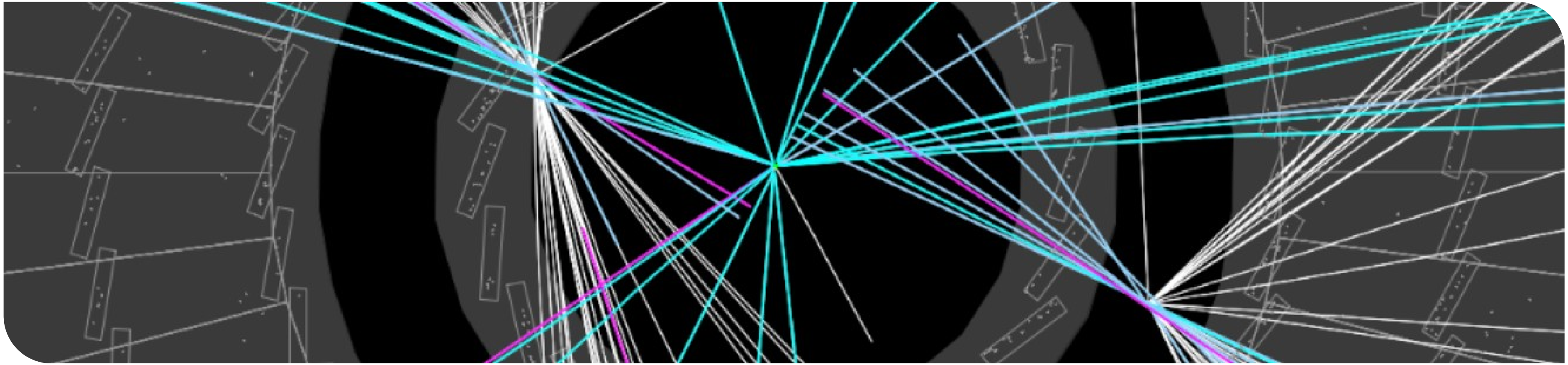
Hidden Sectors benchmark models and status

Felix Kahlhoefer
Synergy workshop between ep/eA and pp/pA/AA physics experiments
CERN, 1 March 2024



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:

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

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Portal interactions

- Light particles must be gauge singlets
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$F^Y_{\mu\nu}$ → $$\mathcal{L}_{\text{int}} = \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu}$$ Dark photon

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

LH → $$\mathcal{L}_{\text{int}} = y_{ij} L_i H N_j$$ 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)

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

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

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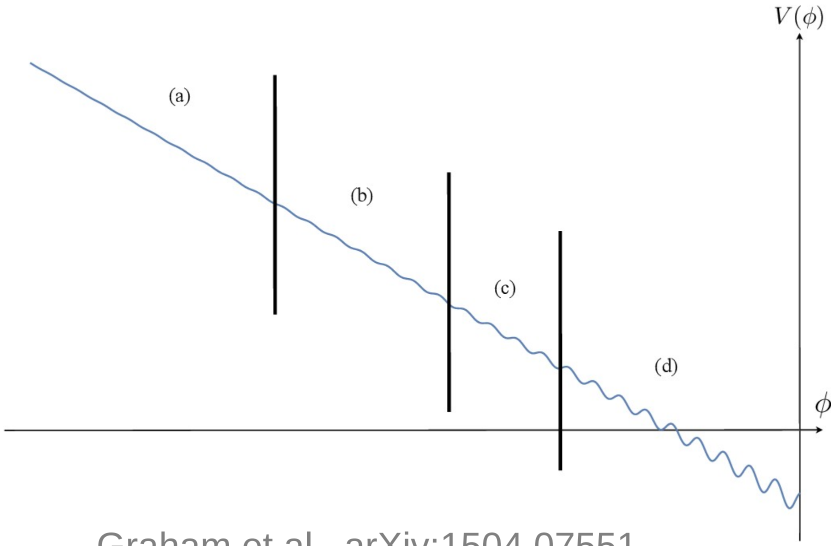
Theory example 1: Hierarchy problem

- 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

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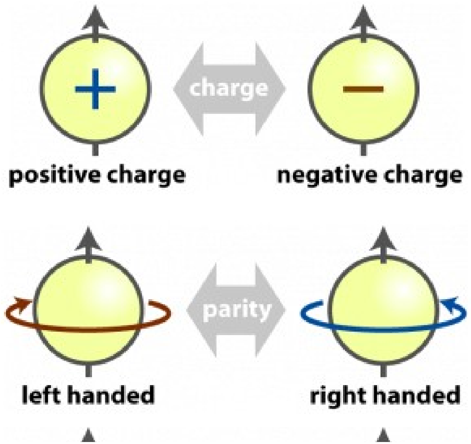
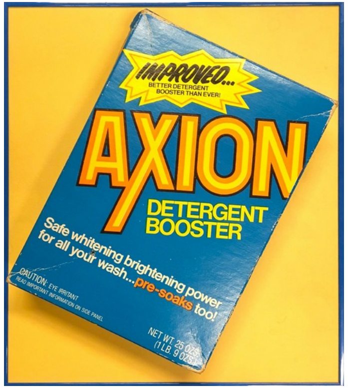
Theory example 2: Strong CP problem

- 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

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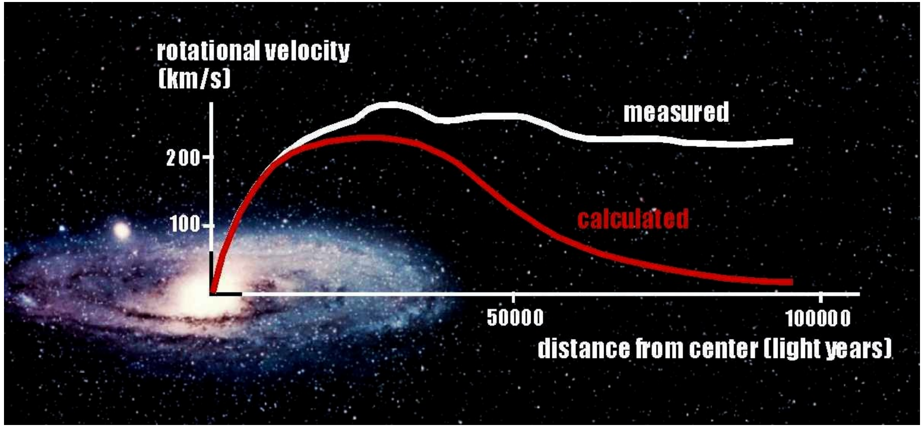
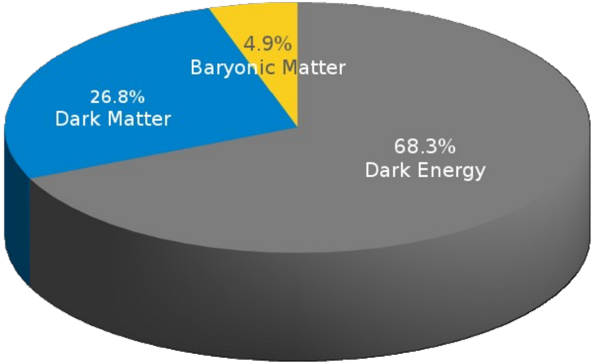
Experiment example 2: Dark matter

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



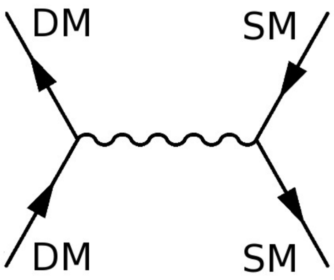


- There must be about 5 times more dark than visible matter to explain observed amounts of structure in the present universe

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



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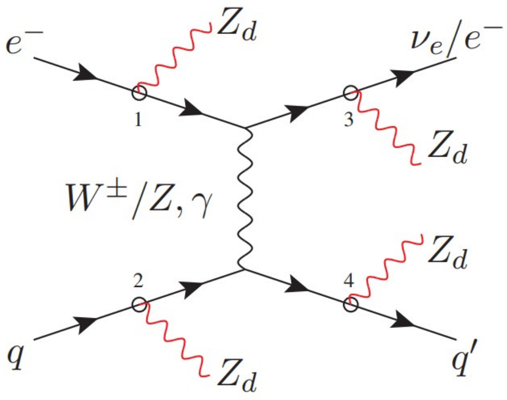
Why electron-hadron colliders?

- Sufficient centre-of-mass energy to probe particles masses above 10 GeV (i.e. beyond the reach of B factories)
- Sufficiently clean environment to observe complicated final states (which face overwhelming backgrounds at proton colliders)
- Unique production processes and/or signal enhancement

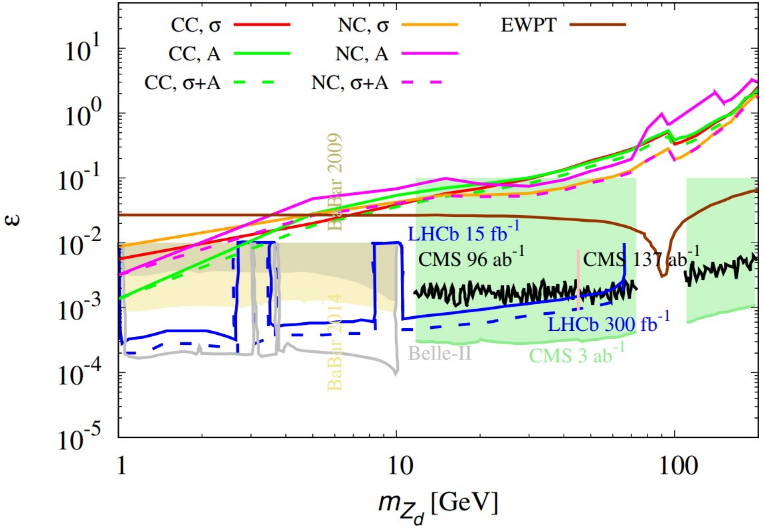
New particles in the 10–100 GeV mass range

- **Example:** Dark photons with kinetic mixing



- **Idea:** Any particle that can produce a photon can instead produce a dark photon with probability ε

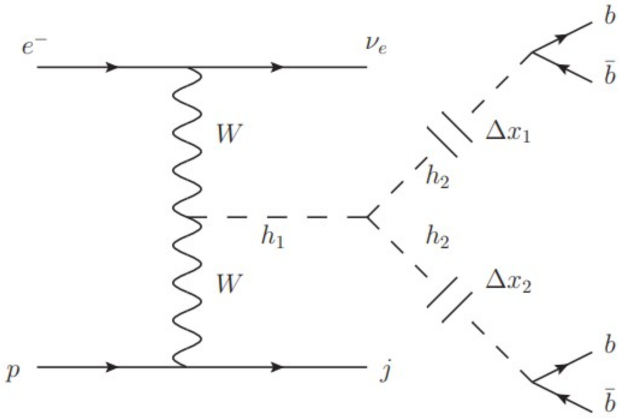
Goyal et al., arXiv:2209.03240



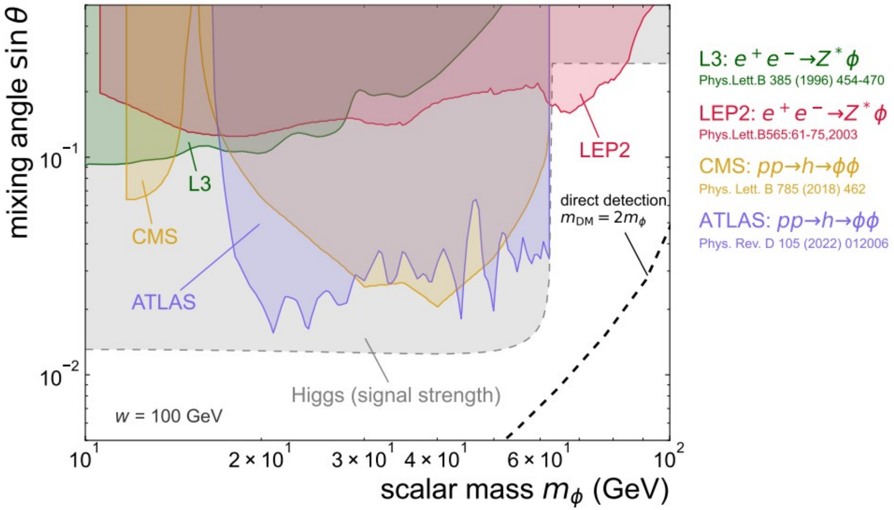
- So far not studied in detail. First study suggests uphill battle for electon-hadron colliders (LheC with L = 1 ab^{-1})

Exotic final states

- **Example:** Dark Higgs boson mixing with SM-like Higgs boson



- **Idea:** Decay of SM-like Higgs boson into pair of dark Higgs bosons, which decay into b quarks



- Leading constraints from Higgs signal strength requires sin θ < 0.01

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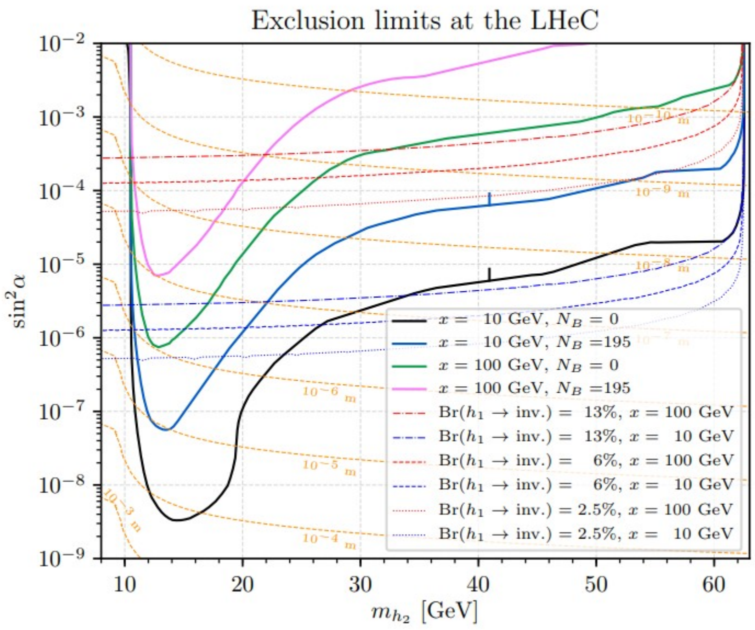
Displaced jets at the LHeC

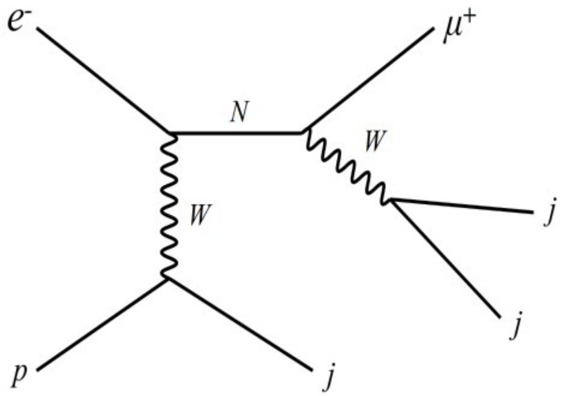
- LHeC provides clean environment for displaced hadronic vertices
- Unique opportunity to search for dark Higgs bosons between 10 and 30 GeV
- In optimistic scenarios sensitivity down to sin θ < 10^{-4}
- Model-independent analysis also possible



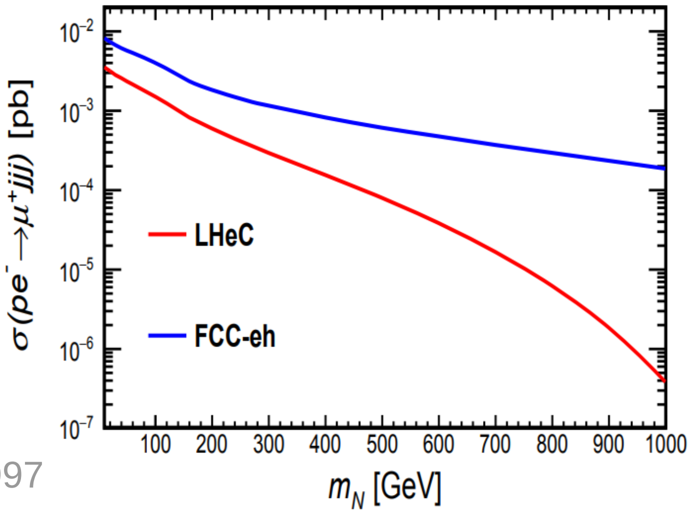
Cheung et al., arXiv:2008.09614

New production modes

- **Example:** Heavy neutral leptons



- **Idea:** Production possible via t-channel W boson (at LHC: only s-channel production)



- Promising final states: μ+3j or τ+3j

Gu et al., arXiv:2201.12997

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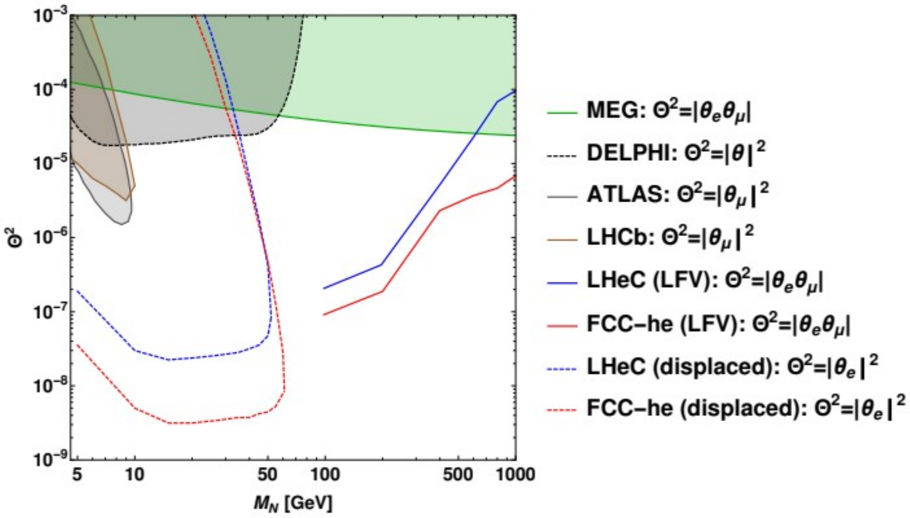
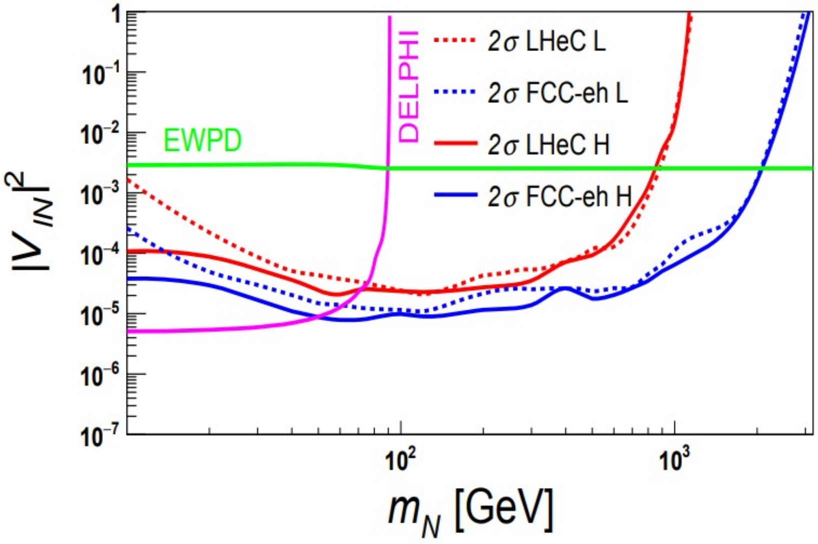
Heavy neutral leptons at LHeC and FCC-eh

Coupling to electrons and muons
Antusch et al., arXiv:1908.02852



Coupling to electrons and taus
Gu et al., arXiv:2210.17050



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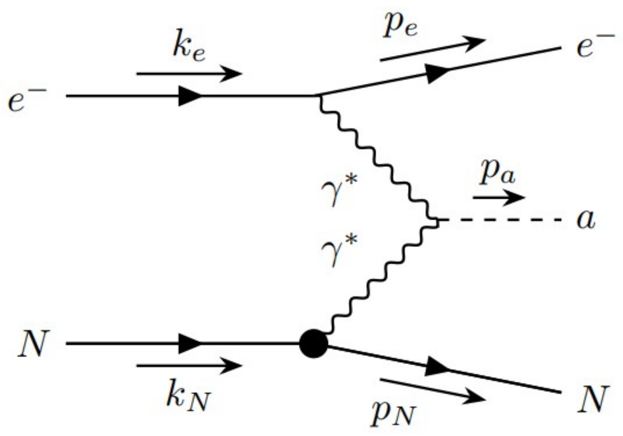
Signal enhancement

- **Example:** Axion-like particle coupled to photons

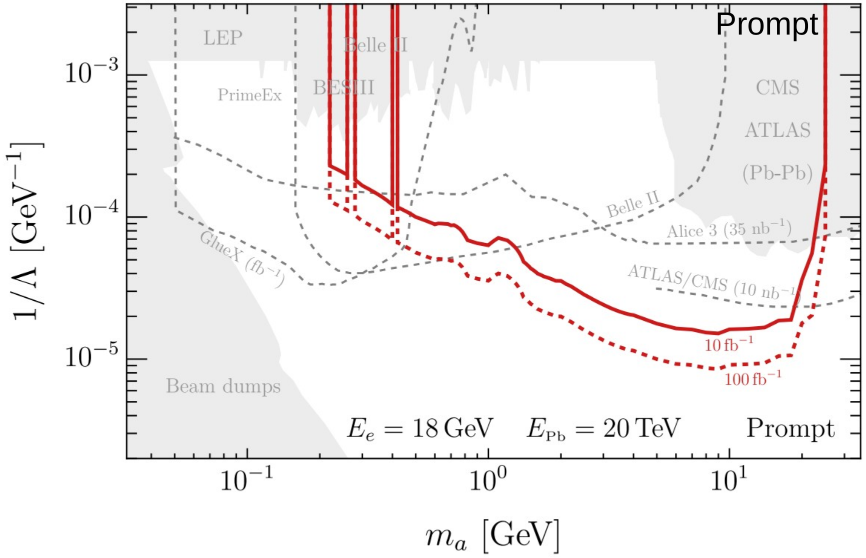


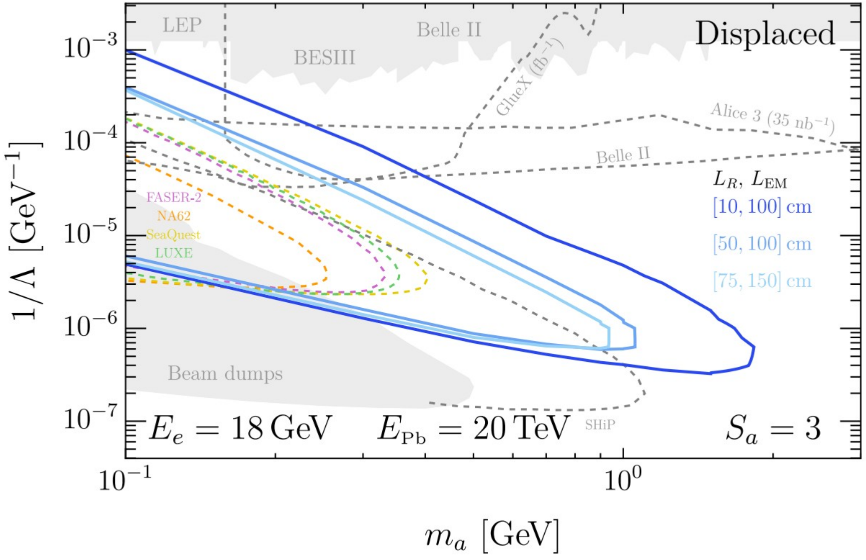
- Idea: Coherent production through photons that couple to the entire nucleus rather than to individual protons
  - → Cross section enhancement proportional to Z^2 (rather than Z)
  - → Effect used to search for ALPs in Pb-Pb collisions at LHC

Knapen et al., arXiv:1709.07110

Axion-like particles from photon fusion

- So far only e-p considered for LheC and FCC-eh — Yue et al., arXiv:1904.10657
- Recent study of e-A in the context of EIC by Balkin et al. (arXiv:2310.08827)





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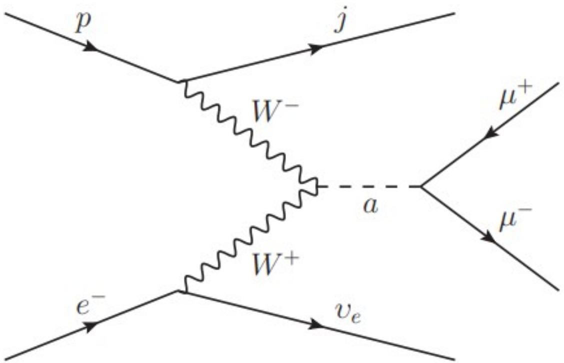
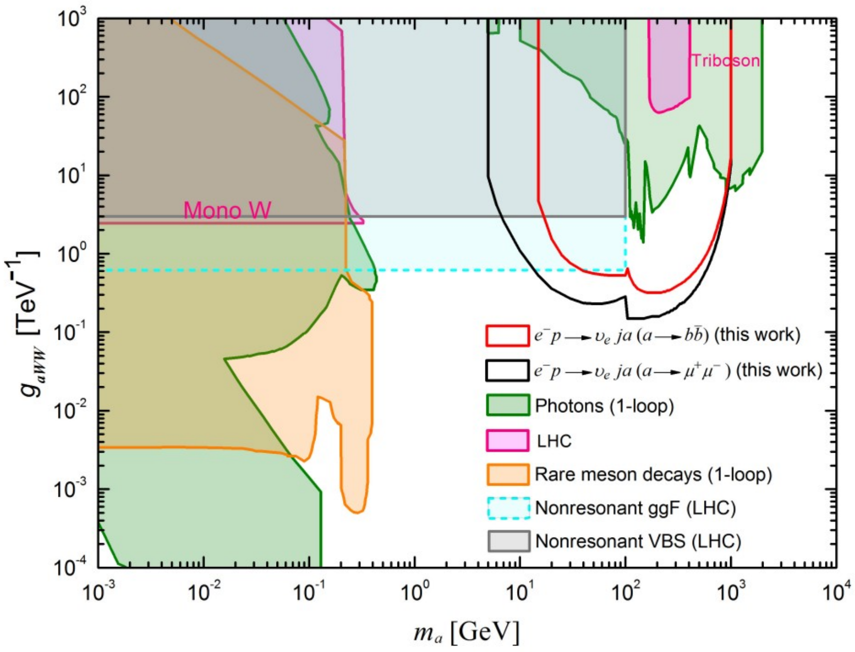
Axion-like particles with other couplings

- Also of interest: ALPs with couplings to W bosons and fermions

Yue et al., arXiv:2305.19561





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 analogous ways to SM counterparts and decay into variety of final states

- Electron-hadron colliders offer a promising environment to perform a broad range of searches for FIPs and provide model-independent constraints