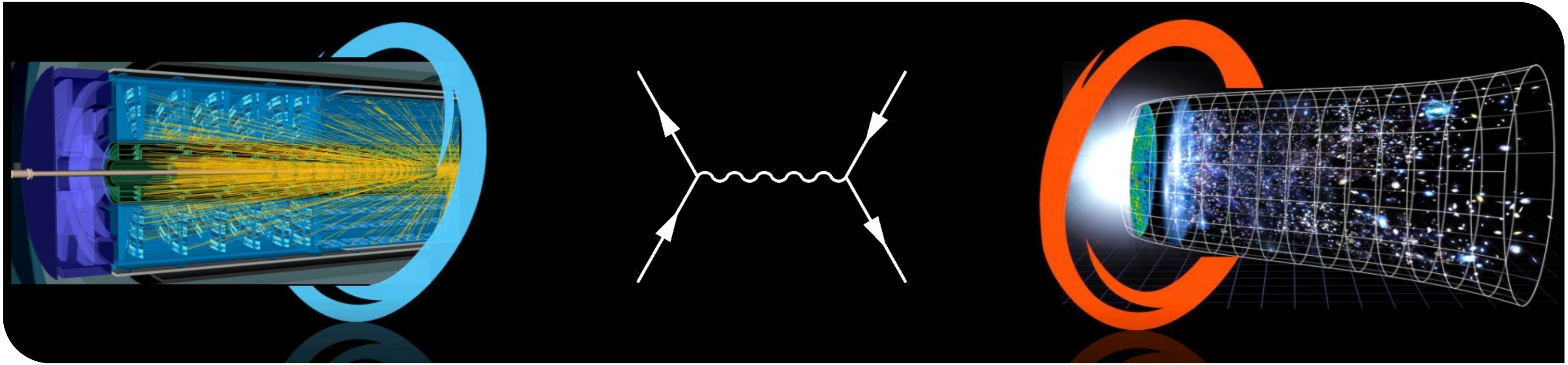
Dark sectors at accelerators

Felix Kahlhoefer

Dark Tools

Torino, 18 June 2025



Outline

- Introduction on dark sectors
- Dark sector searches at the LHC
- Dark sector searches at B factories
- Dark sector searches at beam-dump experiments
- Tools and reinterpretation
- Global fits
- Outlook

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Dark sectors: Definition

Dark matter particles do not appear in isolation, but together with other (unstable) particles

The interactions between these particles are (much) stronger than their couplings to the SM

Examples:

- Extended gauge groups:
  - DM charged under new (Abelien or non-Abelian) gauge group, while SM particles are uncharged
- Dark Higgs mechanism:
  - DM particle obtains its mass from the vacuum expectation value of a (SM singlet) scalar field
- Inelastic DM:
  - DM particle comes with heavier excited states that decay into DM and SM particles

- In realistic models, several (or all) of these features may appear together
  - **Example:** Dark Higgs breaks new gauge symmetry and/or generates mass splitting

Dark sectors: Definition (part 2)

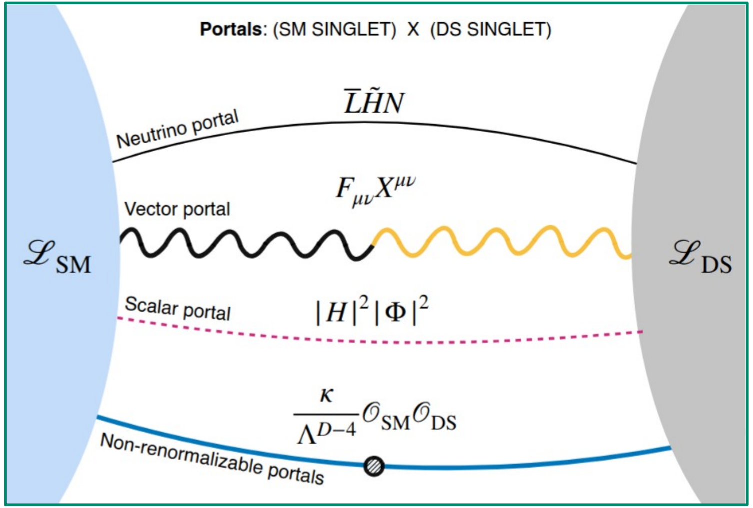
- To realise feeble coupling between dark and visible sector, all dark sector particles must be SM singlets

  ➞ They can only couple to gauge-invariant SM operators

- Only 3 possible combinations with d < 3:

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

Abdullahi et al., arXiv:2505.05663



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

$\bar{\psi}\gamma_\mu\psi$ $\quad$ $\bar{\psi}\gamma_\mu\gamma_5\psi$ ⟶ Coupling to Z’ gauge bosons and axion-like particles

Dark sectors: Motivation

- Given complexity of the visible sector (making up only 5% of the present universe), it seems preposterous to assume that the dark sector (25% of the present universe) is much simpler

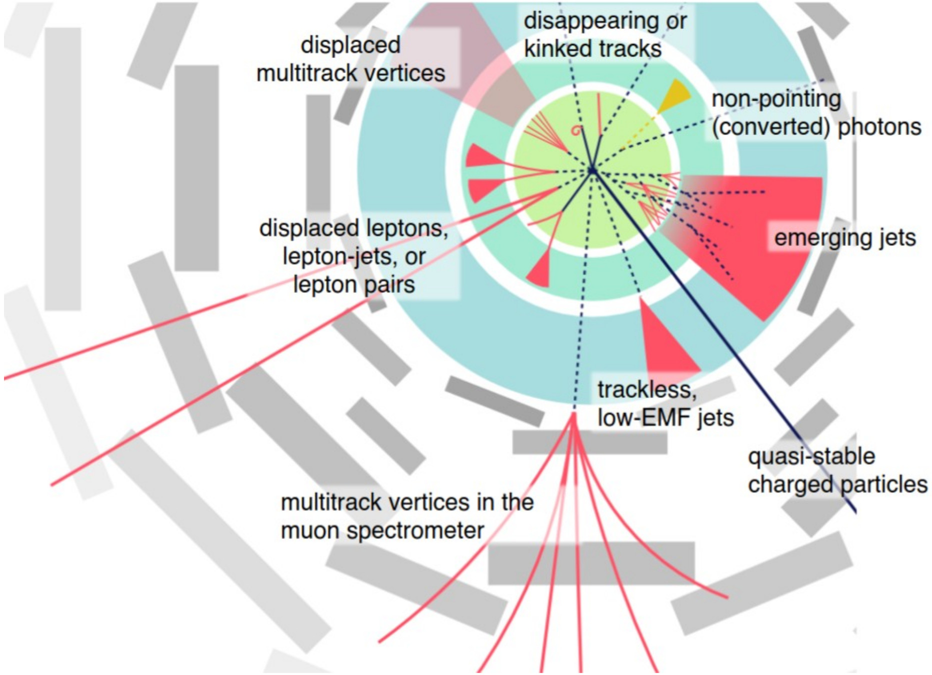
- Interactions within the dark sector open up new possibilities to set the DM relic abundance
  - Secluded annihilations
  - Number-changing processes
  - Conversion processes

- Dark sectors may address experimental/observational anomalies
  - Hints for a new particle with m_X = 17 MeV at ATOMKI and PADME
  - Excesses in $B \to K$ + invisible and $K \to \pi$ + invisible
  - INTEGRAL 511 keV excess
  - Nano-Hertz gravitational waves
  - Cosmological tensions (Hubble constant, time-dependet dark energy, neutrino masses)

Dark sectors: Phenomenological features

- Dark matter particles produced at accelerators carry away part of the collision energy
  - ➞ Search for missing (transverse) energy
- But not all dark sector states are stable (i.e. invisible)
  - ➞ Search for new resonances and/or high-multiplicity final states
- Unstable dark sector states may have small masses and/or tiny couplings
  - ➞ Expect long lifetimes
  - ➞ Search for displaced vertices and other exotic signatures

Alimena et al., arXiv:1903.04497



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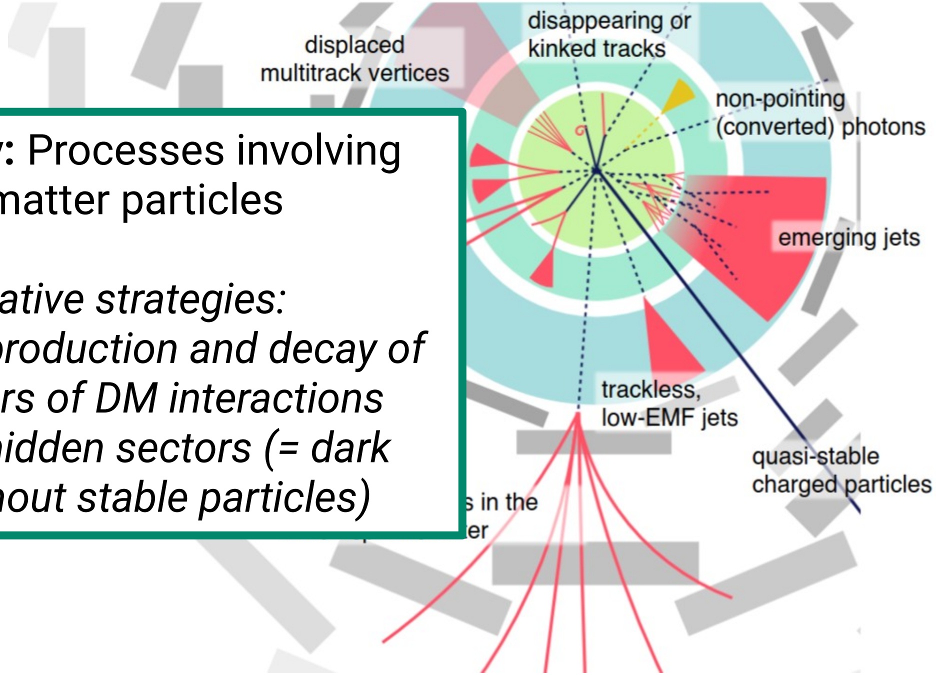

Focus today: Processes involving dark matter particles

Alternative strategies:
- *Search for production and decay of the mediators of DM interactions*
- *Search for hidden sectors (= dark sectors without stable particles)*

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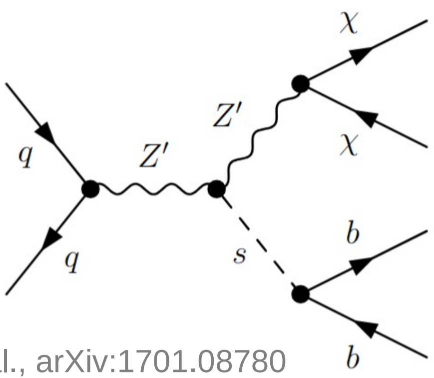
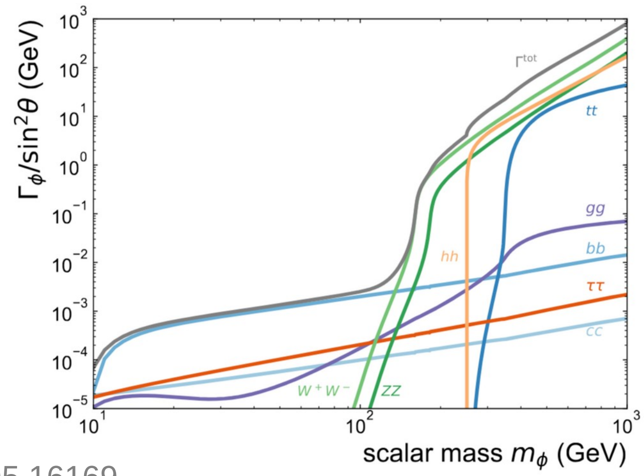
Dark Higgs bosons at the LHC

- Consider complex scalar field Φ and fermion χ charged under new U(1)’ gauge group
- Scalar field obtains vev: $\Phi = (s + w)/\sqrt{2}$
  - → Spontaneous breaking of gauge symmetry
  - → Generation of gauge boson mass and DM mass
- Consider the case $m_{Z'} > 2\, m_\chi > 2\, m_s$
  - → Z' decays into other dark sector states
  - → Dark Higgs boson decays into SM states via Higgs mixing
  - → Branching ratios inherited from SM Higgs boson
  - → Additional decay mode: $s \to hh$



Duerr, FK et al., arXiv:1701.08780



Ferber, Grohsjean & FK, arXiv:2305.16169

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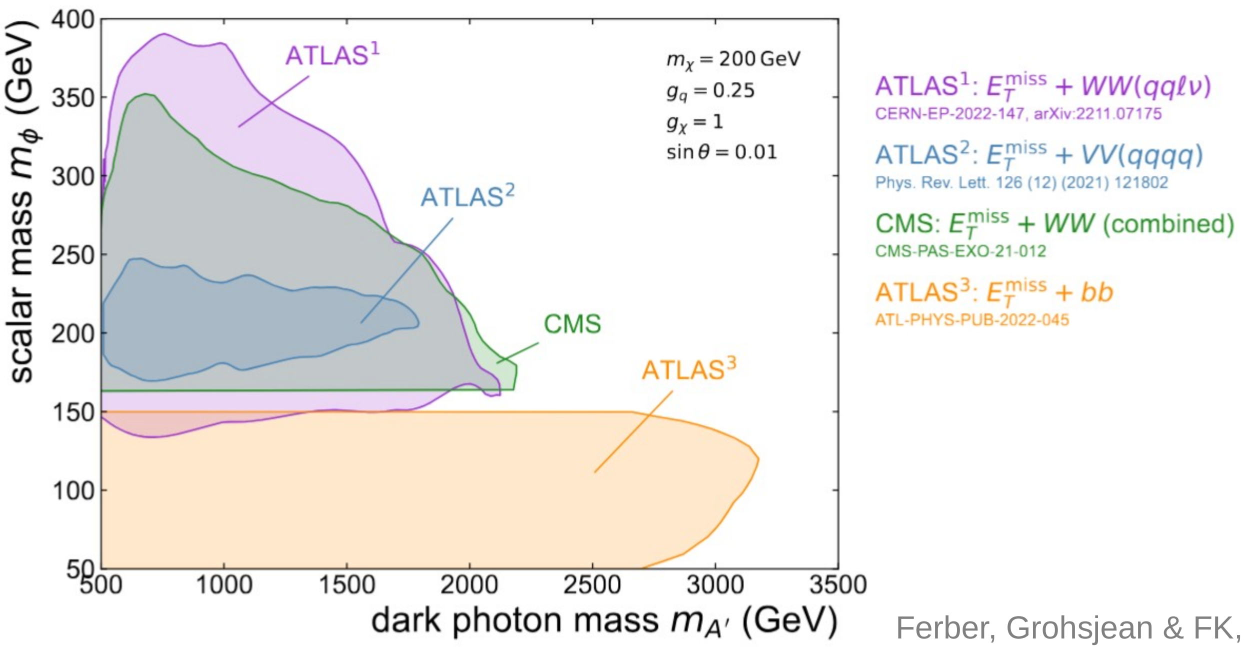
Signature: Resonance + missing E_T

- Most favourable final state depends on dark Higgs boson mass
- Various searches have been carried out (+ more ongoing)

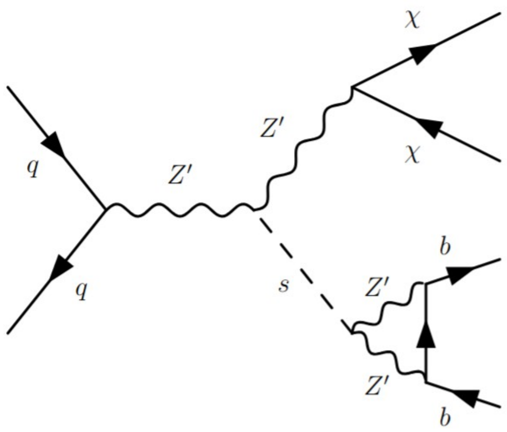


Ferber, Grohsjean & FK, arXiv:2305.16169

Dark Higgs variations: Loop-induced decays

- Assume negligible Higgs mixing
  → Dark Higgs boson decays through gauge-boson loops
  → Different branching ratios depending on Z' charges
  → No decays into SM gauge bosons

$$\Gamma(s \to q\bar{q}) = \frac{3\, g_q^4\, g_\chi^2\, m_s}{32\pi^5} \frac{m_q^2}{m_{Z'}^2} \left(1 - \frac{4m_q^2}{m_s^2}\right)^{3/2} \left| I\left(\frac{m_s^2}{m_{Z'}^2}, \frac{m_q}{m_{Z'}}\right)\right|^2$$



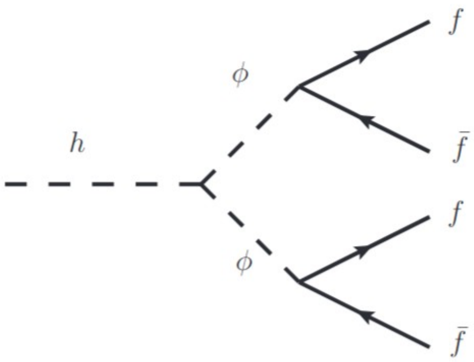
Bernreuther, FK et al., arXiv:2011.06604

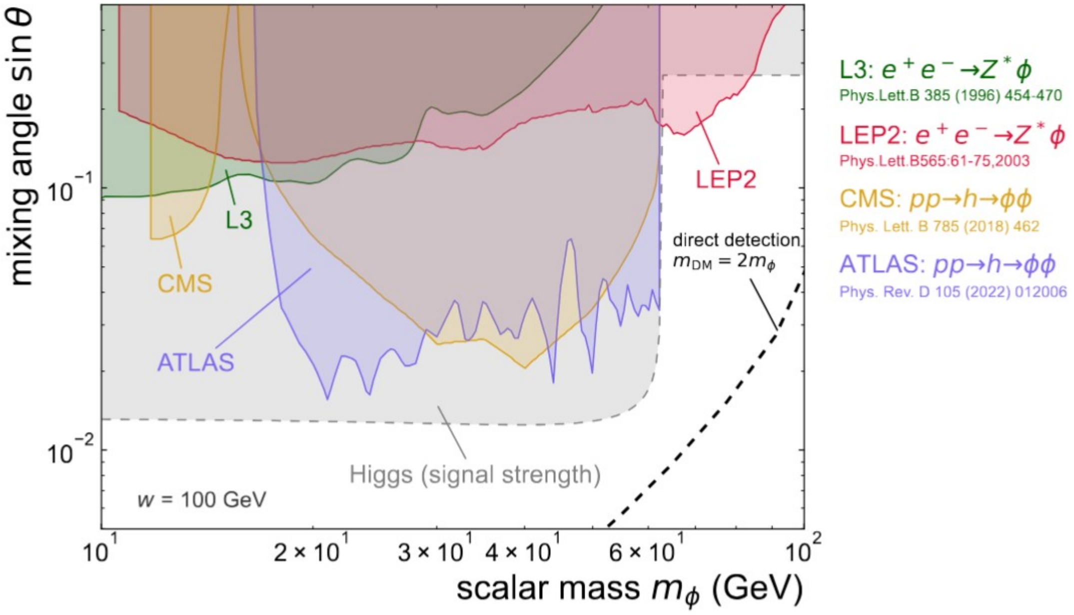
- Loop suppression increases dark Higgs boson lifetime
  → Signature: Single displaced vertex + missing E_T

- No targeted search for this model
- Model-independent searches difficult to reinterpret

Dark Higgs variations: Exotic Higgs decays

- For $m_s < m_h/2$, dark Higgs bosons can be produced in decays of the SM-like Higgs boson





- Direct searches not (yet?) competitive with model-independent bound on Higgs signal strength

Ferber, Grohsjean & FK, arXiv:2305.16169

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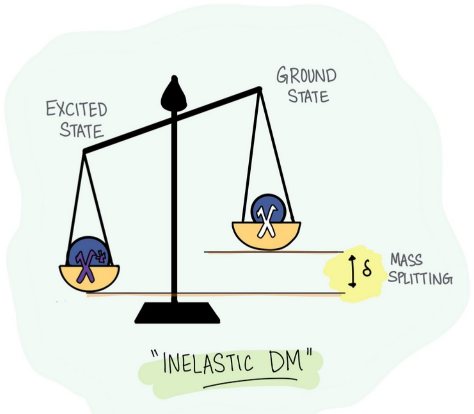
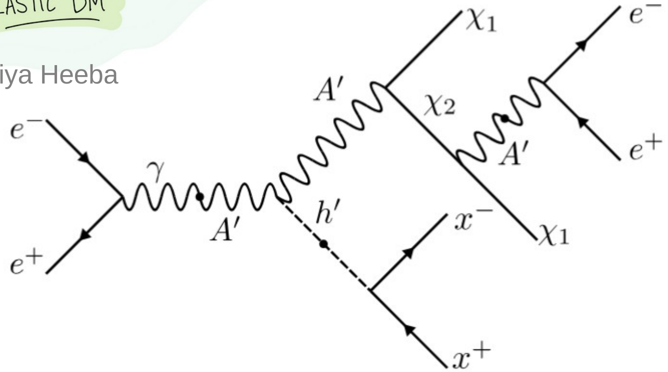
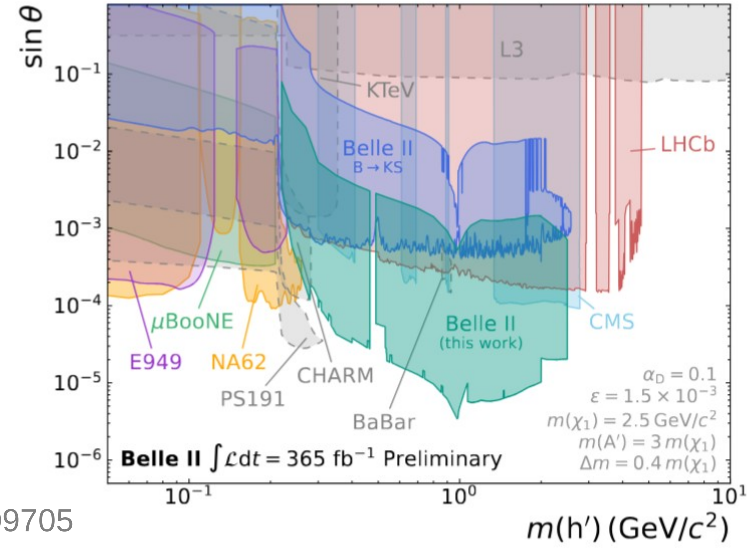
Dark Higgs variations: Inelastic dark matter

- Consider two DM particles χ and χ* with small mass splitting Δm
- Assume all interactions must involve both states
- Z’ boson decays into χχ*, followed by decay χ* → χ + SM
- So far no search at LHC, but recent result from Belle II



by Saniya Heeba





Belle II, arXiv:2505.09705

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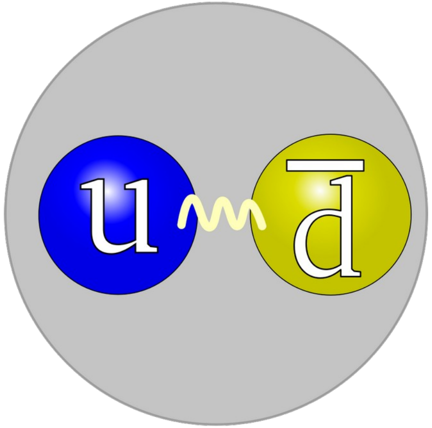
Strongly-interacting dark sectors

- Exciting alternative: Dark sector with non-Abelian gauge symmetry (like QCD)
- At high energies: dark sector **contains dark gluons and dark quarks:**

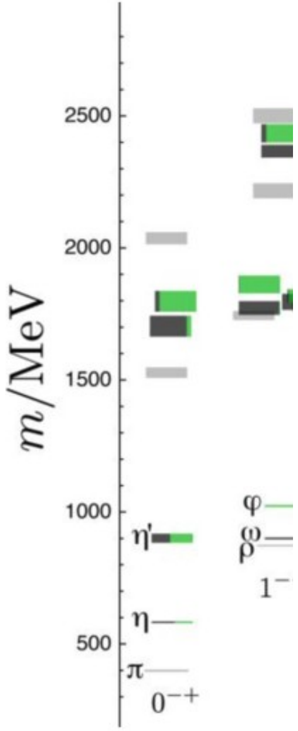
$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \overline{q}_\mathrm{d} i \not{D} q_\mathrm{d} - \overline{q}_\mathrm{d} M_q q_\mathrm{d}$$

- Quark masses small or comparable to confinement scale Λ_d
- At low energies: Confinement into dark mesons and baryons
- In case of particle-antiparticle asymmetry, dark baryons could be DM, otherwise they annihilate away



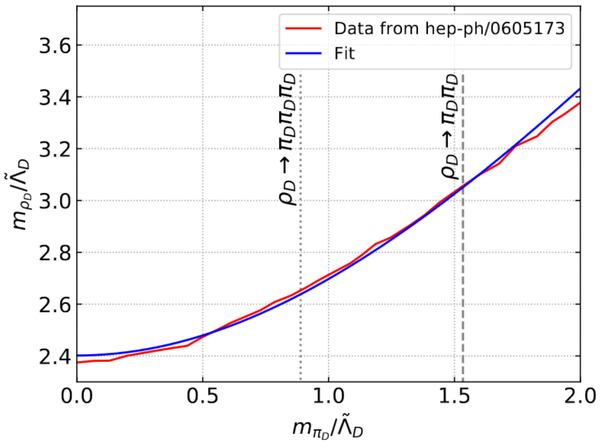
Cline & Perron, arXiv:2204.00033

Describing dark mesons



- Low-energy theory features many different states:
  - Dark pions (Pseudo-Goldstone bosons of chiral symmetry breaking)
  - ➞ Can be stable and viable DM candidates
  - Dark rho mesons (spin-1)
  - ➞ Generally expected to decay via mixing with other vector states
- Apparently many free parameters:
  - Masses of various dark mesons (dark pions, dark rho mesons, …)
  - Interactions between them
  - Interactions with SM particles
- Some guidance from lattice simulations.

Dark showers Snowmass report, arXiv:2203.09503



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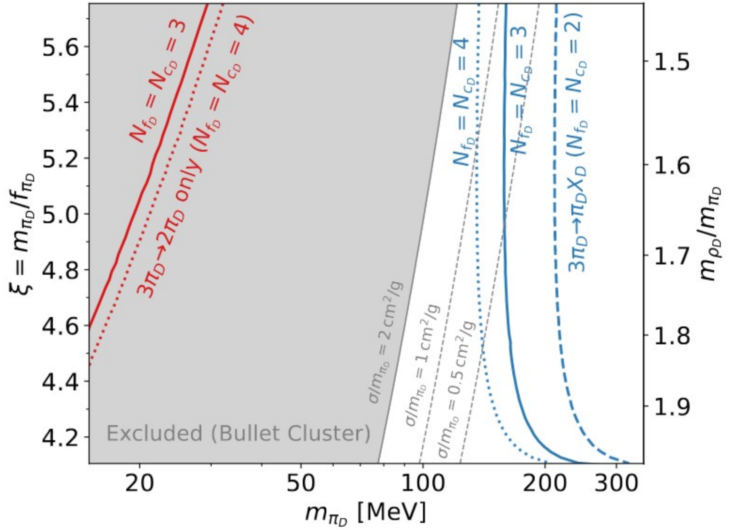
Dark meson relic density

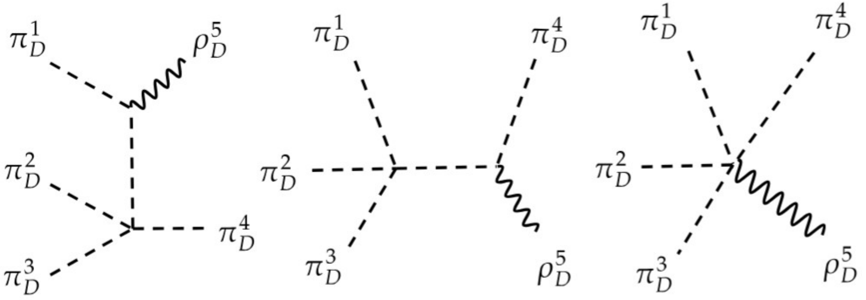
Bernreuther, FK et al., arXiv:2311.17157

- Combination of astrophysical constraints (Bullet Cluster) and cosmological data (relic density) prefer the case that $m_\rho < 2\, m_\pi$
  - ➙ Dark rho mesons cannot decay into pairs of dark pions
  - ➙ Mixing of dark rho meson with gauge bosons leads to effective coupling



$$\mathcal{L}_{\text{eff}} \supset \frac{2}{g}\frac{m_{\rho_d}^2}{\Lambda^2}\rho_d^{0\,\mu}\sum_f q_f \bar{f}\gamma_\mu f$$

- ➙ Dark rho mesons decay into SM particles
- ➙ Mix of visible and invisible final states



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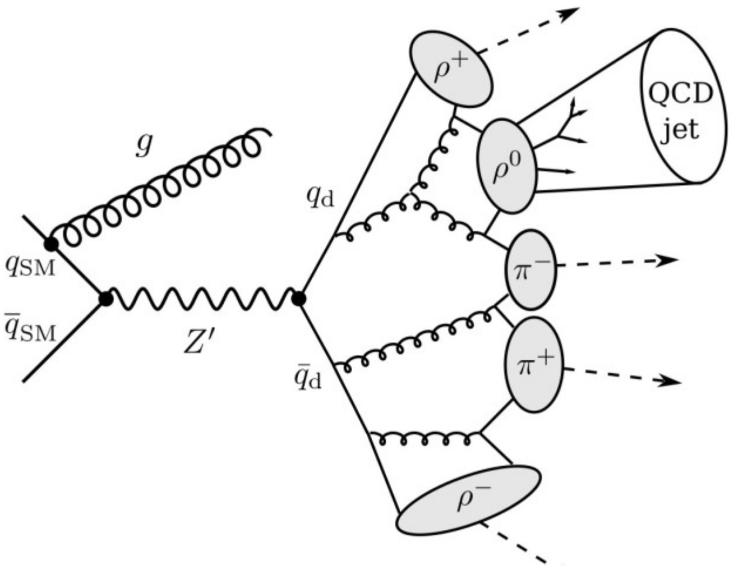
Dark showers

- At the LHC the dark quarks may be directly produced, followed by fragmentation and hadronisation in the dark sector



- Result: dark shower containing 10+ dark mesons
- Most dark mesons are stable and will escape from the detector
- Any ρ_0 meson will decay into SM particles and give rise to QCD jets (or leptons)

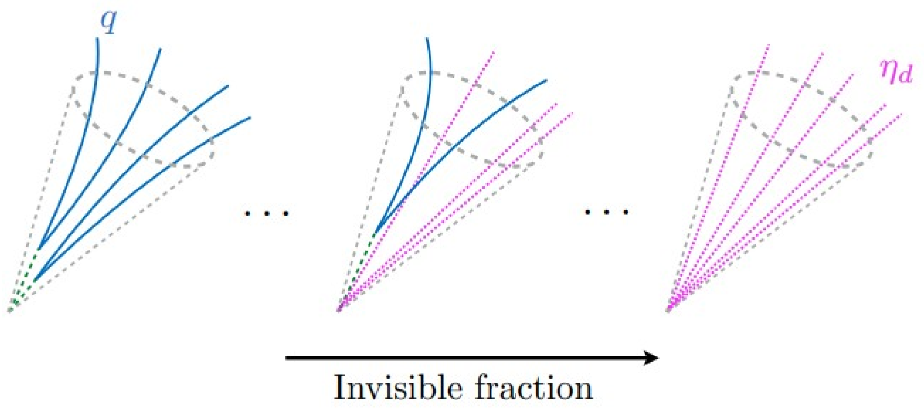
➞ Usually simulated with the Hidden Valley module of Pythia

Carloni et al., arXiv:1006.2911 & arXiv:1102.3795

➞ New development: Dark shower implementation in Herwig

Kulkarni et al., arXiv:2408.10044

Dark shower classification



Does the dark shower contain stable particles?

Are the unstable particles in the dark shower long-lived?

	No	Yes
No	QCD-like jets	Semi-visible jets
Yes	Emerging jets	Displaced vertex + MET

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Semi-visible jets

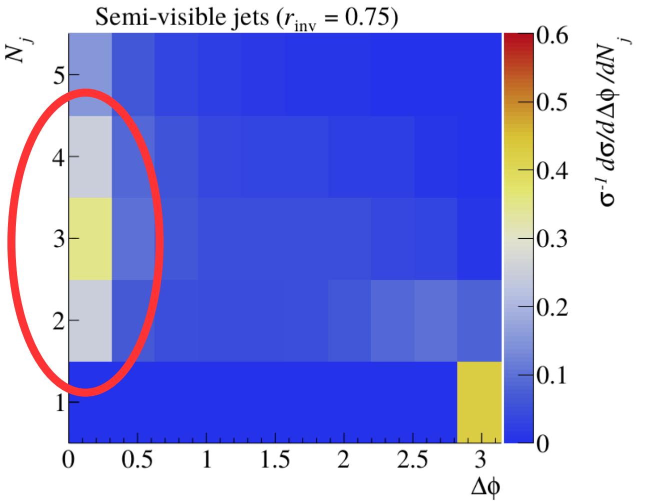
- **Peculiar feature:** Since missing energy and QCD jets arise from the same dark shower, they will often point in the same direction

- Unfortunately, events with small Δφ are vetoed in most analyses because of challenging backgrounds from misreconstructed jets

- **Strategy 1:** Use machine learning (e.g. graph neural networks) to distinguish semi-visible jets from QCD

  Bernreuther, FK et al., arXiv:2006.08639

- Strategy 2: Use event-level kinematic variables to suppress backgrounds



$$\Delta\phi = \min_j \Delta\phi(j, \not{E}_T)$$

Bernreuther, FK et al., arXiv:1907.04346

→ Many different signatures and searches

→ Very active research area with dedicated workshops

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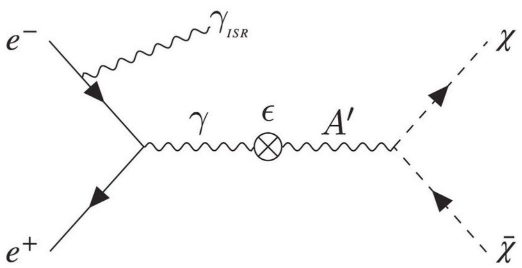
Dark sector searches at B factories

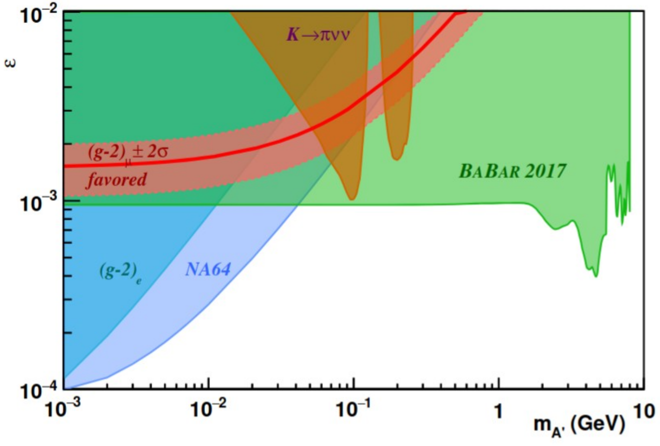
- Lower centre-of-mass energy ($\sqrt{s} \sim 10.6$ GeV) may be compensated by higher luminosity, cleaner initial state, lower backgrounds and better detection/reconstruction

  → Possible to directly search for missing energy (instead of missing transverse energy)



- Example: Single-photon search $e^+ e^- \to \gamma + A'$ ($\to$ invisible)
- Signature: Mono-energetic photon + missing energy
- BaBar gives strong constraint on dark sector models

BaBar, arXiv:1702.03327



- Search at Belle II ongoing

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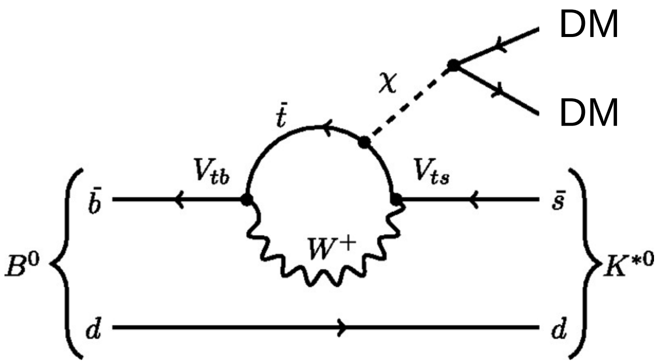
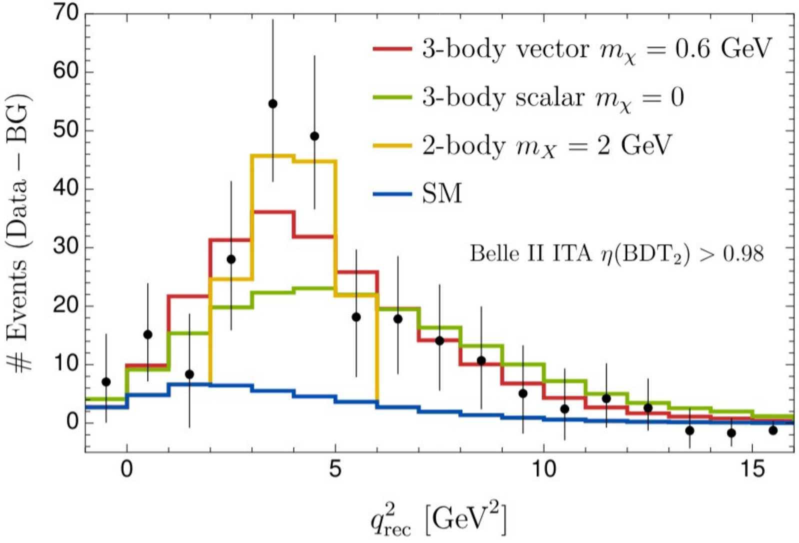
Dark sectors in rare decays

- Searches for the rare SM processes B → Kνν and K → πνν sensitive to dark sectors



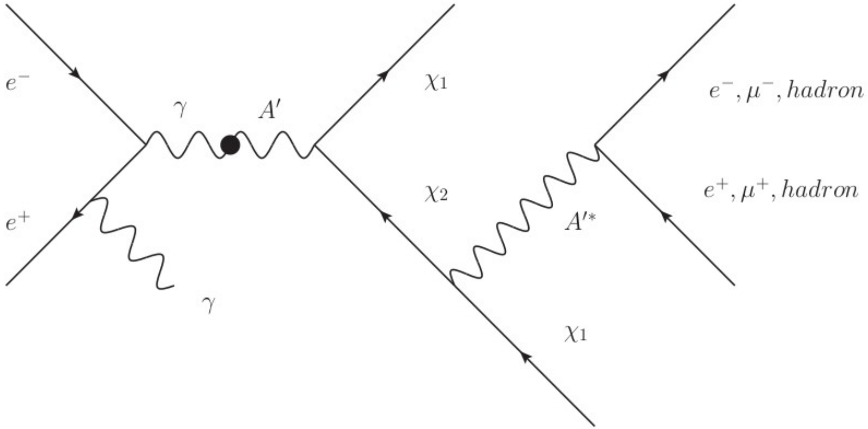
Fridell et al., arXiv:2312.12507

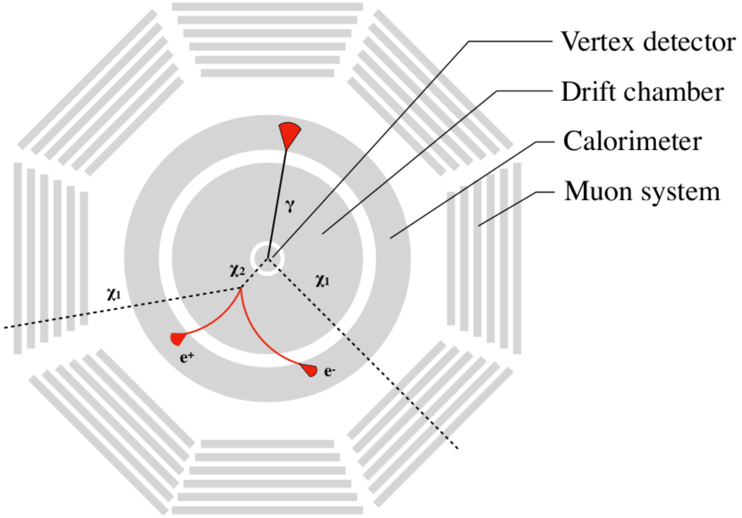


- The mediator χ could be a scalar (e.g. dark Higgs) or pseudoscalar (axion-like) particle
- B → K + invisible: 2.7σ above SM prediction (Belle II, arXiv:2311.14647)
- K → π + invisible: 1.5σ above SM prediction (NA62)

Long-lived particle searches at Belle II

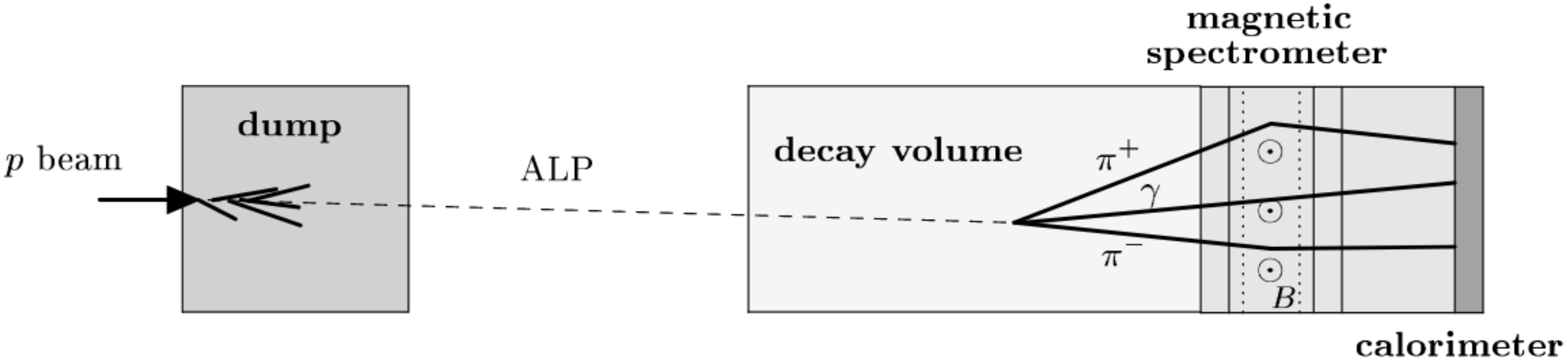
- The Belle II detector has excellent sensitivity for displaced vertices in the mm-cm range
- Many exciting applications for dark sectors:
  - Inelastic DM (Duerr, FK et al., arXiv:1911.03176)
  - Strongly-interacting dark sectors (Bernreuther, FK et al., arXiv:2203.08824)
  - Dark Higgs models (Acanfora & FK, in preparation)





Intensity frontier: Beam-dump experiments

- Idea: Shoot highly energetic particle beam into absorber (“dump”)
  → All SM particles (except neutrinos) stopped in the dump
  → Dark sector particles with feeble interactions may escape



- Possible signatures:
  - Missing energy
  - Downstream scattering
  - Displaced decays

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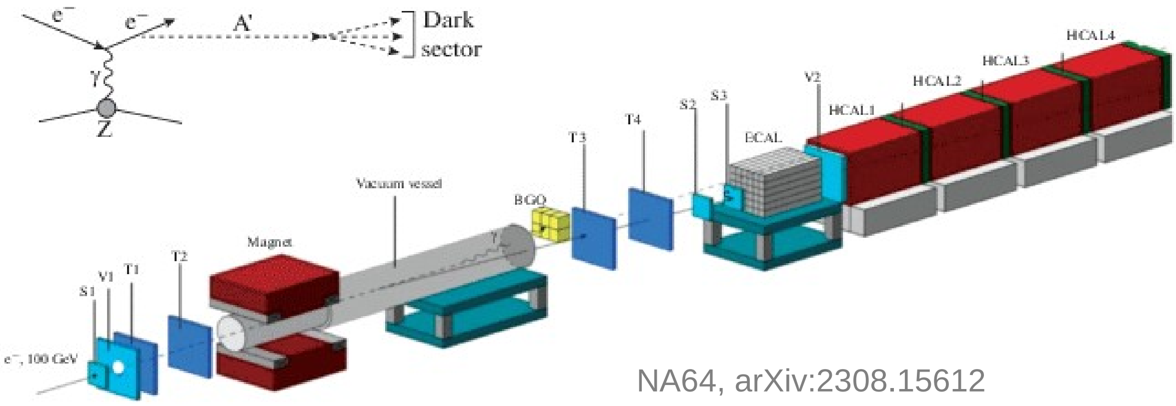
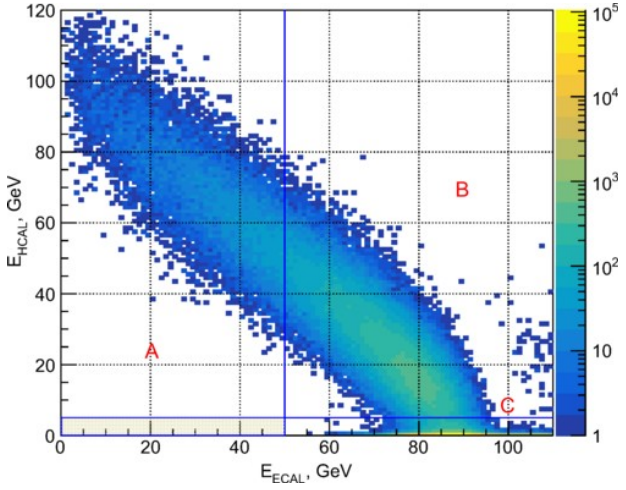
Missing energy searches at NA64

- Idea: Active beam dump
  - → Fully reconstruct energy deposited by incoming particle
  - → Energy carried away by stable particles shows up as deficit
  - → Very sensitive to sub-GeV dark sectors



NA64, arXiv:2308.15612



- Future plans: Muons or hadrons instead of electrons
- Proposed successor: LDMX

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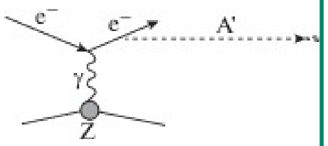
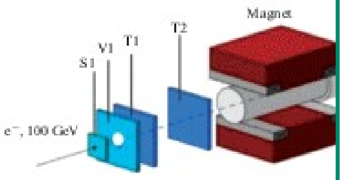
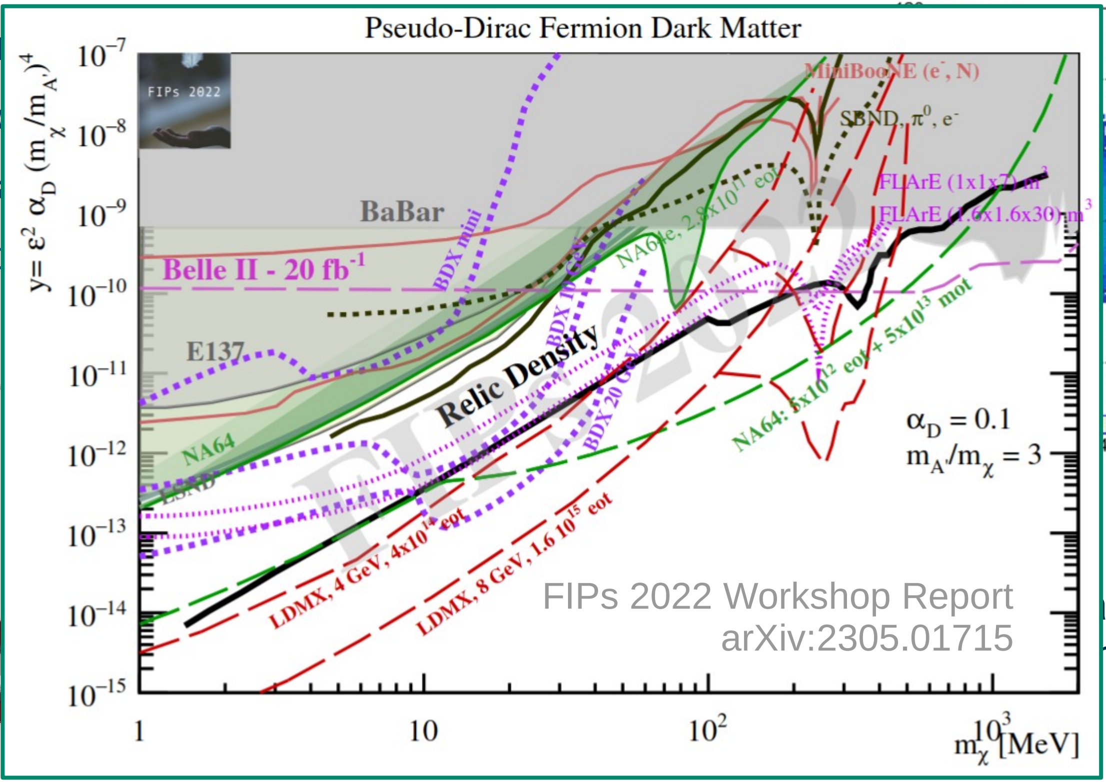
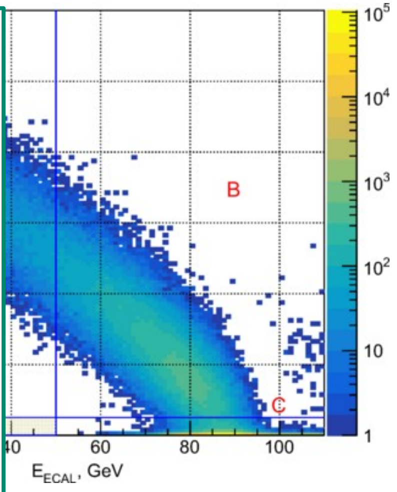
Missing energy searches at NA64

- Idea: Active bea
  - → Fully reconstru
  - → Energy carried a
  - → Very sensitive t







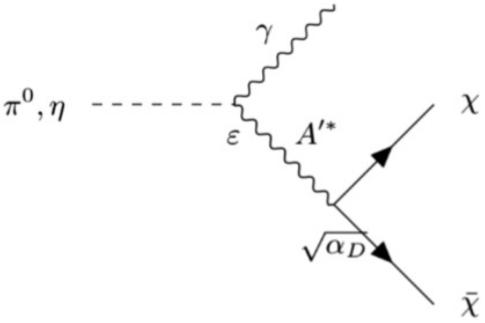


ns: Muons or
nstead of electrons

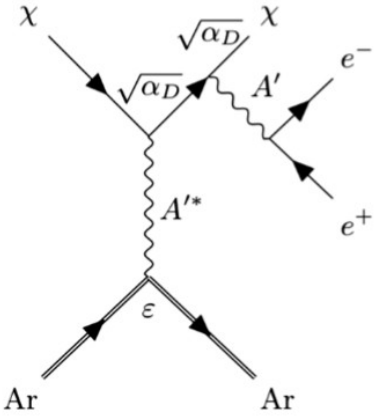
successor: LDMX

Downstream scattering

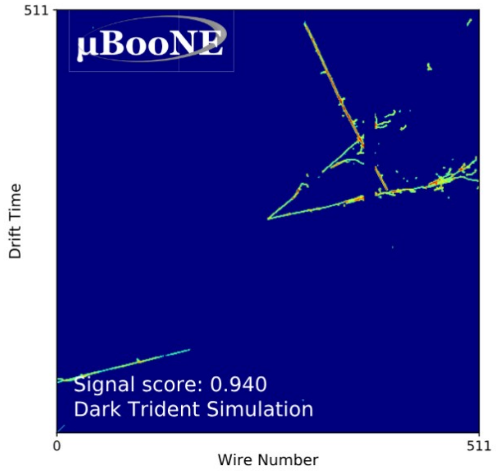
- Step 1: Dark matter production in rare meson decays

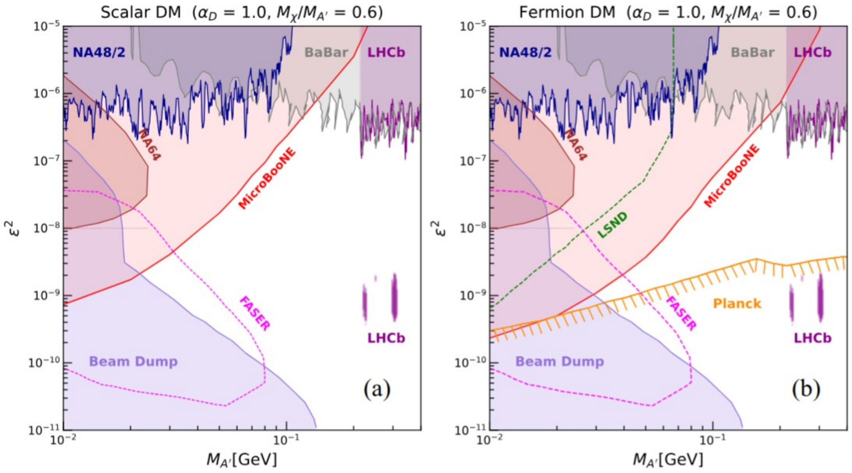


- Step 2: Downstream scattering of relativistic DM particle off target nuclei



MicroBooNE, arXiv:2312.13945





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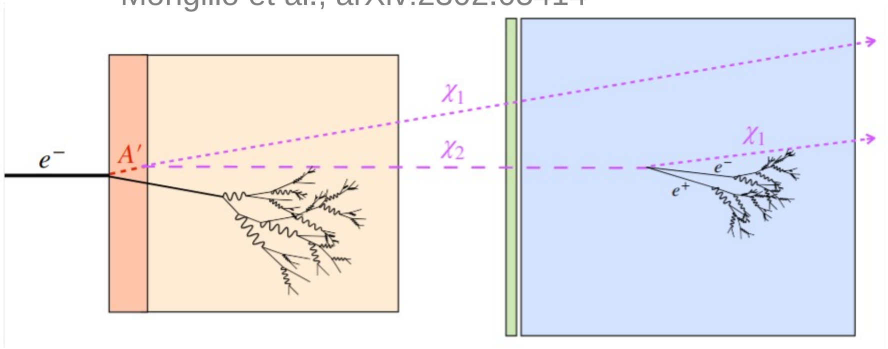
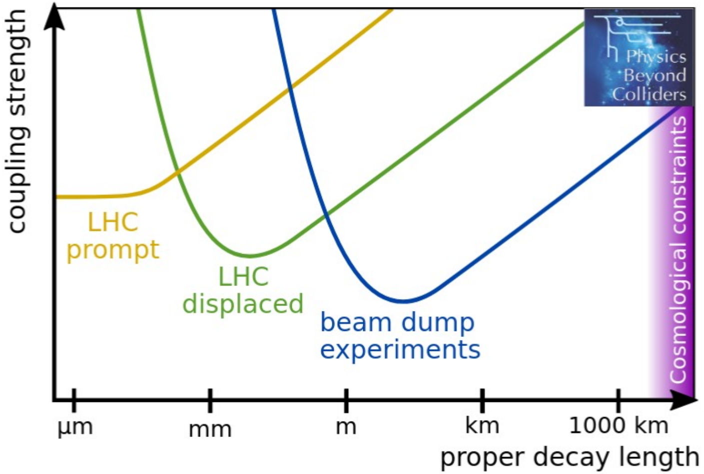
Displaced decays

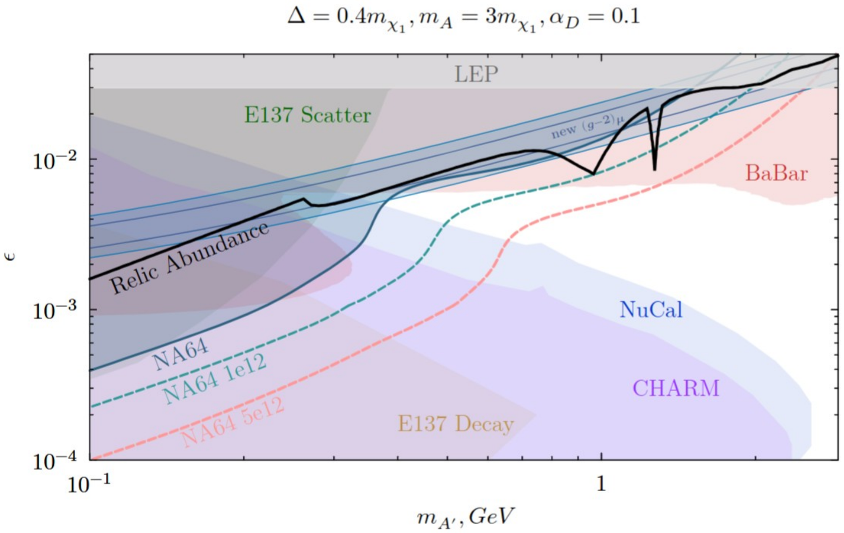
- Beam-dump experiments are ideally suited to search for long-lived dark sector states (e.g. inelastic DM)

Mongillo et al., arXiv:2302.05414



Ahdida, FK et al., arXiv:2310.17726



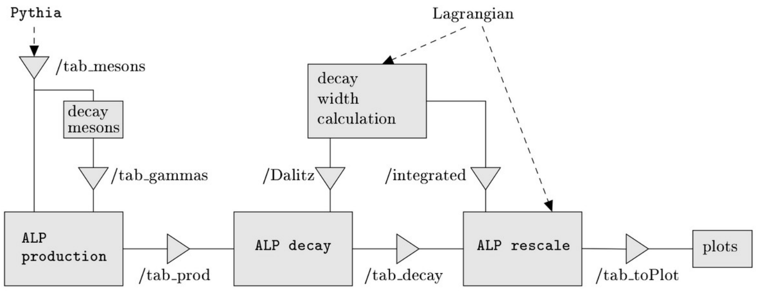


Tools: Simulations

- Monte Carlo simulations are crucial for studying dark sectors at accelerators
  - LHC/Belle II: Madgraph + Pythia/Herwig (dark showers) + Delphes
  - Beam dumps: BdNMC (https://github.com/pgdeniverville/BdNMC)
    Maddump (https://github.com/mg5amcnlo/Maddump)

- For long-lived particle searches: Often possible to factorise production and decay
- Use pre-tabulated particle distributions with analytical rescaling functions
  - ALPINIST (https://github.com/jjerhot/ALPINIST)
  - FORESEE (https://github.com/KlingFelix/FORESEE)
  - SensCalc (https://arxiv.org/pdf/2305.13383)

- For GeV-scale particles: Need additional tools/methods to calculate decay widths (perturbative calculation not reliable)



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Tools: Reinterpretation

- ATLAS dark Higgs boson search based on active-learning reinterpretation and use of RECAST framework (https://iris-hep.org/projects/recast.html)

- Implementation of LHC searches for strongly-interacting dark sectors in MadAnalysis

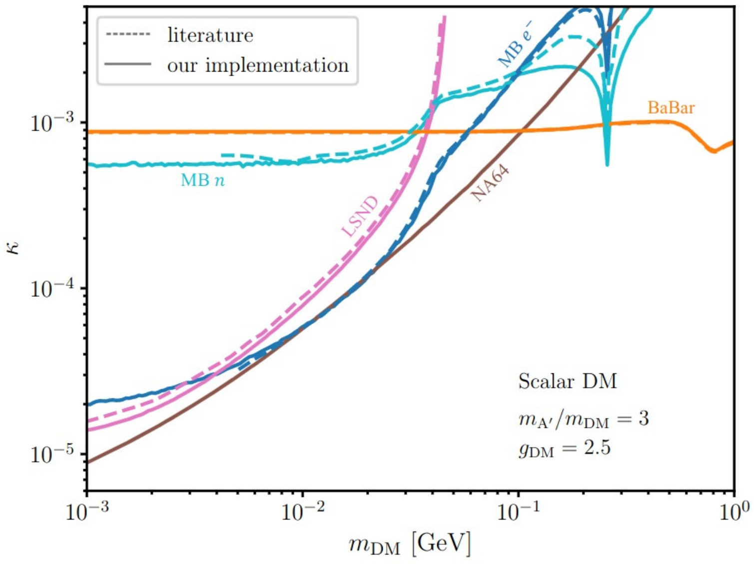
  Fuks, Genest, Goodsell, Hemme, FK, Sinha, Wojtkowski, in preparation

- Database of various constraints on invisibly decaying Z' gauge bosons and dark photons in GAMBIT

  Balan, FK et al., arXiv:2405.17548

  Chang, FK et al., arXiv:2209.13266

  Chang, FK et al., arXiv:2303.08351



GAMBIT: The Global And Modular BSM Inference Tool

- An international community with 50+ collaborators (experiments + theorists)
- A software framework for global fits developed over the past decade
  - Automated construction of composite likelihoods for a given model
  - Efficient scans of multi-dimensional parameter space
  - Consistent treatment of uncertainties and nuisance parameters
  - Maximum of flexibility and modularity in terms of data sets and models
  - Optimized for parallel computing & fully open source

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- A software framework for global fits developed over the past decade
- First dark sector models implemented over the past few years
  - Accelerator constraints (EWPT, B factories, beam dumps)
  - Relic density calculation (using DarkCast and DarkSUSY)
  - Direct detection constraints (using DDCalc & obscura)
  - Indirect detection constraints (using HERWIG4DM)
  - Cosmological constraints (using CLASS, AlterBBN & ACROPOLIS)
  - Gravitational wave constraints (TransitionListener & PTArcade)
  - Astrophysical constraints (Bullet Cluster)

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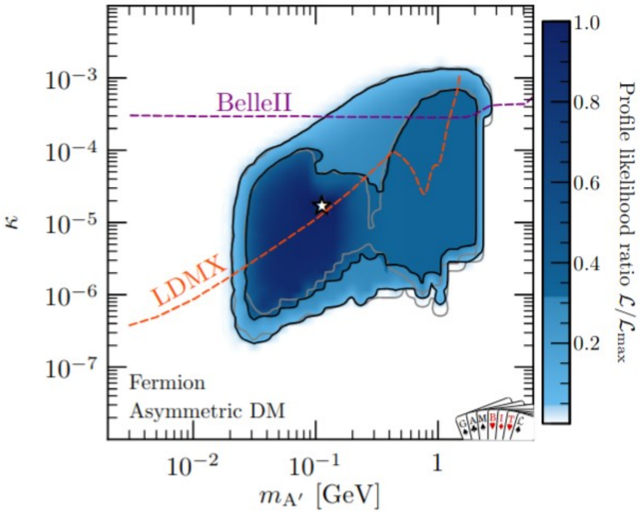

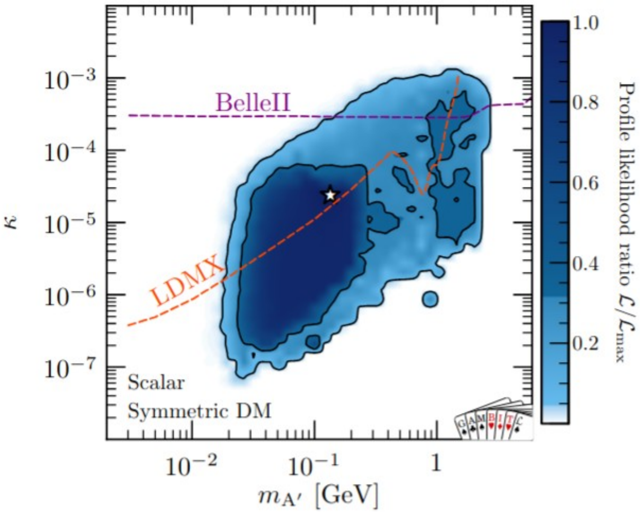

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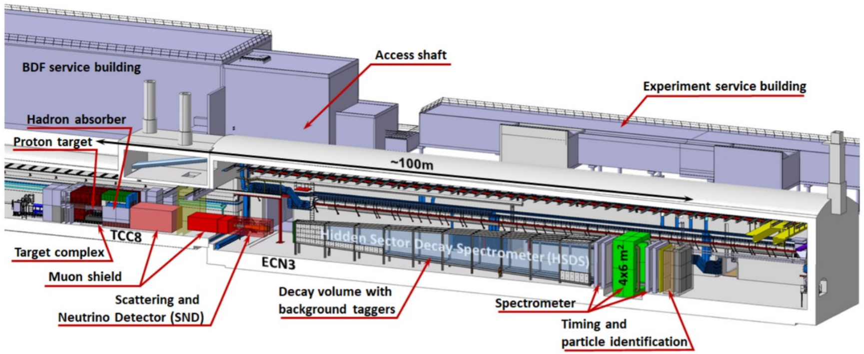
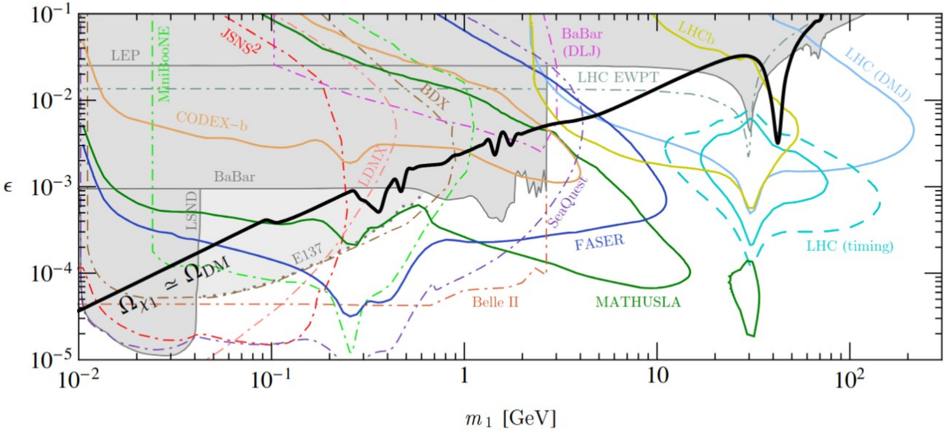
Outlook: Exciting prospects for dark sectors

- Sensitivity improvements and new dark sector searches at HL-LHC and Belle II
- Ongoing sensitivity studies for strongly-interacting dark sectors at FCC-ee

  Cazzaniga, De Cosa, FK & Sitti, in preparation
- SHiP: Approved beam-dump facitity at CERN



- MATHUSLA, ANUBIS, Codex-b, FASER II: Proposed new detectors at the LHC



Berlin & Kling, arXiv:1810.01879

See also the Physics Beyond Colliders Initiative input to EPPSU:
Alemany Fernández, FK et al., arXiv:2505.00947

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Conclusions

- Dark sectors (= rich internal structure + portal interactions) are well motivated and offer exciting phenomenology
  - New resonances (e.g. dark Higgs bosons)
  - High-multiplicity final states (e.g. dark showers)
  - Long-lived particles (e.g. inelastic dark matter)
- Many different experimental directions
  - LHC (+ proposed detectors for long-lived particles)
  - Belle II (+ rare meson decays)
  - Beam dump experiments (running and under construction)
- Wide range of tools for event simulation, reinterpretation and global fits