# Dark Photon Exploration Beyond LHC

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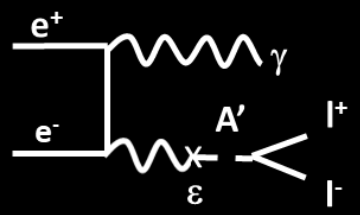
LHCDMWG workshop – May 2024

# Dark photon

A new massive gauge boson (A') coupling to the SM photon / Z through kinetic mixing with strength $\varepsilon$ (one of the four dark sector portal)

$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$



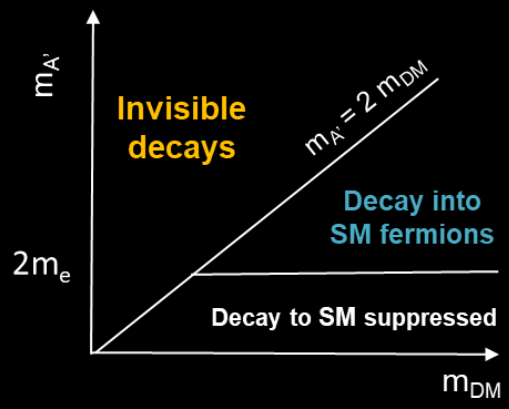

$$\Gamma_{A'} = \frac{1}{3} m_{A'} \varepsilon^2$$

Dark photon lifetime depends on mass and kinetic mixing, decay length ranging from $\mu$m (prompt) to macroscopic distances (LLP)

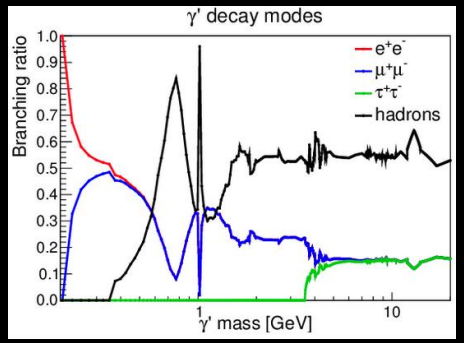
Dark photon decay depends on the dark sector structure:

- **$m_{A'} > m_{DM/2}$**
  invisible decays into DM if dark sector state exists

- **$m_{A'} < m_{DM/2}$**
  $m_{A'} > 2m_e$ : visible decay into SM fermions, final state depends on R-ratio and exclusive $\sigma(e^+e^- \rightarrow \text{hadrons})$ cross-sections
  $m_{A'} < 2m_e$ : decays into photons via loops, A'-$\gamma$ mixing




Extensions can be constructed by gauging accidental symmetries of the SM or individual flavor numbers, e.g. B-L or $L_i$-$L_j$ i,j=e,$\mu$,$\tau$.
- constraints can be significantly modified depending on the model




**This talk will focus on dark photon searches at accelerators in the MeV-GeV range**

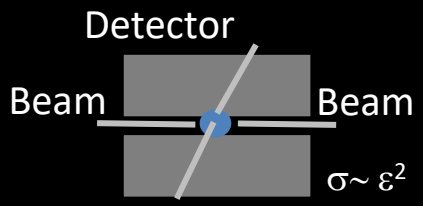
# Dark photon taxonomy

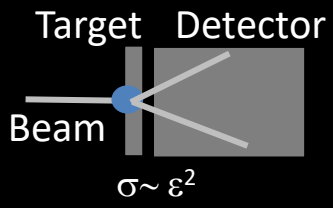
| **Theory**<br>mediator portal | **Facilities / production**<br>type of experiment | **Final state**<br>experimental signature |
|---|---|---|
| Vector – $\varepsilon B^{\mu\nu} A'_{\mu\nu}$ | Colliders | (Semi-) visible decays |
| Scalar – $H^2 (\mu S + \lambda S^2)$ | Fixed target and beam dump (electron and protons) | Re-scattering (aka recoil) |
| Neutrino – yHLN | Neutrino experiments | Missing mass |
| Axion – $g_{a\gamma} F^{\mu\nu} F_{\mu\nu} a$ | Meson factories ($K,\pi,\eta,\ldots$) | Missing momentum / energy |
| | Muon beams | |

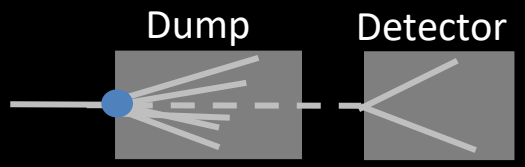
I'll briefly discuss the different experimental signature before reviewing a selection of experiments and facilities. The choice reflects my own experience and biases more than the science – my apologies if your favorite experiment isn't included

# Visible / semi-visible decays

## *(Semi-) Visible*




$c\tau_{A'} \approx 1\text{mm} \times (10^{-9} / \varepsilon^2) \times (100\ \text{MeV}/m_{A'})$

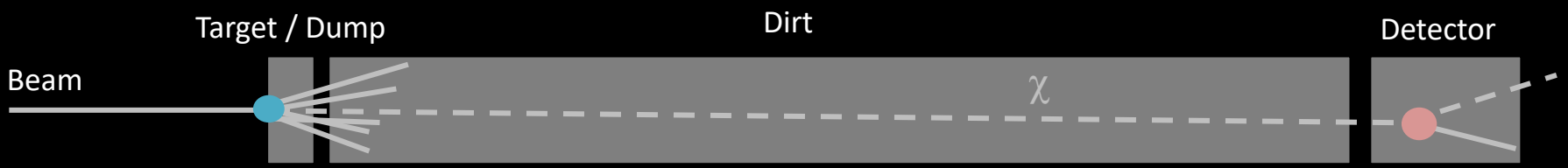
## Main features – visible decays

- Wide variety of collider signals, usually simple topologies to detect all particles
- Large signal yield ($\sigma \sim \varepsilon^2$)
- Collider constraints typically cover "large $\varepsilon^2$" (small lifetimes) over large mass regions
- Beam dump constraint have typical "triangular" shape dictated by geometrical constraints and rates – decade old experiments still provide leading constraints in some part of the parameter space!

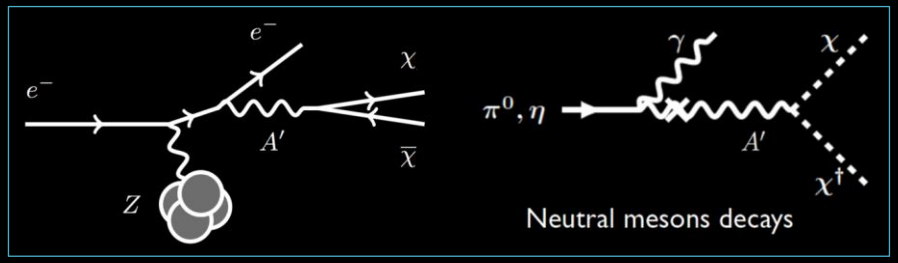
## Main features – semi-visible decays

- More complicated decay chains, multiple lifetimes and mass scales
- Example include inelastic DM, SIMP, dark showers,….

# Re-scattering (recoil)

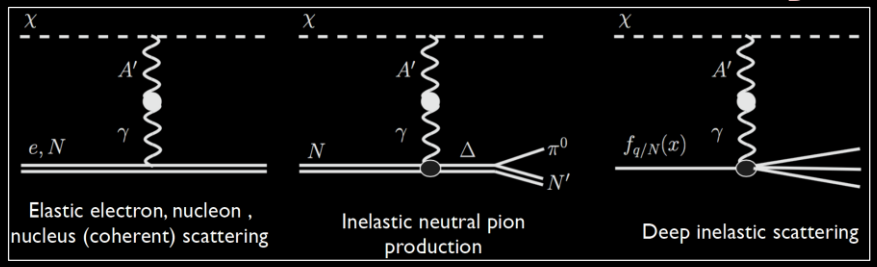



$\sigma \propto \varepsilon^2$




+direct production
+...

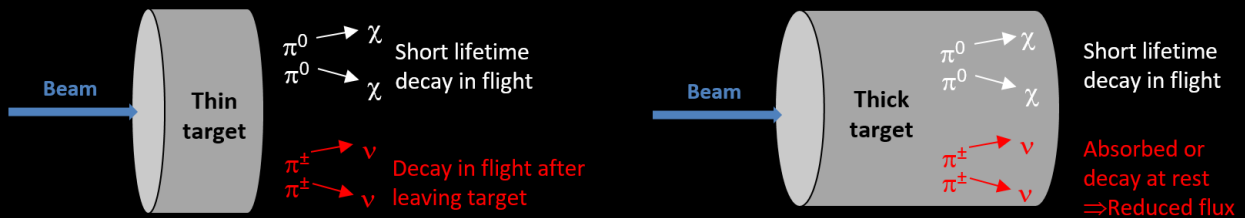
$\sigma \propto \alpha_D \varepsilon^2$




+inelastic DM
+ electron
+...

## Main features

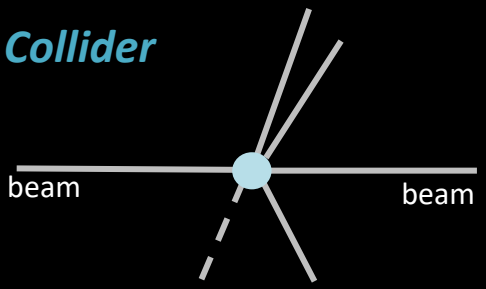
- Low signal yield ($\sigma \sim \varepsilon^4$), need very large flux to compensate
- Sensitive to dark sector coupling constant, $\alpha_D = g_D / 4\pi$
- Non-negligible neutrino background. Mitigate using timing + thick target (beam dump mode)



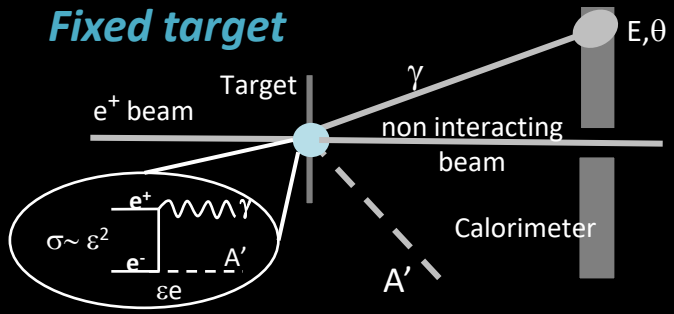

MiniBooNE, 1807.06137

# Missing mass

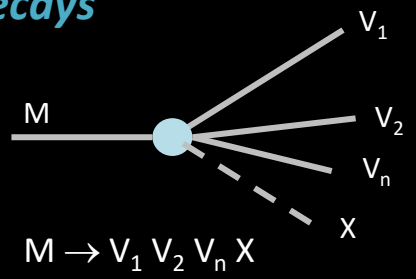
***Collider***




***Fixed target***




***Decays***

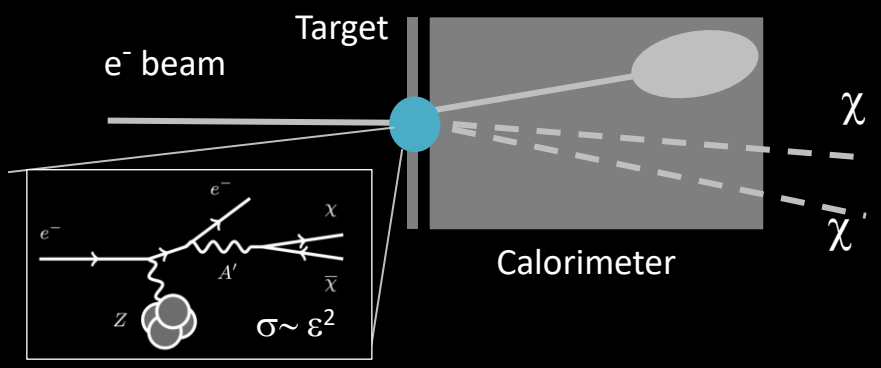



## Main features

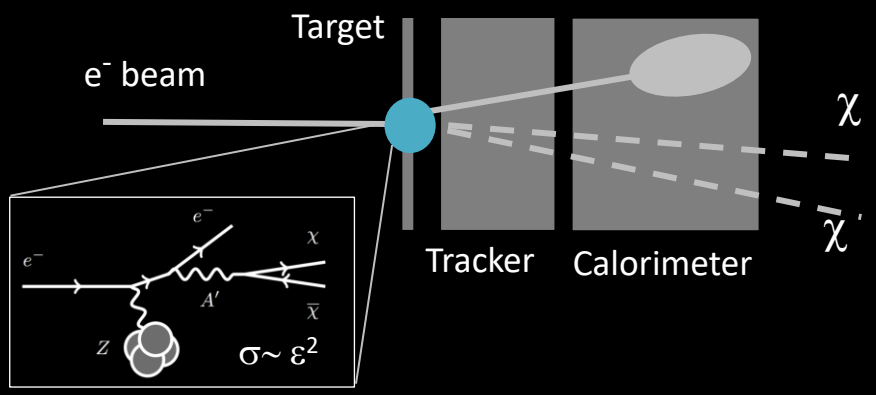
- Less sensitive to dark sector structure
- Need good detector hermeticity to measure all remaining particles, often restricted to low-multiplicity reactions in clean environment
- Typically bump hunt over large background
- Need high-intensity colliders or positron / meson beams

# Missing energy / momentum

## *Missing energy*




## *Missing momentum*




## Main features

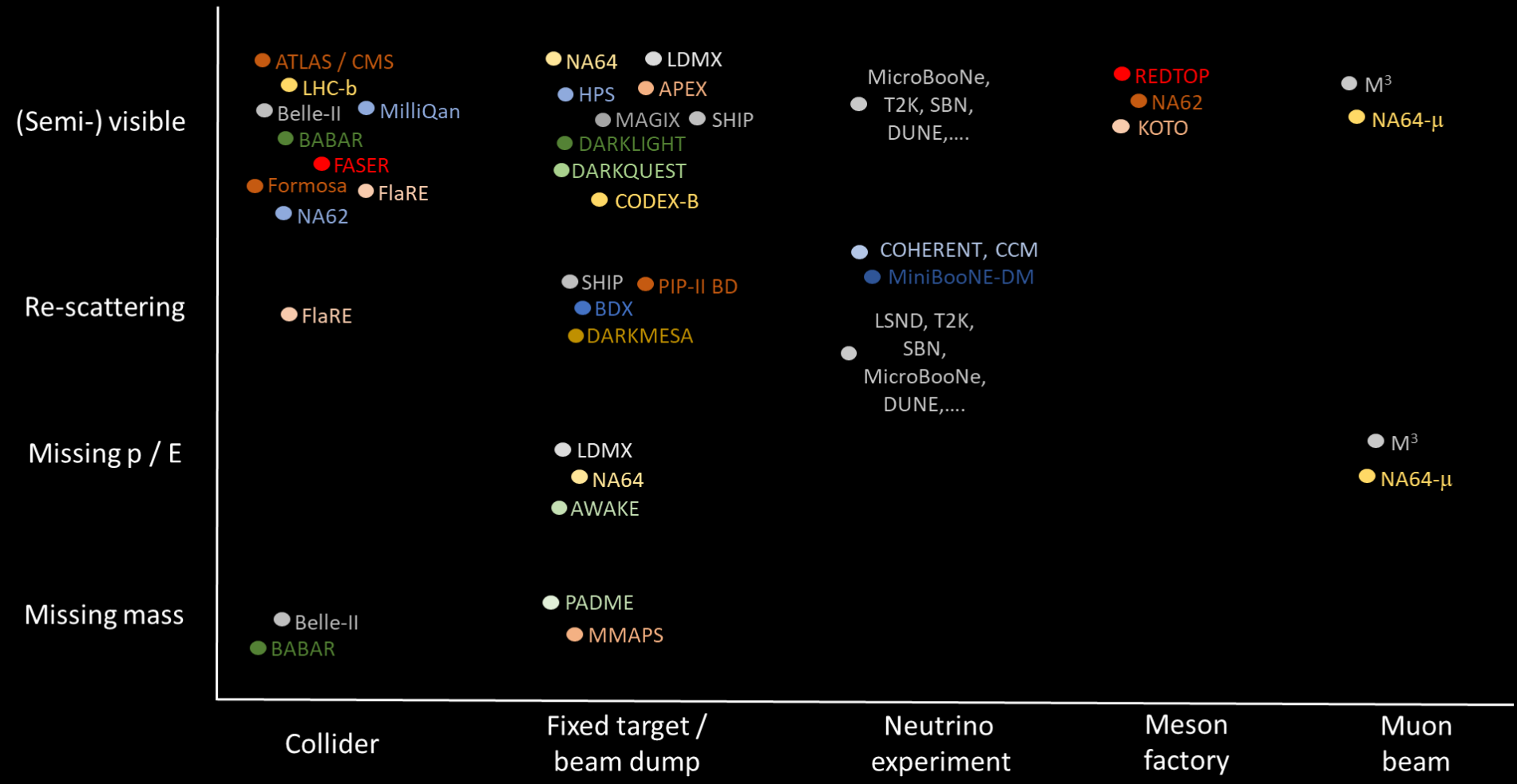
- Measure one electron at a time to uniquely associate incoming / outgoing particle
- Search for events with large $\Delta p$ or $\Delta E$ and no other product in the detector
- Large signal yield, maximizing sensitivity for a given number of electrons

## Missing energy vs missing momentum

- Missing energy has higher signal yield / electrons on target (EOT), but background become challenging beyond $10^{14}$ EOT
- Missing momentum has additional $p_T$ discriminator, and $p_T$ spectrum sensitive to $m_{A'}/m_\chi$. Essentially background free for $10^{16}$ EOT thanks to e-$\gamma$ identification

# A vast landscape

*Dark sectors – a personal selection of current and future experiments*
*(random ordering)*



# Colliders

## Past and present

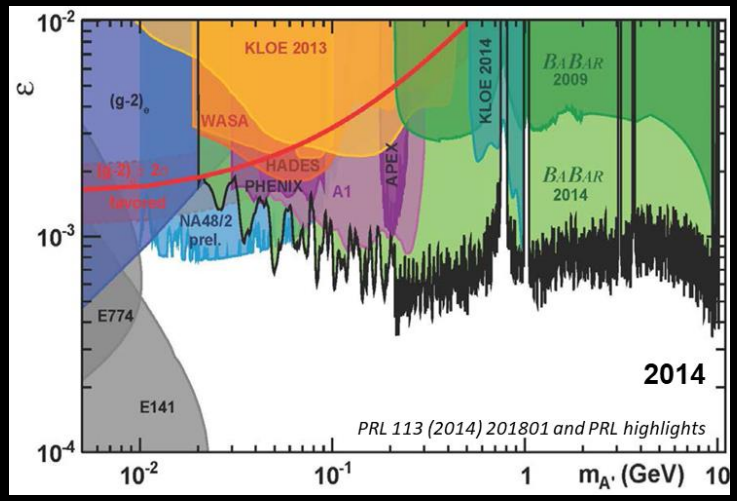
# Colliders

## BABAR @ SLAC

### Search for visible decay in $e^+e^- \to \gamma A', A' \to e^+e^-, \mu^+\mu^-$

Search for a narrow resonance in two tracks and single photon events

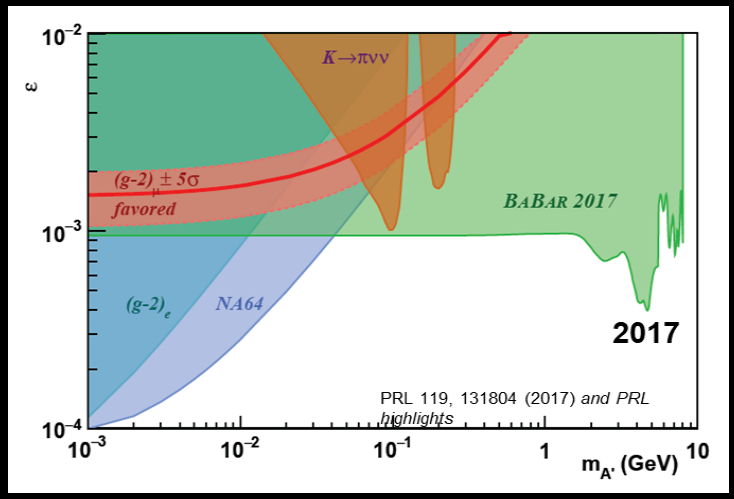
- Based on full BABAR dataset
- Kinematic vertex to improve resolution
- Bump hunt over large QED background in the region 20 MeV – 10 GeV




### Search for invisible decay in $e^+e^- \to \gamma A', A' \to$ invisible

Search for narrow resonance in single photon events

- Based on ~53 $fb^{-1}$ of data with dedicated single photon triggers
- Bump hunt in missing mass spectrum
- Main backgrounds: $e^+e^- \to \gamma\gamma$ and $e^+e^- \to \gamma\, e^+e^-$ with undetected particles



# Colliders

## Belle II @ SuperKEKB

### Already published

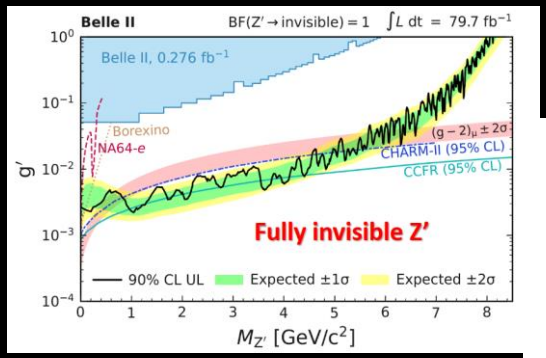
Axion like particle
$a \rightarrow \gamma\gamma$

$L_\mu - L_\tau$ models
$Z' \rightarrow$ invisible, $\mu\mu$, $\tau\tau$

Dark Higgsstrahlung
$h' \rightarrow$ invisible

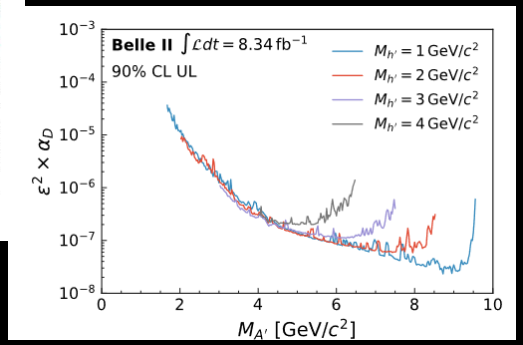
LLP dark scalar in B decays
$B \rightarrow KS$, $S \rightarrow ee$, $\mu\mu$, $\pi\pi$, KK

$Z' \rightarrow$ invisible




PRL 130 231801 (2023)

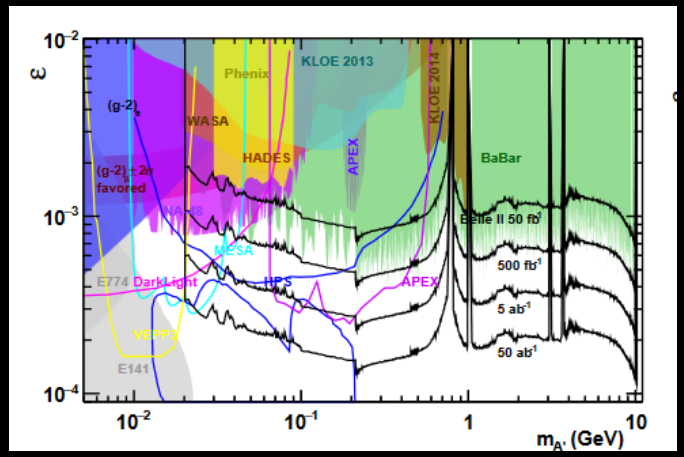
$A'h'$, $A' \rightarrow \mu\mu$ , $h' \rightarrow$ invisible



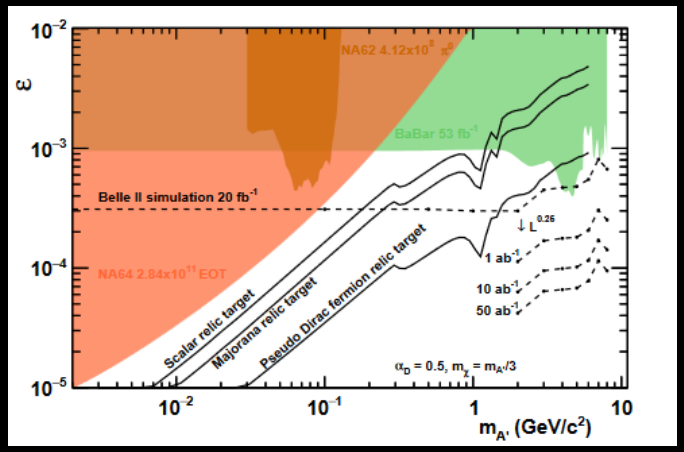

PRL 130 071804 (2023)

### Future prospects

visible




invisible

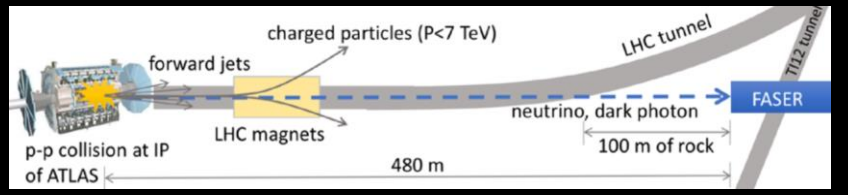


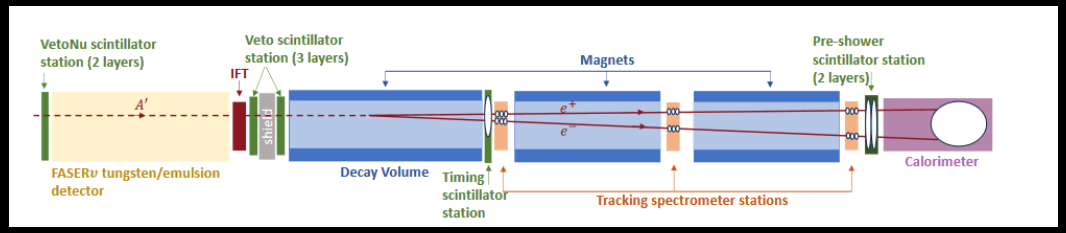

arxiv:2207.06307

# Colliders

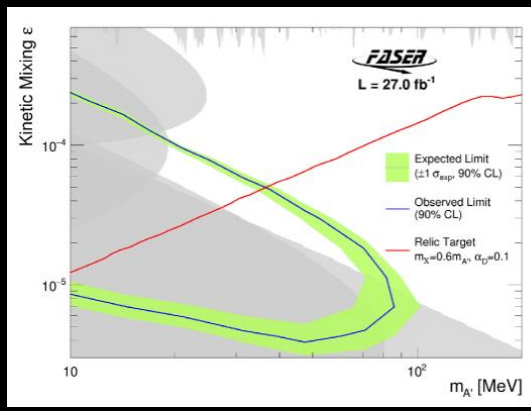
## FASER (and FPF) @ CERN

- Exploit large rate of forward mesons at LHC to search for light long-lived weakly interacting particles
- Tungsten/emulsion detector + tracker + calorimeter situated ~500m from the ATLAS collision point
- Forward Physics Facility proposed to further extend physics capabilities and sensitivity

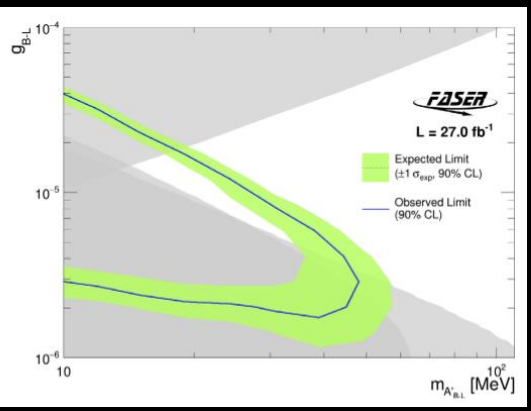


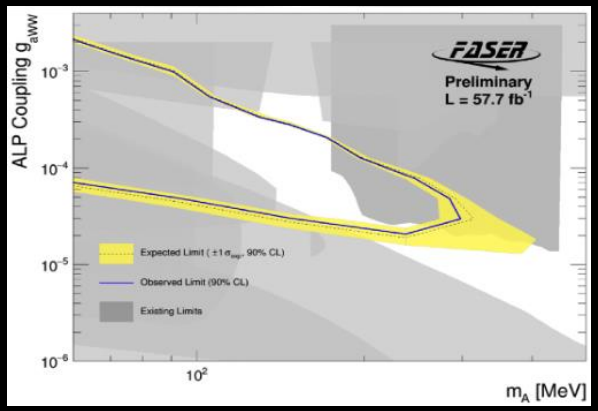

Dark photon




B-L gauge boson




ALP




PLB 848 (2024) 138378

CERN-FASER-CONF-2024-001

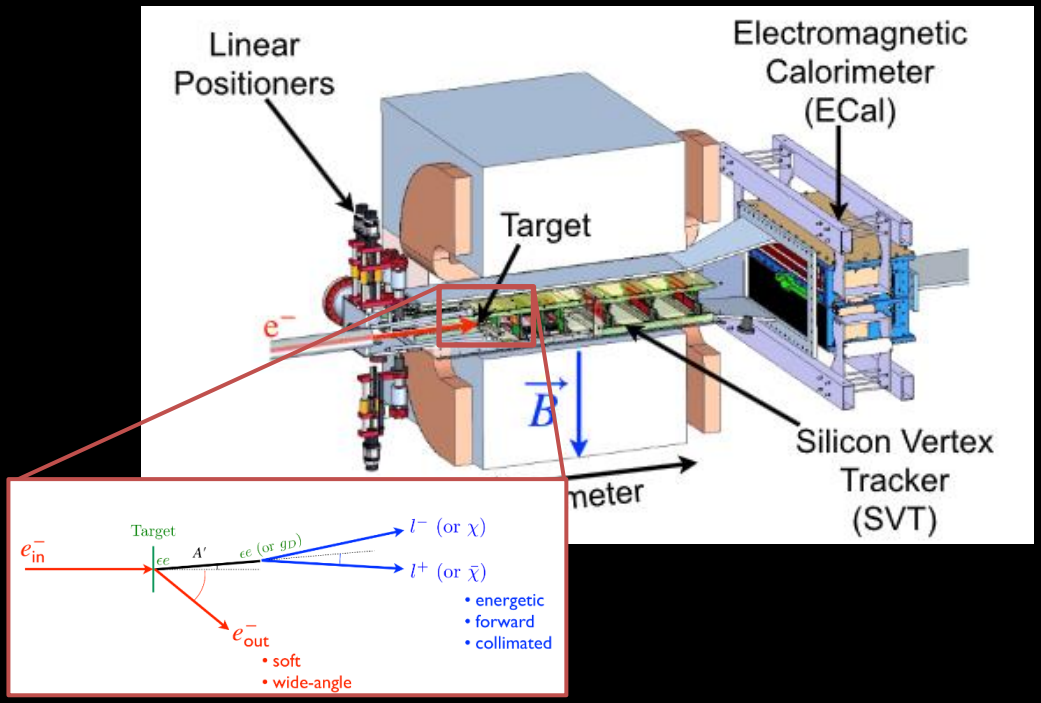
# Beam dump and fixed target

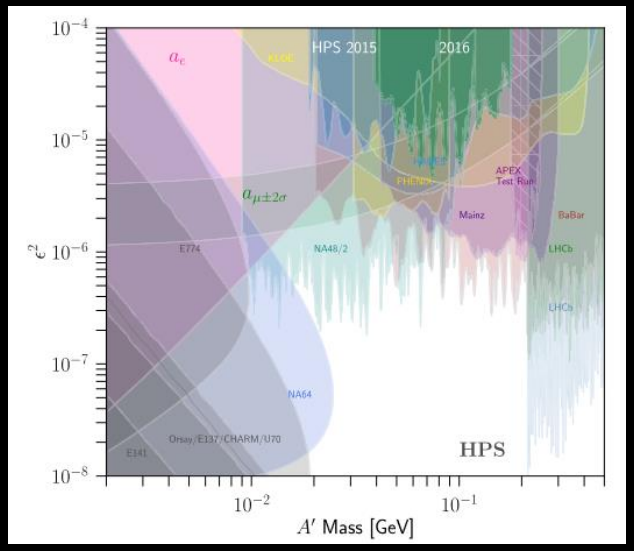
## Electrons and positrons

# Fixed target - electron

## HPS @ JLab CEBAF

- Compact $e^+e^-$ spectrometer located in Hall B
- Low-mass, high-rate silicon vertex tracker and ECal trigger
- Physics runs in 2019 (4.55 GeV) and 2021 (3.94 GeV), more planned in near future
- Prompt and displaced dark photon searches, no new parameter space explored so far but more data would open new territory. Also sensitive to more exotic signatures (e.g. SIDM, iDM)
- Proposal for upgrades to further boost sensitivity for prompt and displaced searches (2203.08324)



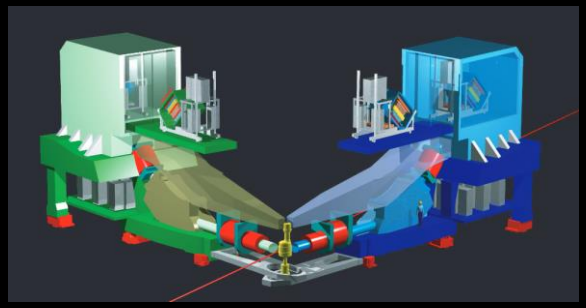




PRD 108, 012015 (2023)

# Fixed target - electron

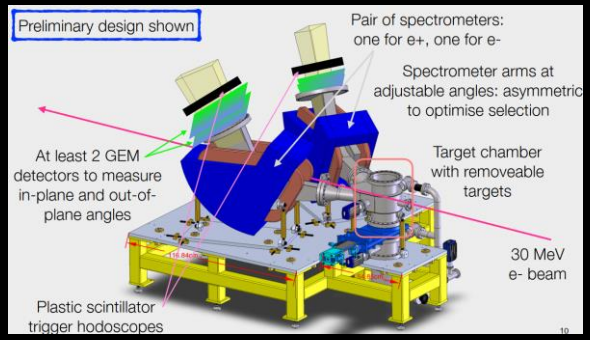
## APEX @ JLab (CEBAF)

- Resonance search using dual arm High-Resolution Spectrometers (Hall A)
- Search for A' $\rightarrow e^+e^-$ resonance
- Proposed in 2010, 15 day run in 2019 at 2.2 GeV



## DARKLIGHT @ ARIEL (TRIUMF)

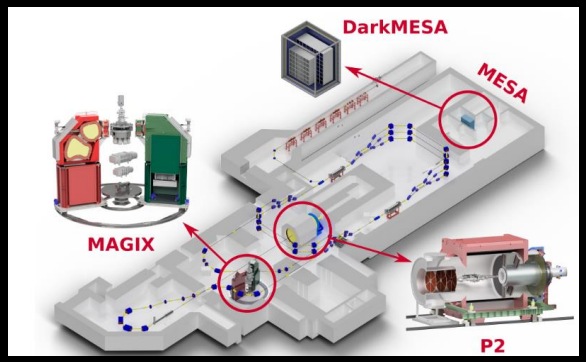
- Pair spectrometer to search for A' $\rightarrow e^+e^-$ with the 30 (50) MeV beam at ARIEL
- Sensitivity limited to the X(17) region
- Under construction




https://indico.cern.ch/event/1077282/contributions/4844982/attachments/2452218/4202366/DarkLight-IPP-2022.pdf

## MAGIX @ MESA

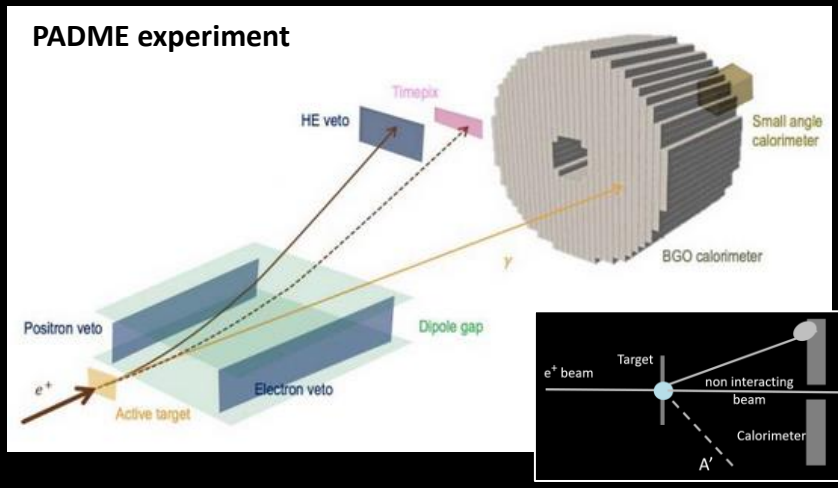
- Dual arm magnetic spectrometer with windowless gas stream target
- MESA energy recovery linac, 105 MeV e- beam
- Search for di-electron resonance and three-body missing-mass (with recoil nucleus reconstruction)



# Fixed target - positron

## PADME @ LNF

- 550 MeV positron beam from LNF linac
- Model-independent search in recoil mass spectrum ($e^+e^- \rightarrow \gamma$ A')
- Run III targeting X(17) region by adding $e^{\pm}$ identification to search for X $\rightarrow e^+e^-$
- Expect new results this summer, fully probing X(17) parameter space

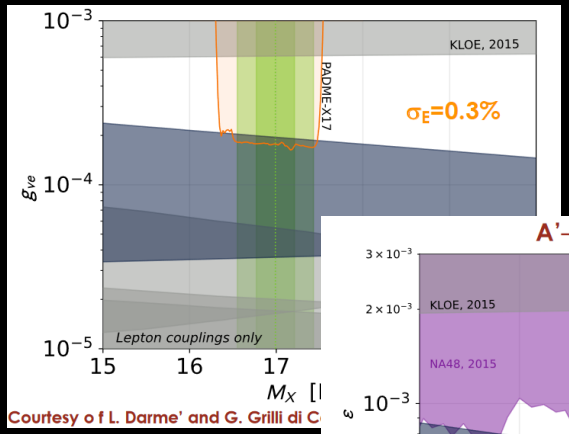



## OTHER FACILITIES

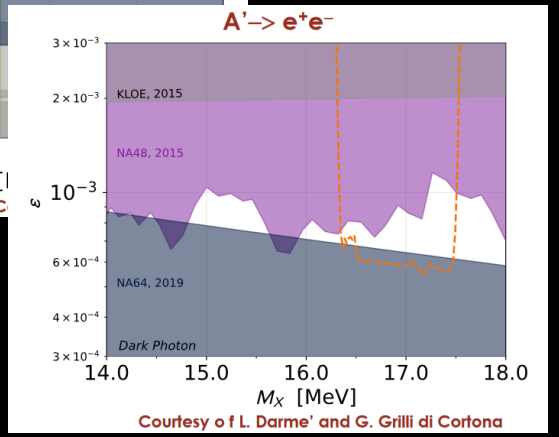
- VEPP3: 500 MeV, $10^{15}$ – $10^{16}$ EOT/ year
- LNF: 550 MeV, $10^{13}$ – $10^{14}$ EOT/ year
- Cornell: 5.3 GeV, $10^{17}$ – $10^{18}$ EOT/ year
- JLab (proposal): 11 GeV

**Mass coverage limited by beam energy**

Vector coupling to electrons




Dark photon

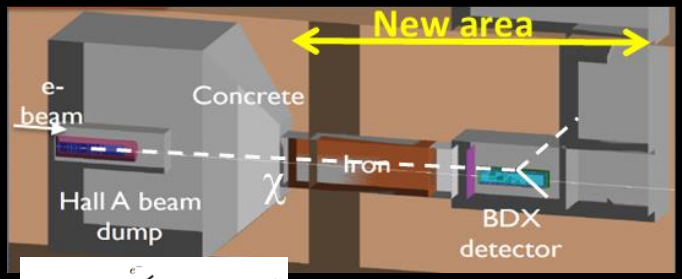


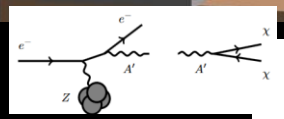

https://padme.lnf.infn.it/wp-content/uploads/sites/37/2023/11/Raggi_WIFAI.pdf

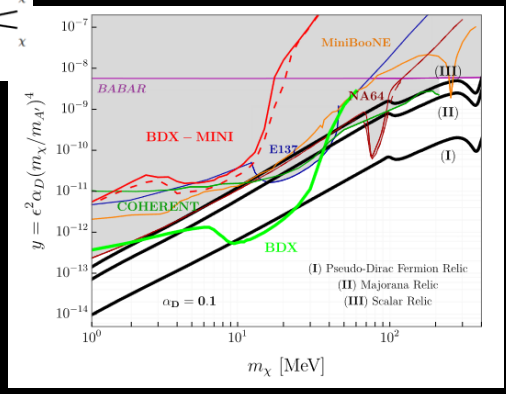
# Beam dump - electron

## BDX @ JLAB CEBAF

- Search for DM scattering producing a visible recoil with 11 GeV beam
- Homogeneous CsI calorimeter and active veto
- Sensitivity limited by irreducible neutrino bkg
- Collected 2x10$^{21}$ EOT with BDX-Mini prototype, full experiment approved at JLab



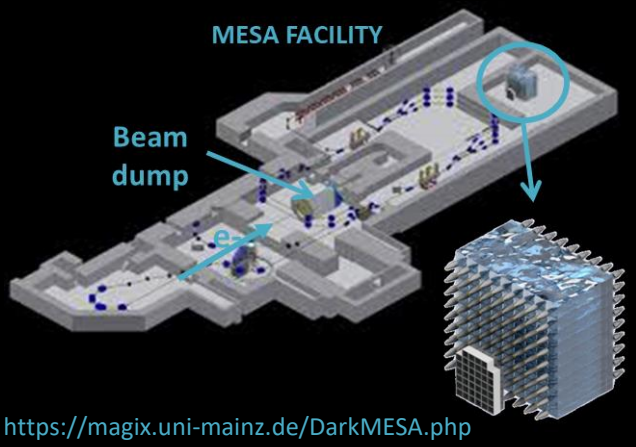






arxiv:2208.01387

## DARKMESA @ MESA

- Search for DM scattering producing a visible recoil with 155 MeV electron beam
- $PbF_2$ and Pb-glass scintillator
- Very low background since below ep $\rightarrow$ en$\pi^+$ production threshold
- Envision staged development in three phases up to O(10) m$^3$




https://magix.uni-mainz.de/DarkMESA.php

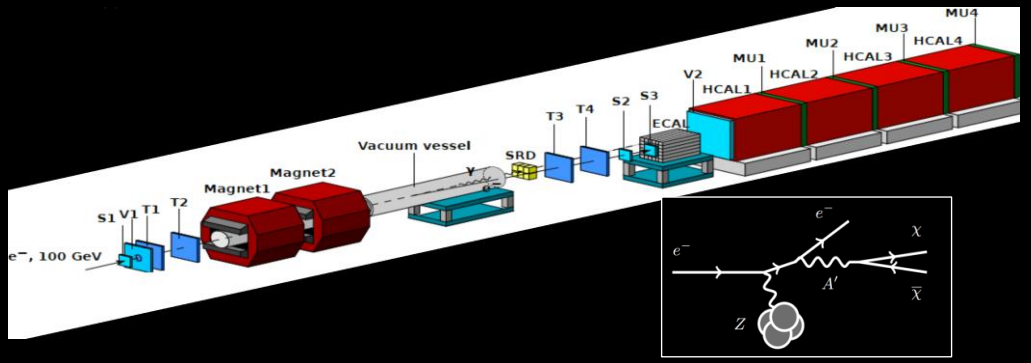
# Missing energy - electron

## NA64 @ CERN

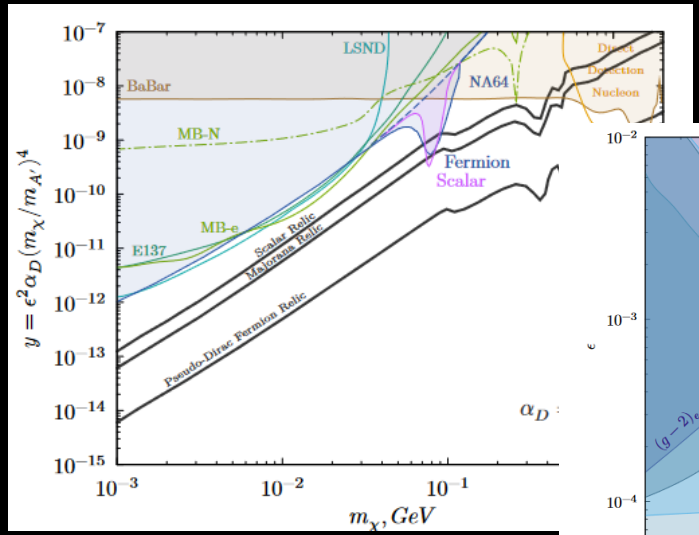
Missing energy experiment at the 100 GeV secondary electron beam line at SPS

### Experimental concept

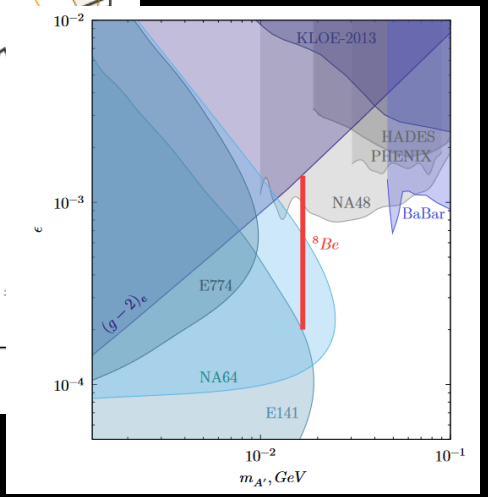
- Tracking system to measure energy of incoming e-
- ECAL as active target to produce A’
- Measure outgoing energy with ECAL and HCAL
- Search for large missing energy
- Insert compact tungsten calorimeter to search for A’ $\rightarrow e^+e^-$ decays
- Possibility to run with muon or hadron beams to probe additional physics (more later)
- Continue to improve detector and take data in the near future




Invisible A’ decays




Visible A’ decays

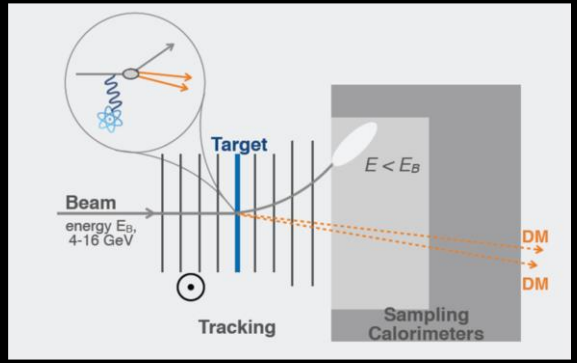


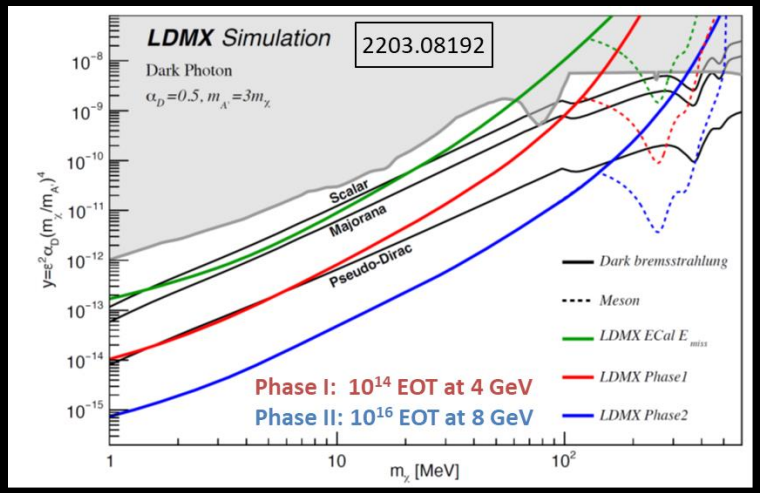

PRL 131 (2023) 16, 161801
PRD 101 (2020) 7, 071101

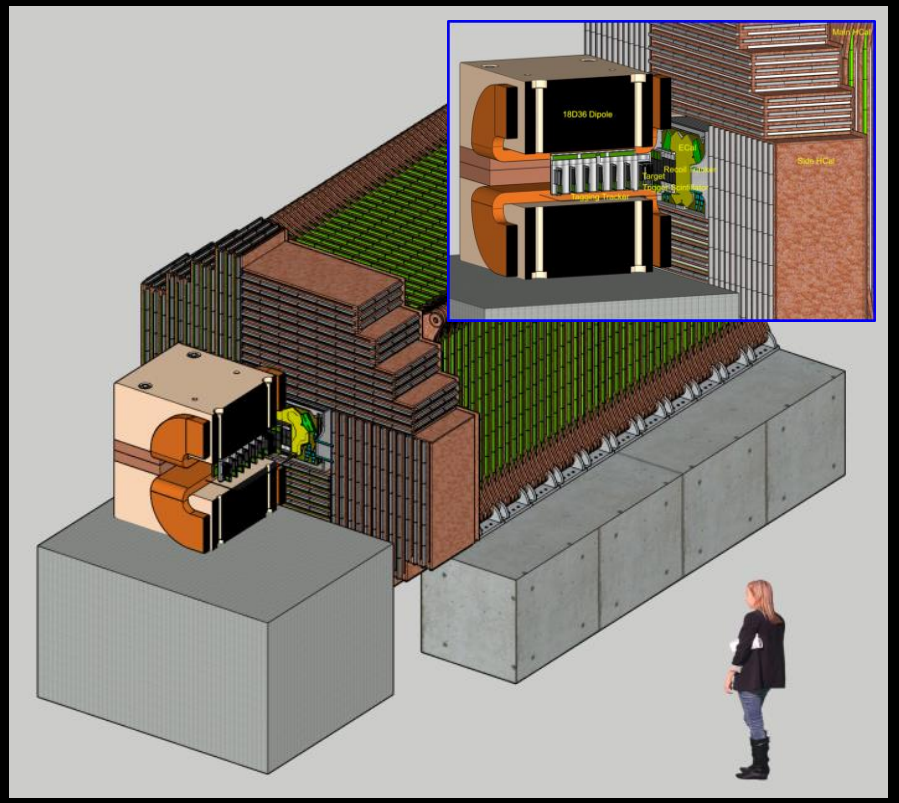
# Missing momentum - electron

## LDMX @ SLAC

- Missing momentum (and energy) experiment at LESA beamline at SLAC
- Search for events with single recoiling electron and no additional activity
- Aim to probe entire thermal DM parameter space in MeV-GeV region with Belle-II + explore many other low-mass new physics scenarios



arxiv:1808.05219

# Beam dump and fixed target

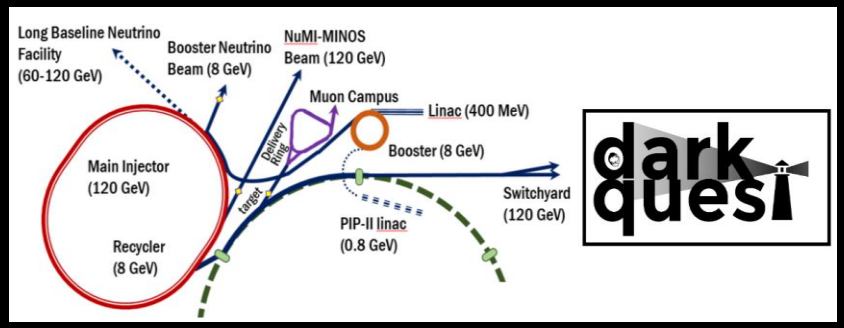
## Protons

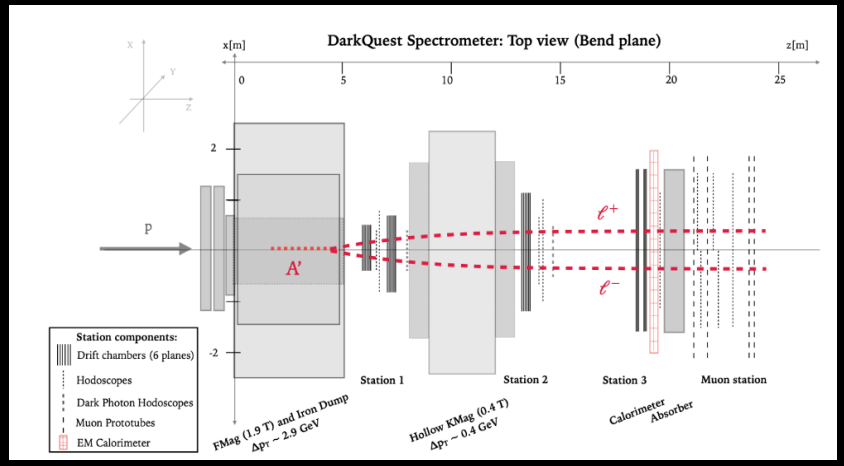
# Beam dump - proton

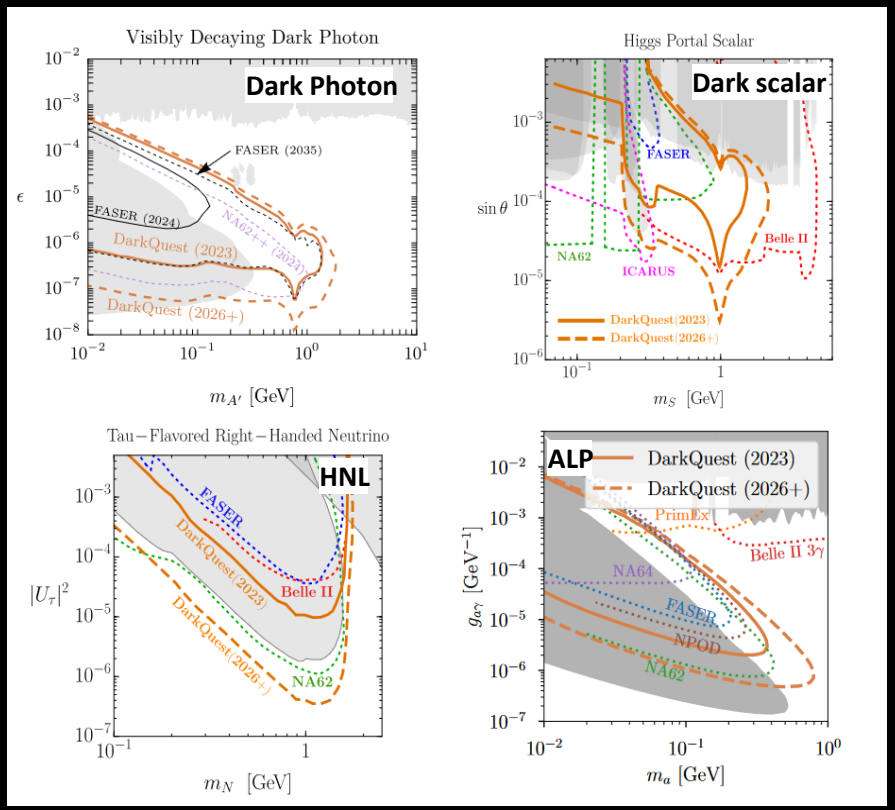
## DarkQuest @ FNAL

Fixed target experiment at 120 GeV proton beam with short decay volume

- Upgrade of SeaQuest expt with additional calorimeter - recently approved
- Sensitive to a wide variety of visible signatures in addition to dark photons
- Proposal for a second upgrade to improve sensitivity – LongQuest (1908.07525)



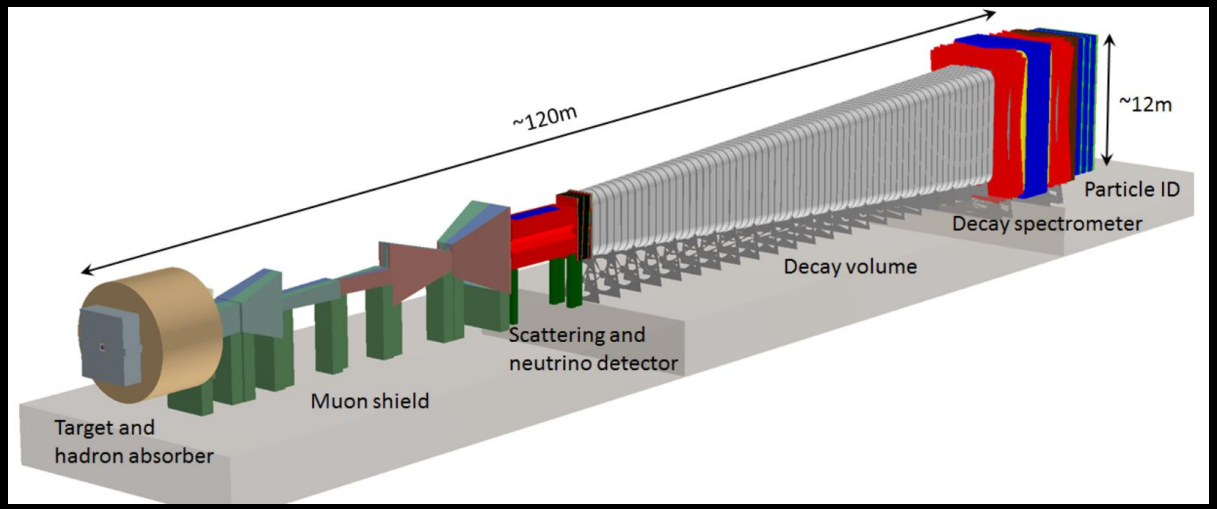




arxiv:2203.08322

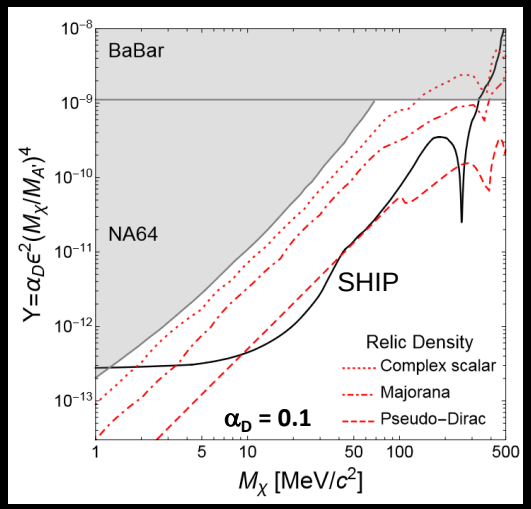
# Beam dump - proton

## SHIP @ CERN

Proton beam dump experiment to search for dark sector signature and study neutrinos




arxiv:1504.04956,1504.04855




JHEP04 (2021) 199

## Detector design

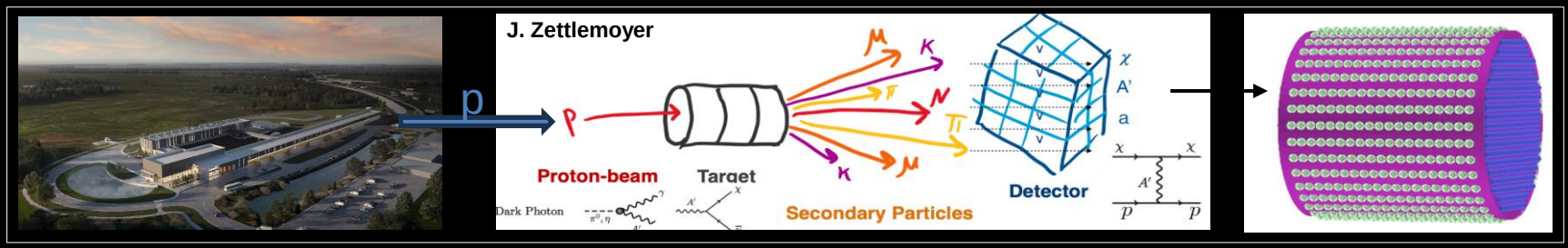
- Two detectors for complementary search strategies:
  - Scattering (LDM and neutrino)
  - Visible decays (DS particles)
- Target and magnetized hadron absorber + active muon shielding → negligible background level (“zero background experiment”)
- Long decay volume to increase sensitivity to LLP, and decay spectrometer with muon ID capabilities to provide flavor identification

# Beam dump - proton

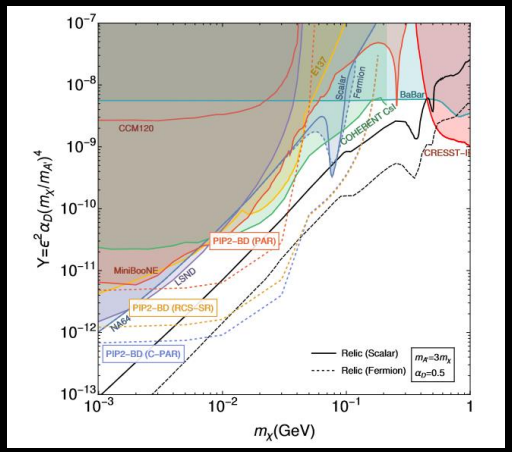
## PIP-II BD @ FNAL

Proposal for a 100-ton LAr experiment after a proton beam dump (full scintillation)

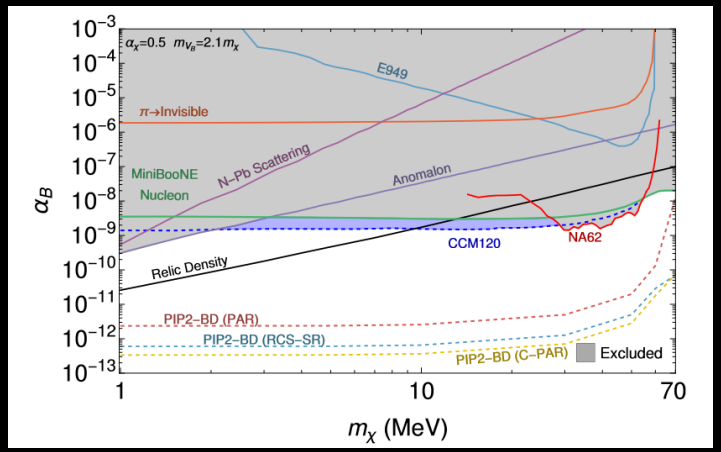
- Take full advantage of unused PIP-II beam (800 MeV proton linac with ~MW power)
- Requires a new accumulator ring (different scenario under consideration)
- Potential synergies with other proposals at PIP-II



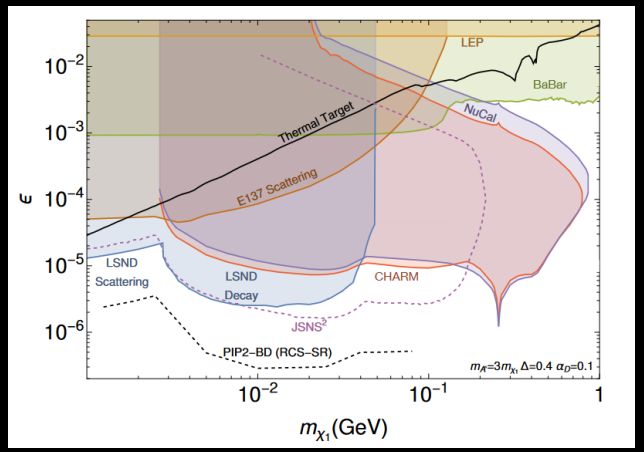

Minimal DM model




Leptophobic DM model




Inelastic DM model




arxiv:2203.08079

# Neutrino experiments

## Past and present

# Neutrino experiments

## LSND @ LANL, MiniBoone-DM @ FNAL

- Search for light DM scattering of detector material (vector portal)
- Large background from neutrino interaction, mitigated with dedicated off-target run for MiniBooNE-DM

## CCM @ LANL, COHERENT @ ORNL

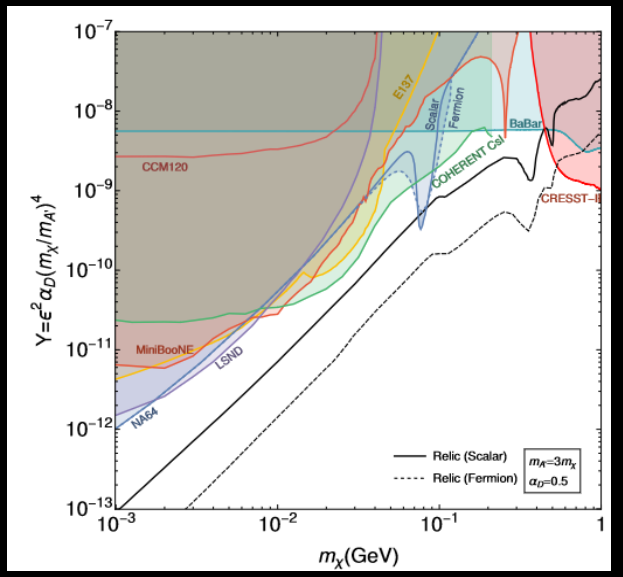
- CEvNS measurements, sterile neutrino search, and vector portal DM
- Also sensitivity to fermiophobic vector portal, millicharged particles,…..

## SBND, MicroBooNE and ICARUS @ FNAL

- Short baseline neutrino experiment with LAr detectors
- Sensitive to inelastic DM with vector portal

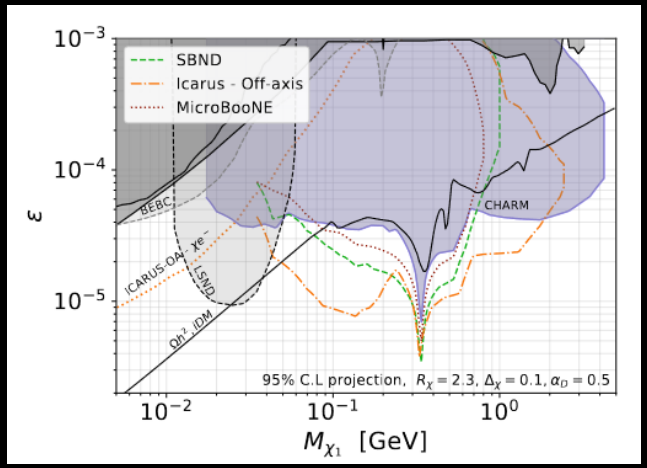
**See 2207.06898 for a comprehensive discussion**

vector portal DM




arxiv:2207.06898

vector portal inelastic DM



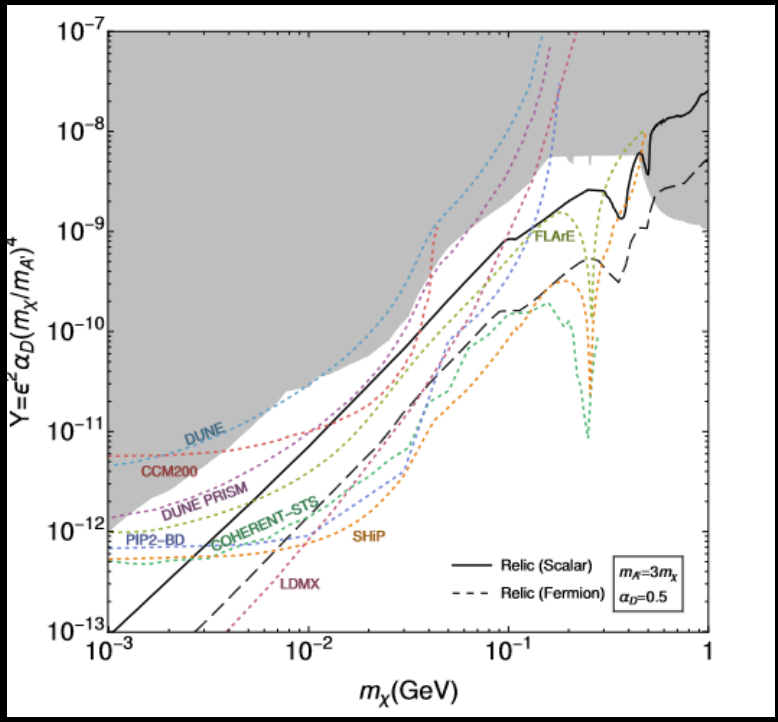

arxiv:2106.04584

# Future neutrino experiments

## Dune ND @ FNAL

- ND-LAr – LAr detector modified for higher rate
- DUNE-PRISM – moving ND-LAr and TMS to 30m off axis
- DM-to-neutrino flux increases as detector is moved further off axis
- Sensitive to wide array of dark sector physics, including vector portal DM

vector portal DM




arxiv:2207.06898

## FLARE @ FPF

- Proposal for a segmented LAr TPC at the Forward Physics Facility at CERN
- Dark matter recoil and neutrino physics, also sensitive to hadrophilic models

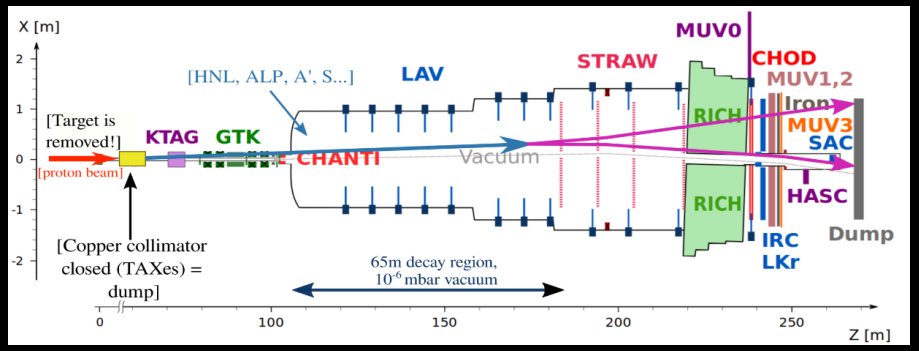
**See 2207.06898 for a comprehensive discussion**

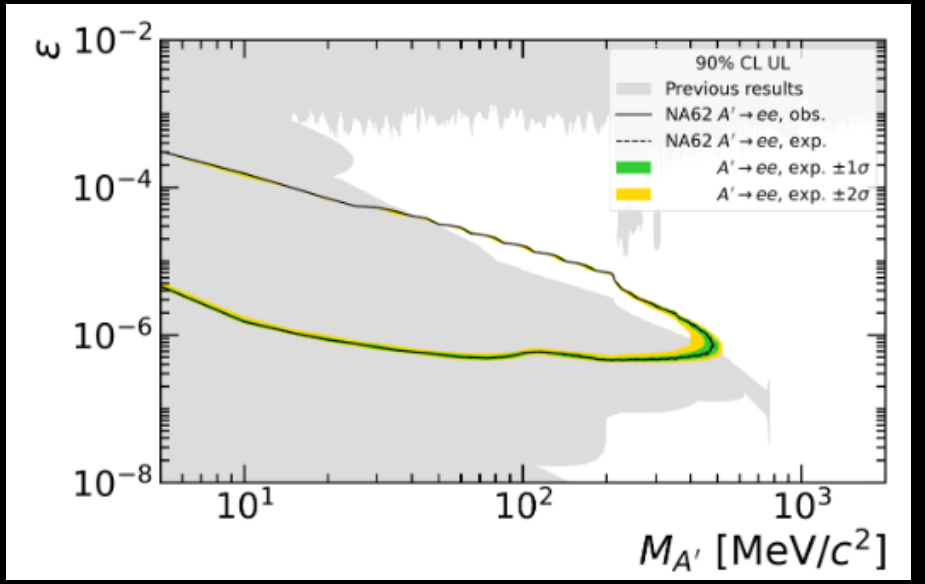
# Meson factories

# Meson factories

## NA62 @ CERN

- Fixed target experiment at CERN SPS to study rare kaon decays
- Run in beam dump mode to increase A' production rate
- Search for dark photon decays to a lepton pair ($e^+e^-$ and $\mu^+\mu^-$)
- Also sensitive to ALP, heavy neutral lepton,…




arxiv:2312.12055

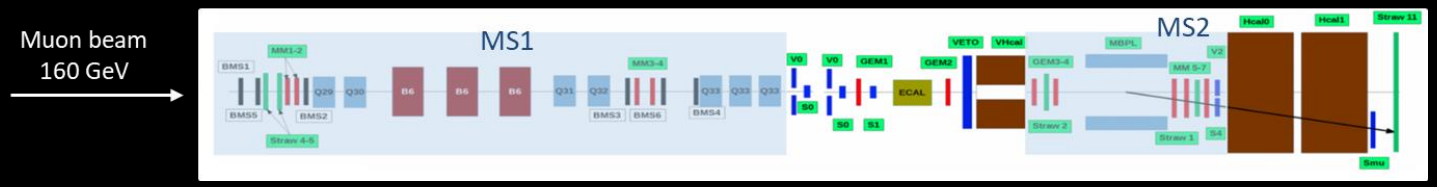
# Muon beam

# Muon beams

## Muon beams

- Uniquely probe couplings to 2nd generation (also flavor agnostic models)
- Clean (minimum ionizing) but hard to come by

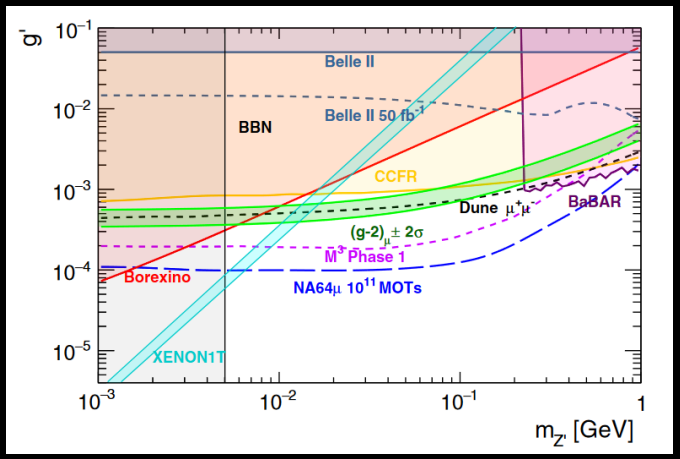
## NA64-mu @ CERN




- Missing energy signature from muon beam radiating Z' boson
- Scattered muon momentum << initial muon momentum
- No energy in all calorimeters
- First data taking in 2022, collected 4x10$^{10}$ MOT

## M$^3$ @ FNAL

- Proposal for a muon missing momentum similar to the LDMX experiment with a muon beam

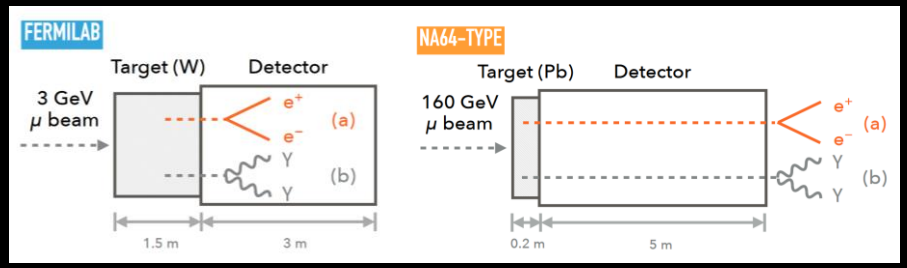



PRD 105, 052006 (2022)

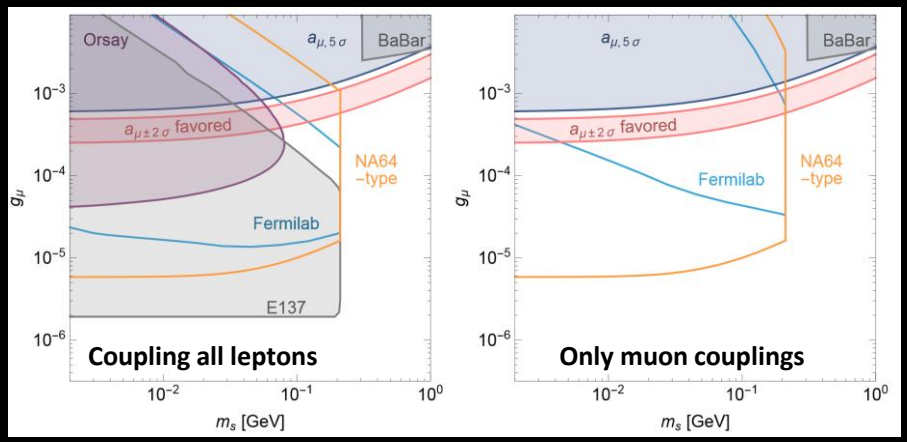
# Muon beams

## Muon beam dump (1701.07437)

- Dark scalar production with beam fully stopped in dump and visible signature
- Dark scalar decay outside detector volume and missing energy signature




Constraints on coupling $g_\mu$



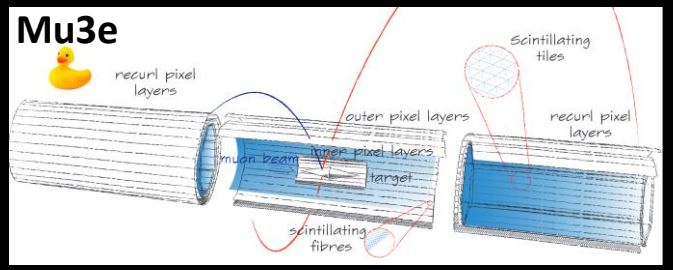

arxiv:1701.07437

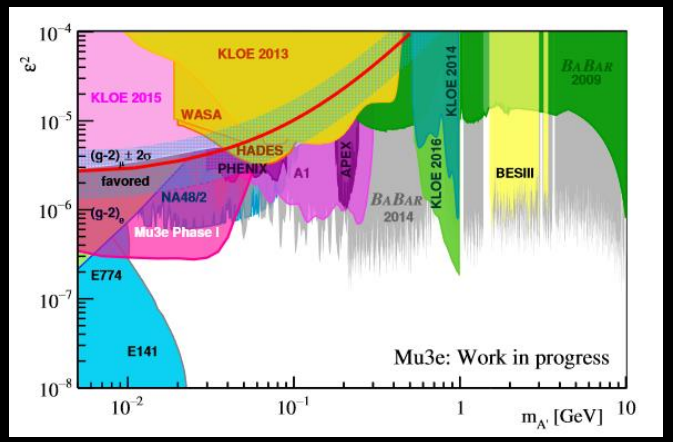
**+ 2310.16110, 2311.10829,…**

## Mu3e experiment

- Use high-intensity stopped muon beam to search for dark photon

$$\mu \rightarrow e\nu\nu A', A' \rightarrow e^+e^-$$



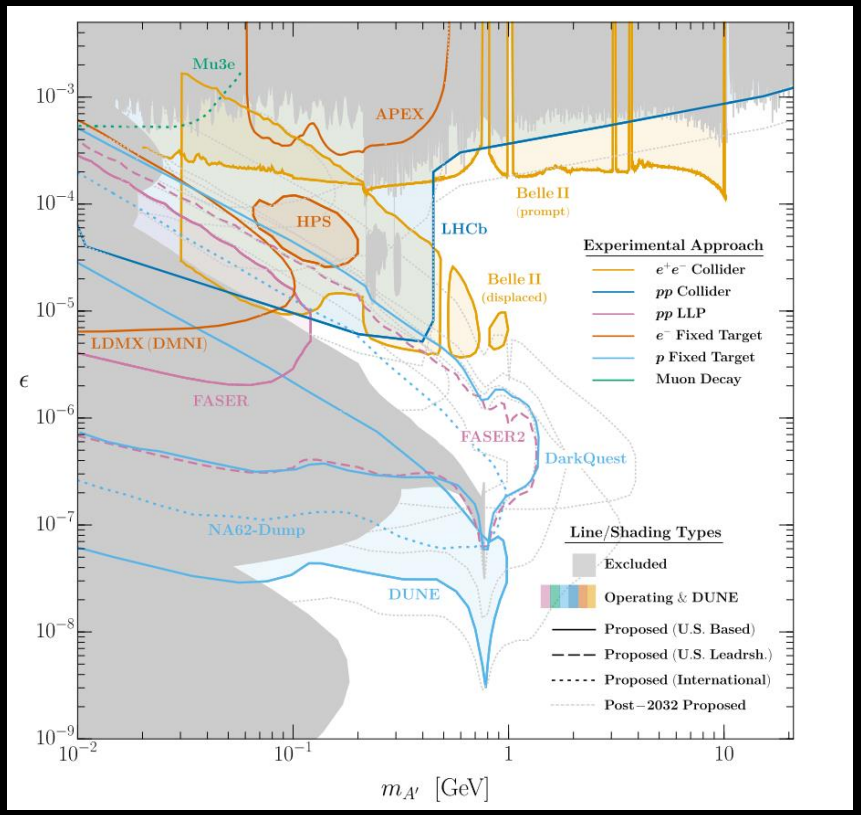




arxiv:2204.00001

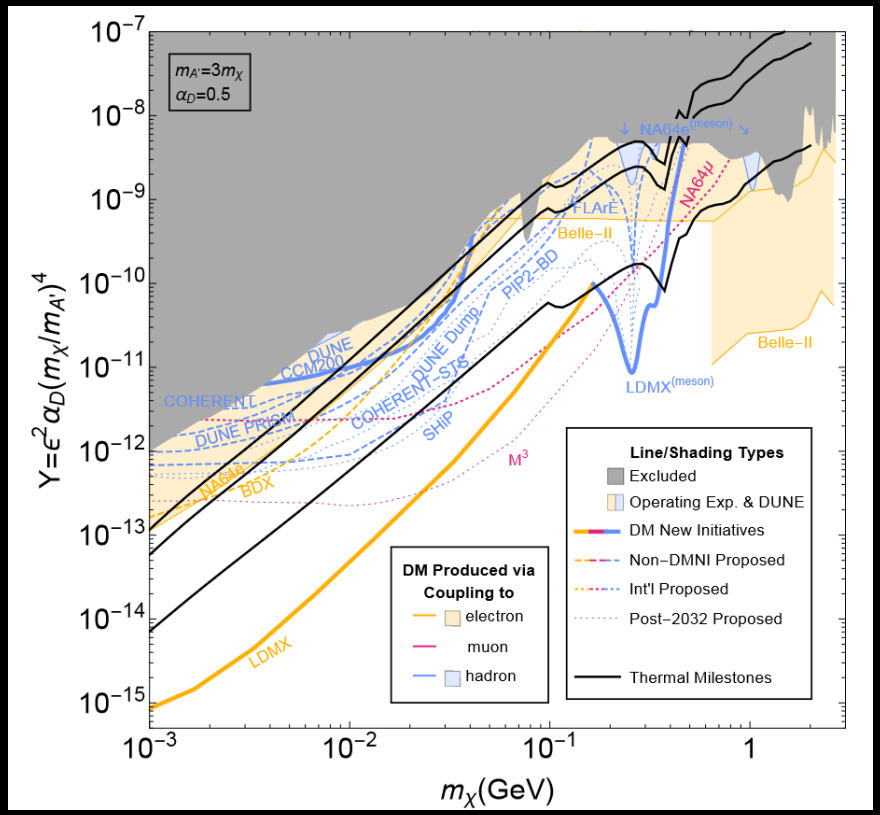
# Epilogue

# The big picture

Visible A’ decays




Invisible A’ decays




RF6 report, arxiv:2209.04671

A significant fraction of the parameter space will be explored in the near future, including the well motivated thermal targets

# Conclusion

Extensive worldwide program to search for feebly interacting particles, including dark photons, ALPs, dark scalars, ….

A wide variety of beam and techniques is needed to explore the vast dark photon parameter space, and a significant fraction of this territory has already been covered

Collider, beam dump, and fixed target experiments will continue to probe the remaining phase space, including the well-motivated thermal dark matter targets

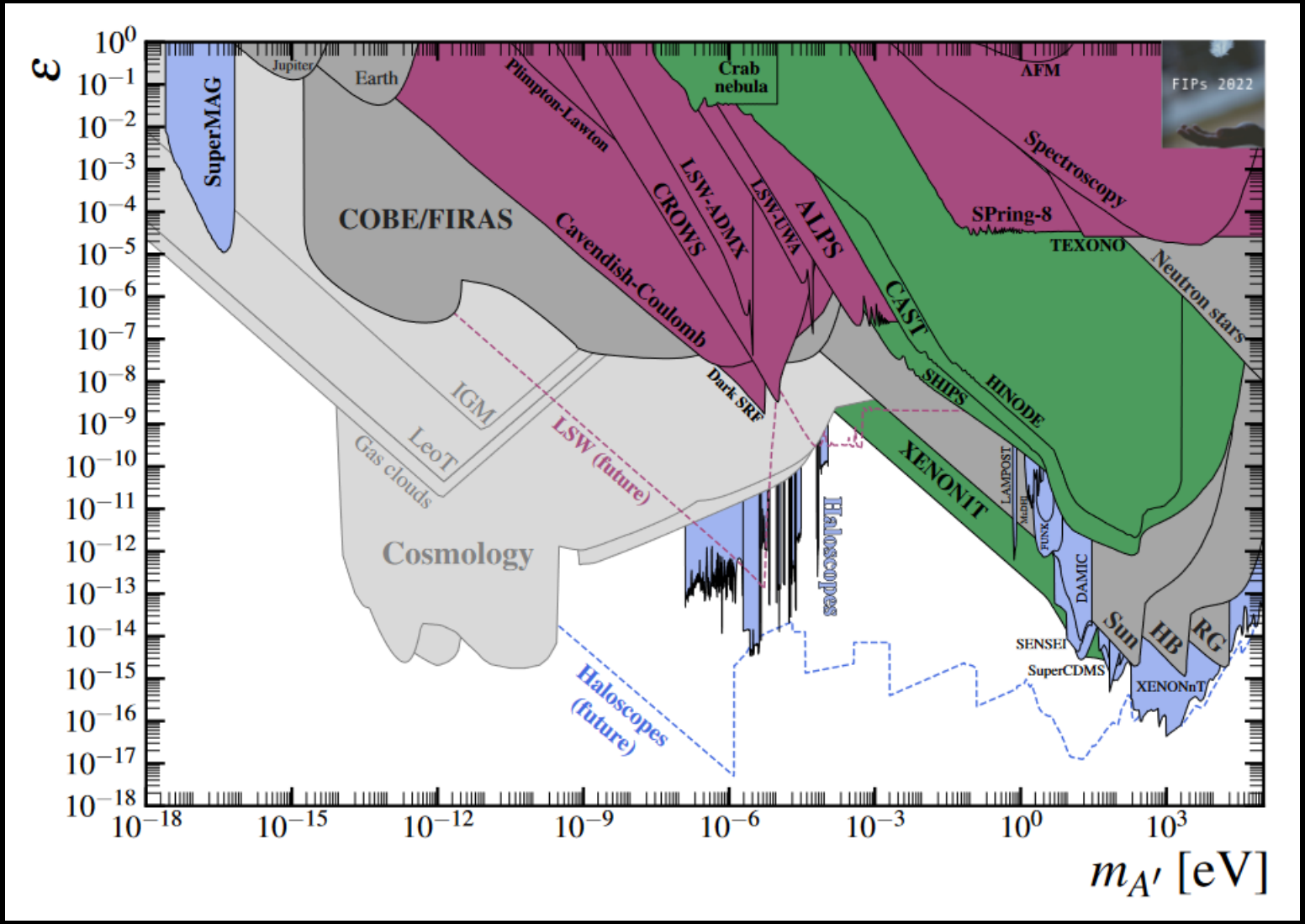
New ideas proposed to further extend the experimental sensitivity could be realized with modest investments, so….

… let’s keep exploring!

Thank you for your attention

# Extra material

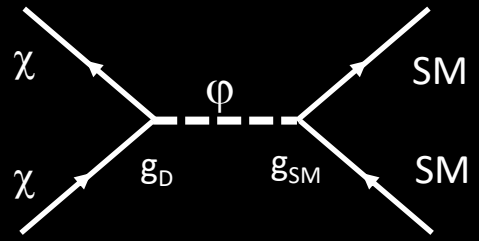
# Light dark photon constraints




FIP 2022 report, arxiv:2305.01715

# Hidden sector dark matter

Thermal DM allows mass down to ~MeV, but requires a new light mediator to explain the relic density, or dark matter is overproduced (Lee Weinberg bound)




$$< \sigma v >_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

$$m_\varphi^4 < \sigma v > \sim g_D^2\, g_{SM}^2\, m_x^2 \leq m_x^2 \qquad \text{since } g \leq O(1)$$

**Mediator must be neutral under the SM interactions, naturally realized in the context of hidden sectors**

Benchmark scenario: light dark matter via vector portal

Interestingly, the DM relic density for direct annihilation via the vector portal depends only on the mass, spin and dark sector couplings

$$< \sigma v > \sim \alpha_D \varepsilon^2 \frac{m_x^2}{m_A^4} \sim y \frac{1}{m_x^2}$$

Dimensionless variable $\quad y = \alpha_D\, \varepsilon^2 \frac{m_x^4}{m_A^4}$