(Fixed-Target) Searches for Light DM and Vector Mediators in the US

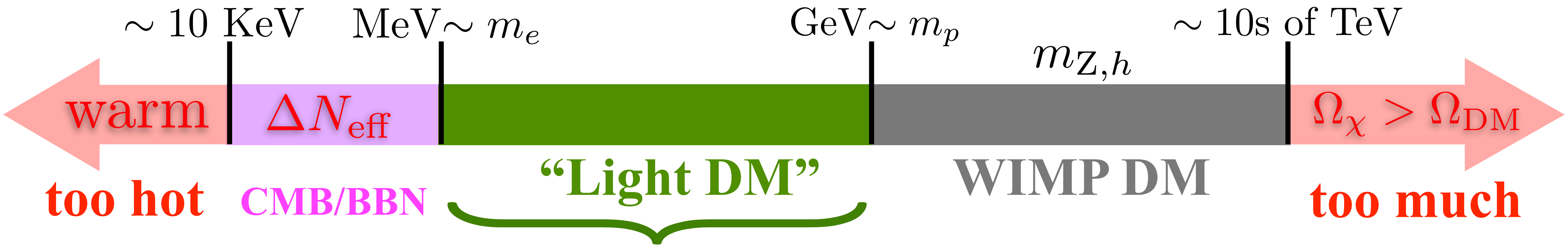
Tim Nelson

FIPs 2020 - September 2, 2020

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

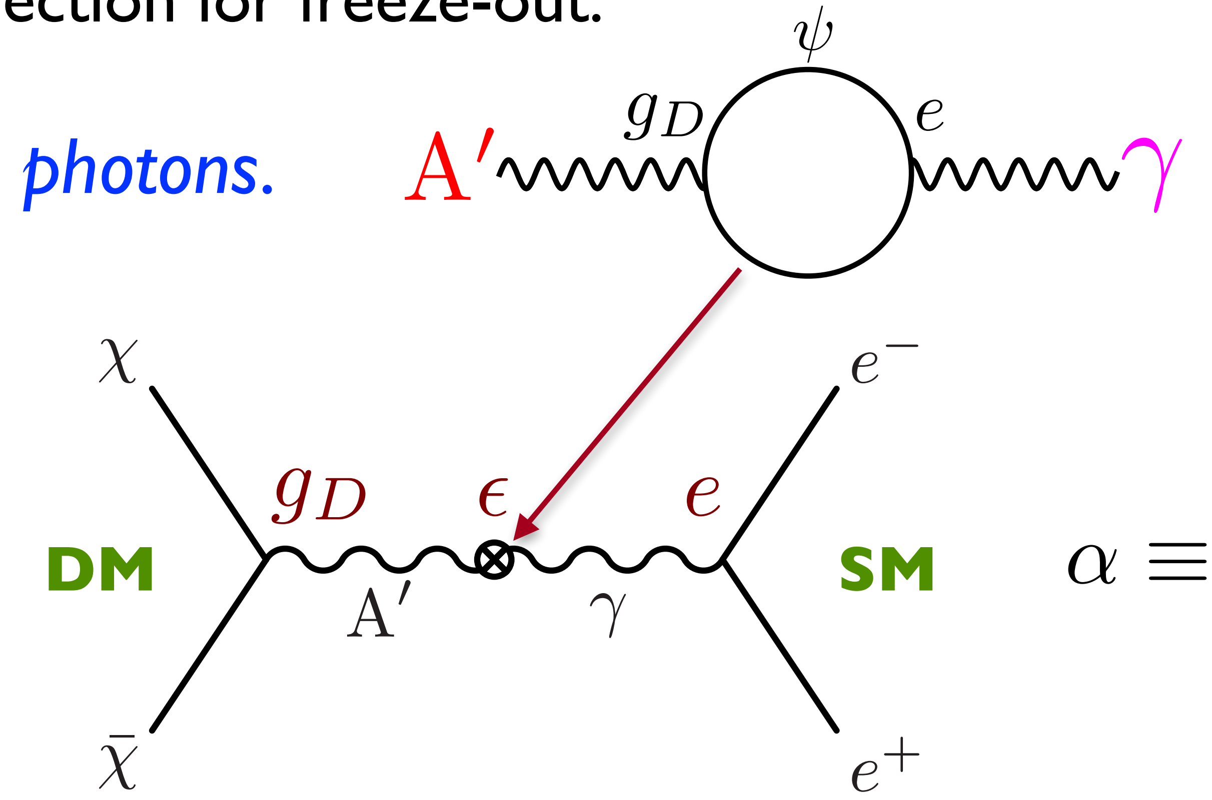
Key Motivation: Low-mass Freeze-out Thermal Relics



Production rates in MeV-GeV range are large at accelerators, esp. fixed target!

MeV-GeV thermal relic DM requires new, comparably light mediators to achieve required annihilation cross-section for freeze-out.

Benchmark scenario: dark photons.

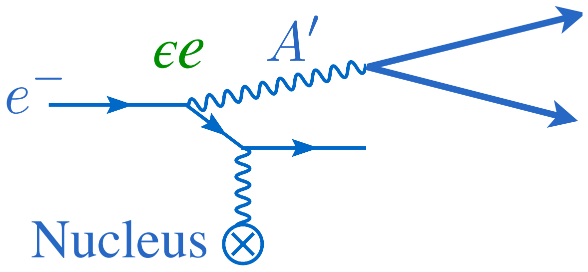


$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$

$$\alpha \equiv \frac{e^2}{4\pi}$$

Dark Photon Production

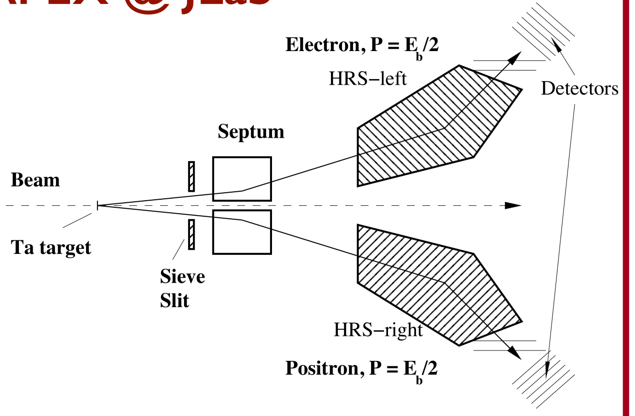
e fixed target



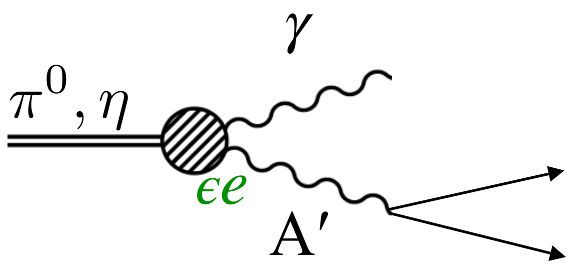
$$N \propto \epsilon^2$$

- dark bremsstrahlung
- $e^+e^- \to A'\gamma$

APEX @ JLab

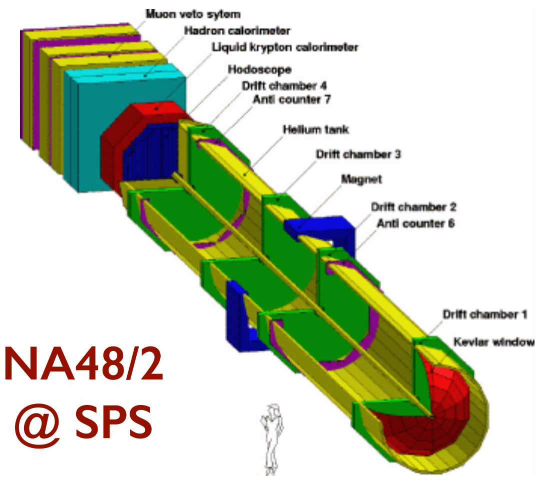


p fixed target



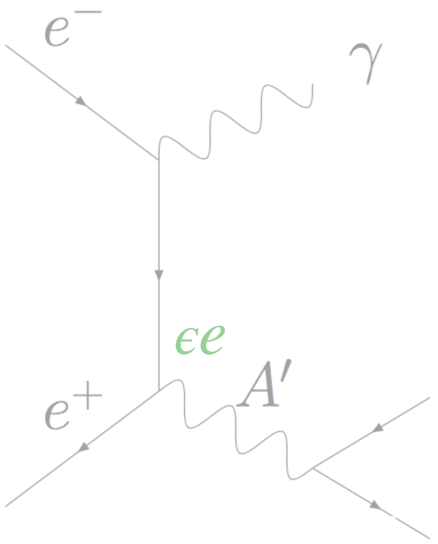
$$N \propto \epsilon^2$$

- meson decays
- dark bremsstrahlung



NA48/2 @ SPS

e^+e^- colliders



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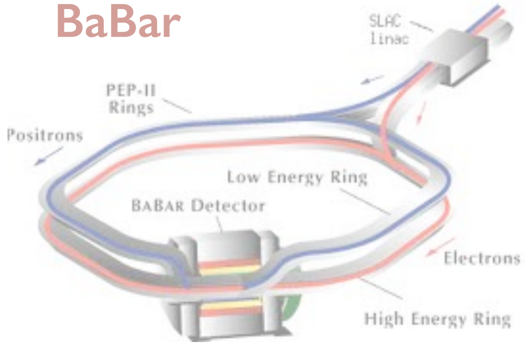
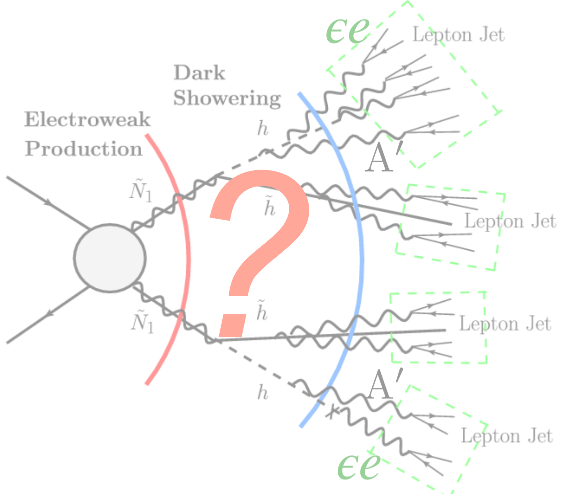
BaBar

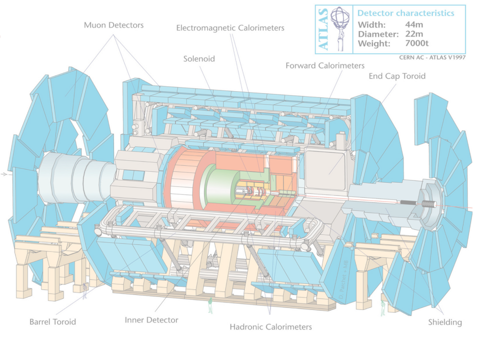


pp collider



- “lepton jets” $N \propto ?$
- meson decays $N \propto \epsilon^2$

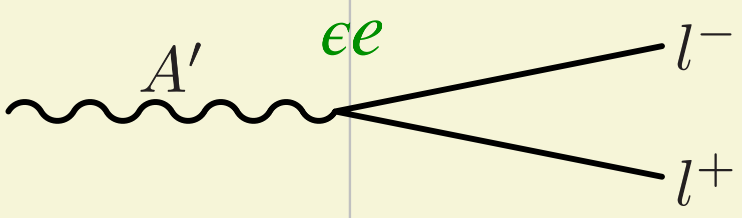
ATLAS
CMS
LHCb

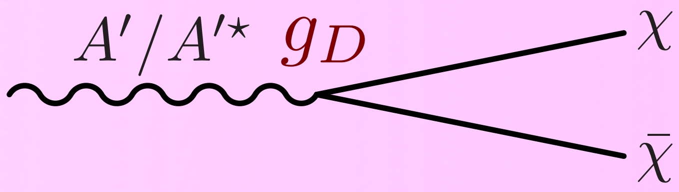


Analogous SM process is irreducible background but allows $(M_{A'},N_{\text{observed}}) \Longrightarrow (M_{A'},\epsilon)$

Mass Hierarchy Determines Search Strategy & Interpretation

Mediator decay in experiments





Search: ***for mediators decaying to SM*** | ***for production of DM***

spectrometers: (e.g. APEX, HPS, DarkQuest)
missing mass: (e.g. PADME @ JLab)

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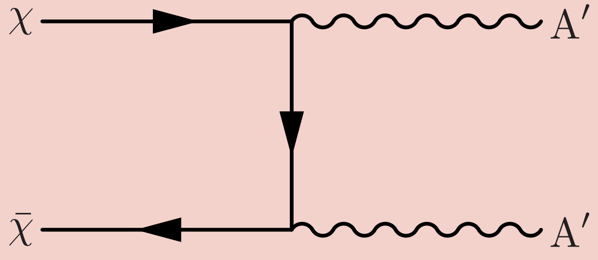
searches typically measure/constrain ϵ^2 as a function of $M_{A'}$

Dominant DM annihilation:

$$\sigma v \propto \alpha_D^2$$

no clear target for ϵ



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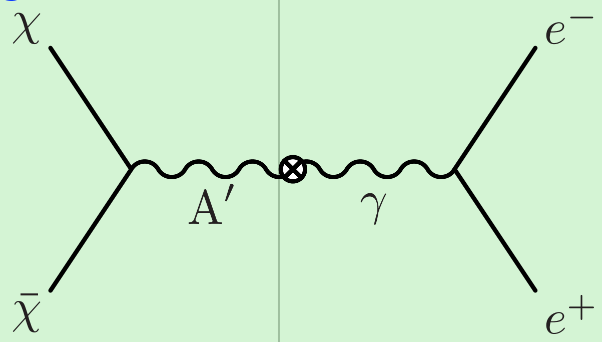
"Thermal Target" - lower limit on ϵ for thermal relics



Mass Hierarchy Determines Search Strategy & Interpretation

$m_{A'}$ → m_χ, $2m_\chi$

Mediator decay in experiments

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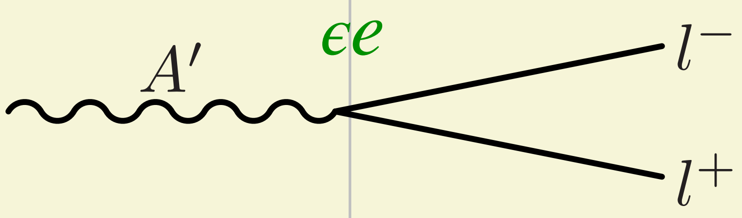

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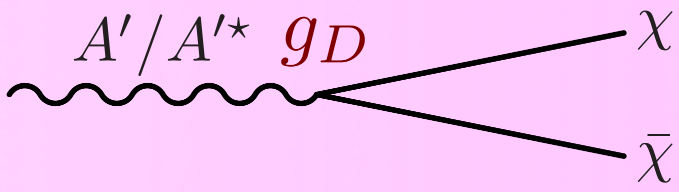

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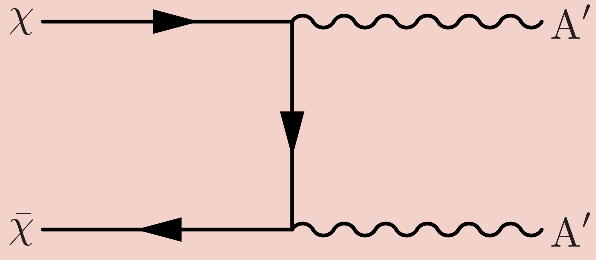

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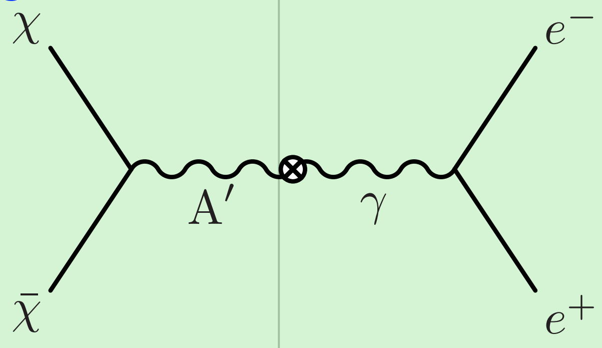
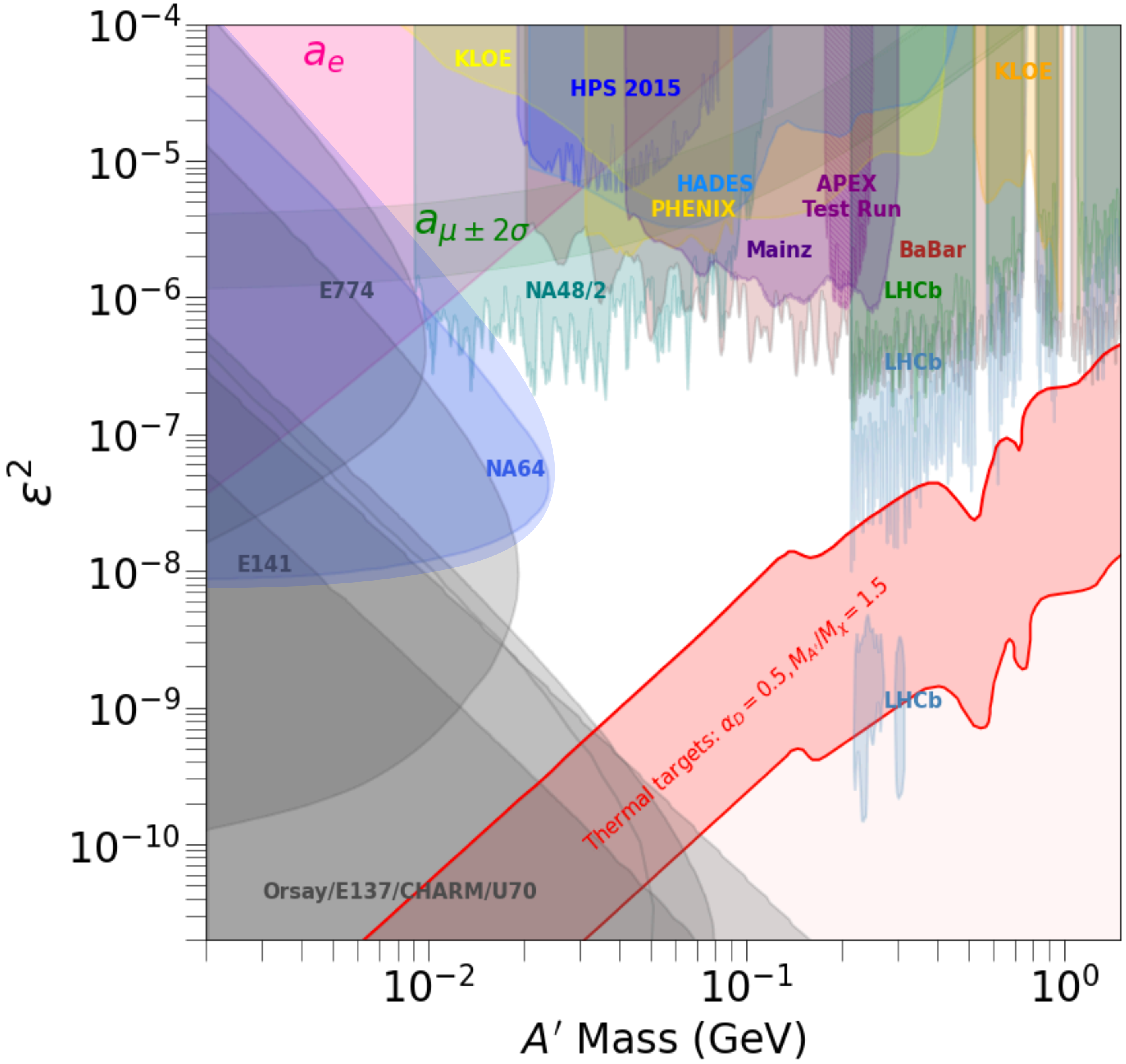


Parameter Space for Mediator Decays to SM

Current A′ Constraints:



Parameter Space for Mediator Decays to SM

Generally, searches are "bump hunts" for $m(l^+l^-)$ resonances.

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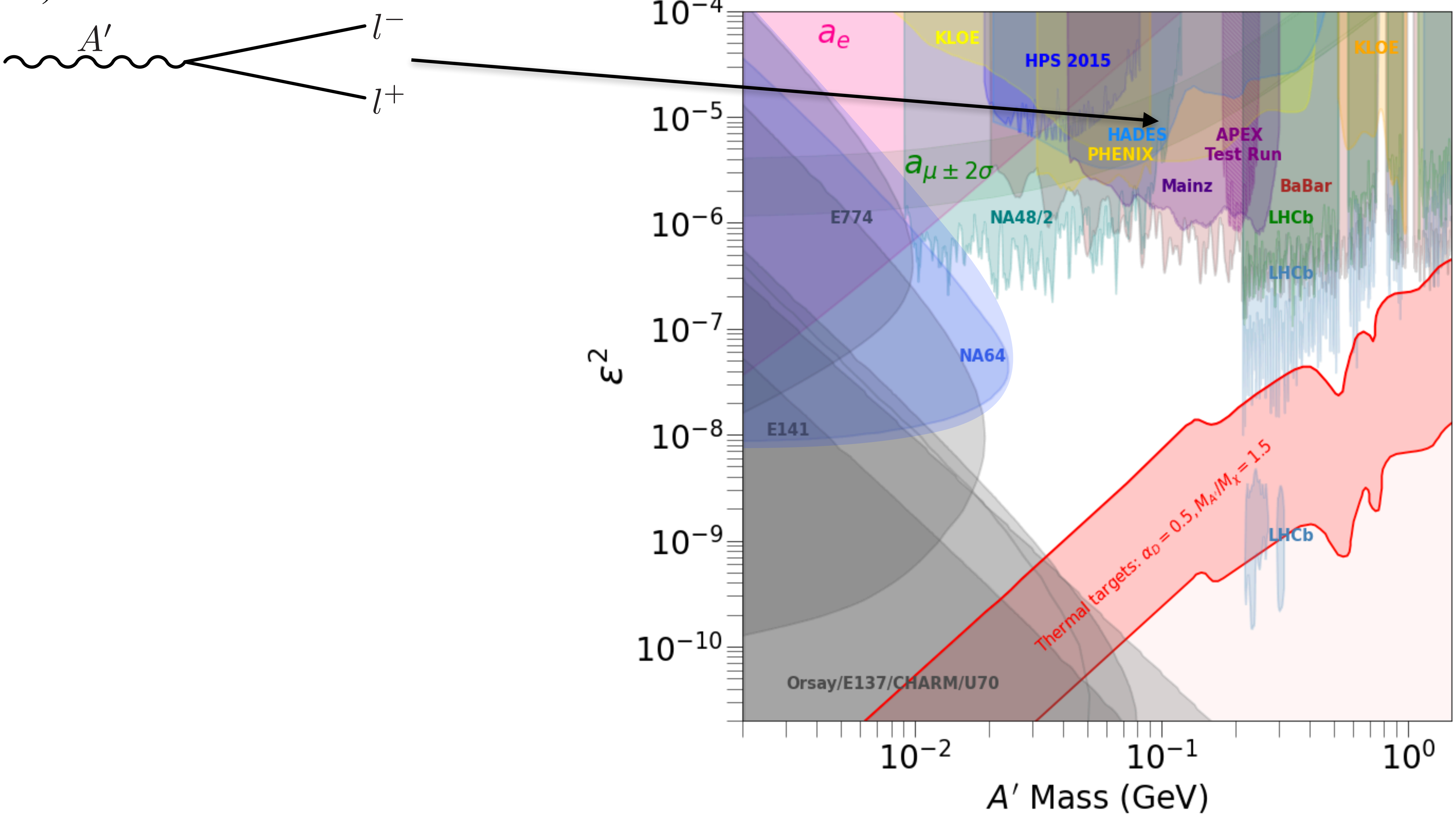

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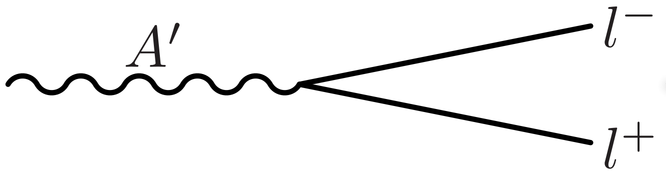
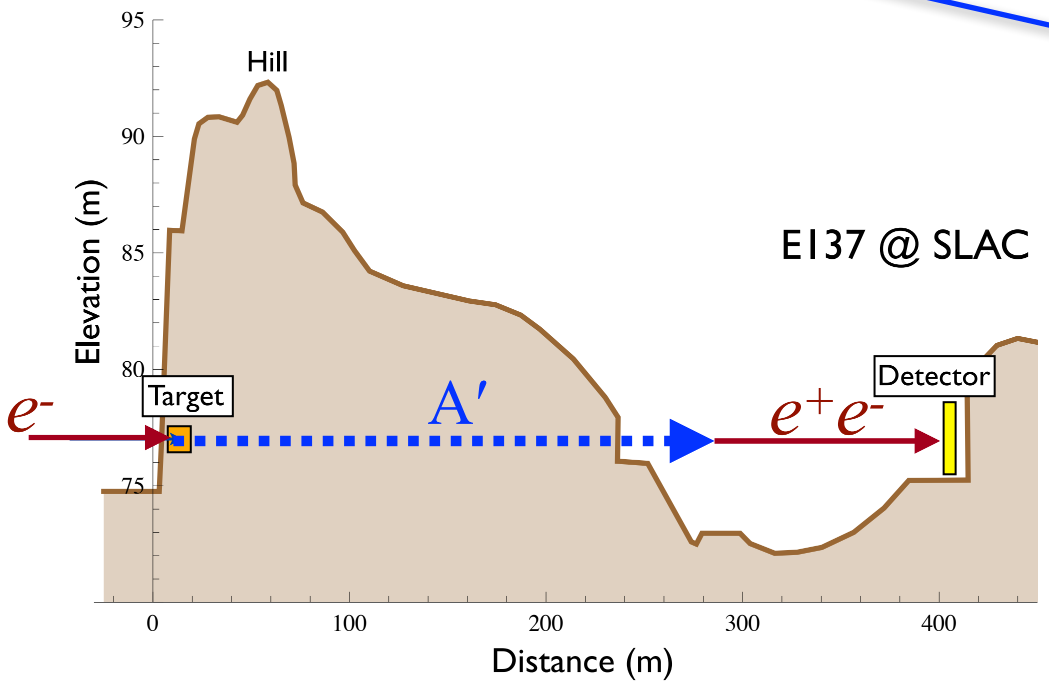


A′ becomes long lived at small couplings.

$$\gamma c\tau \propto \frac{1}{\epsilon^2 m_{A'}^2}$$

Leads to constraints from beam dump experiments



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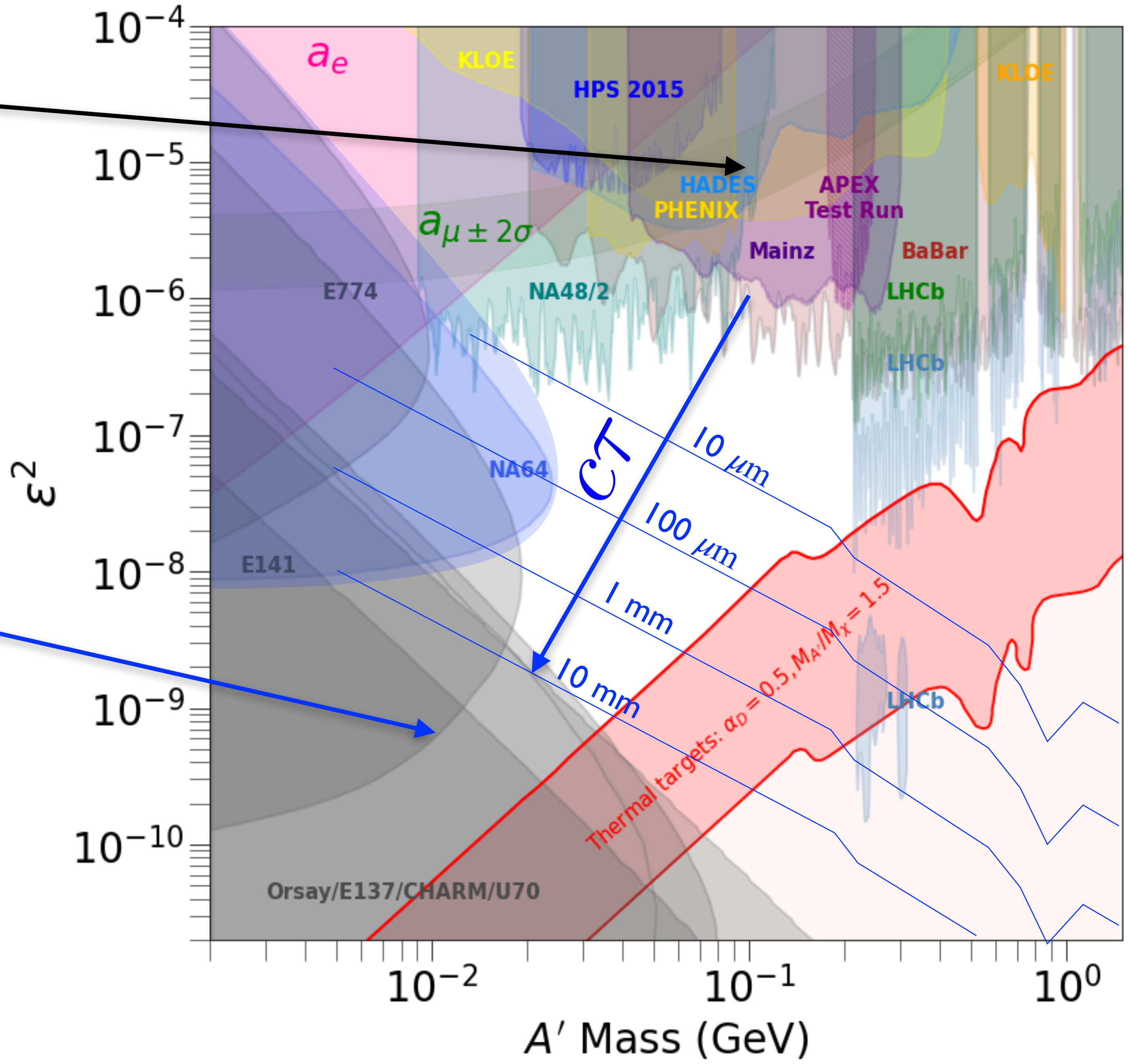

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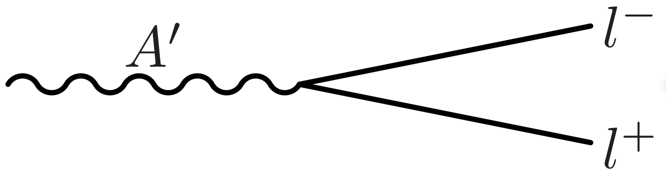

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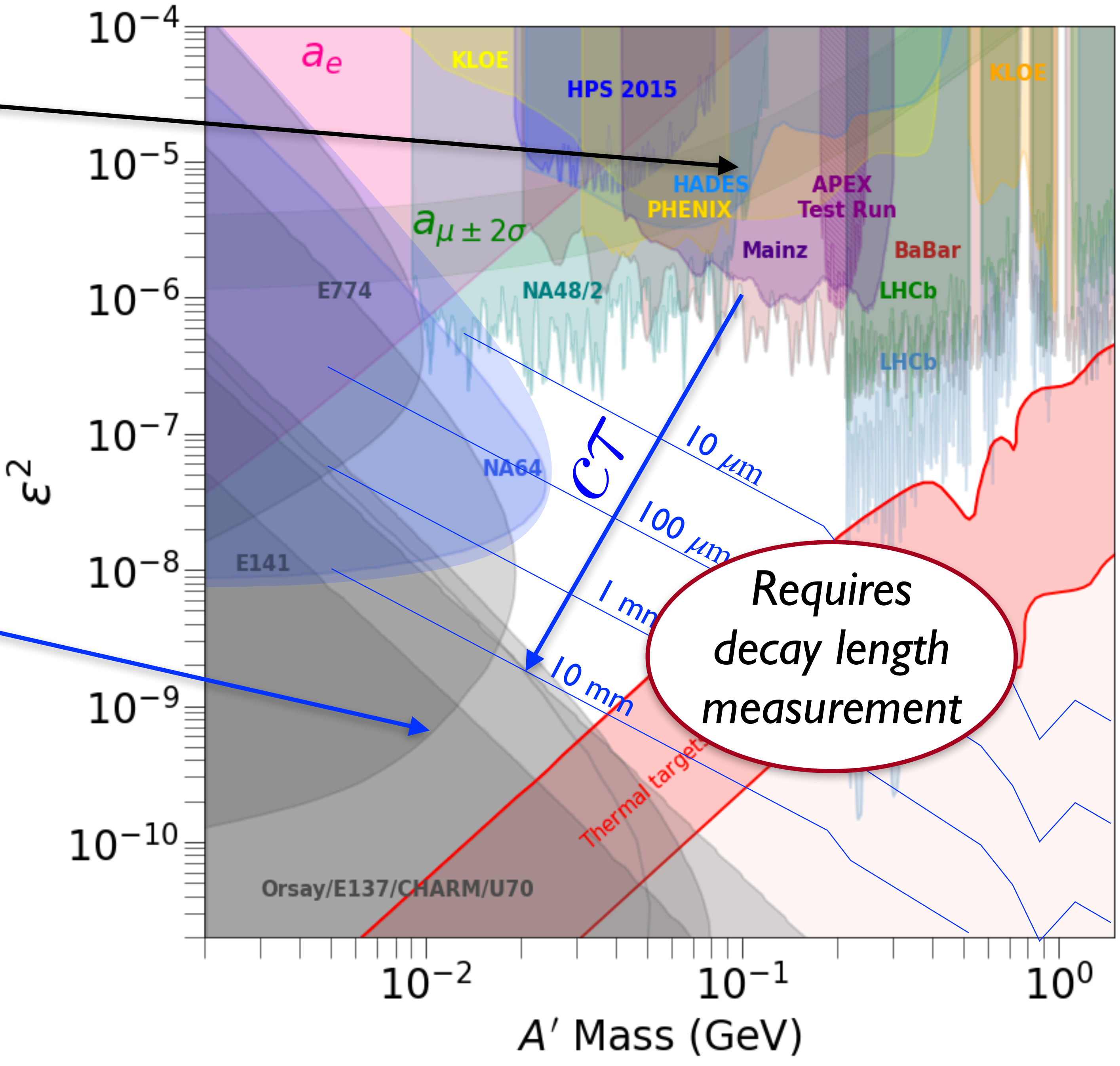

Requires decay length measurement

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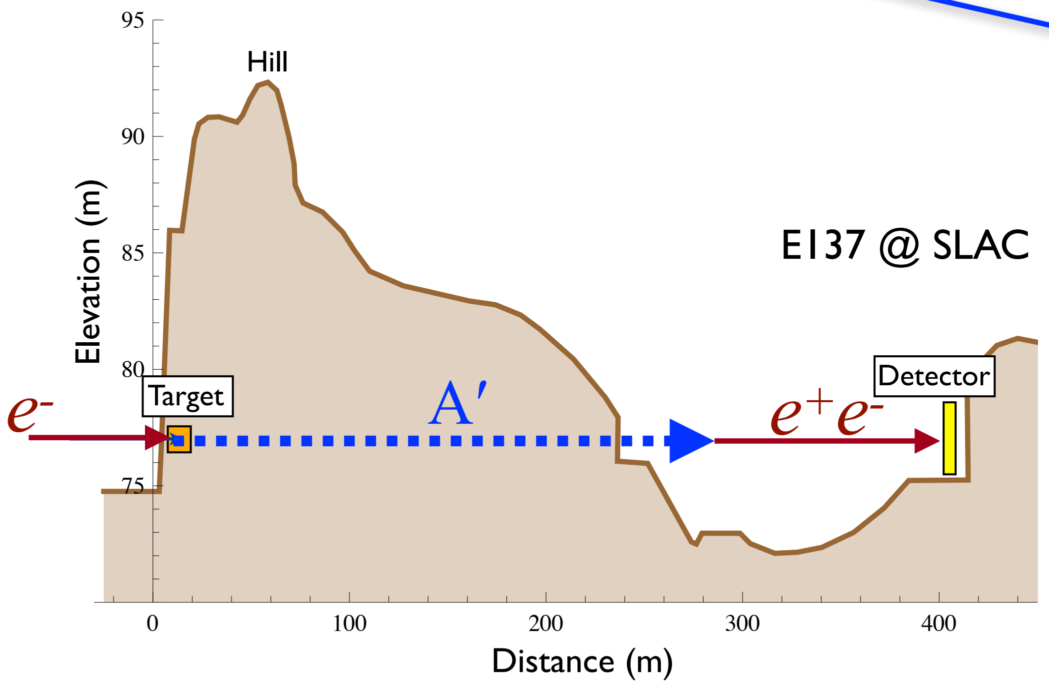
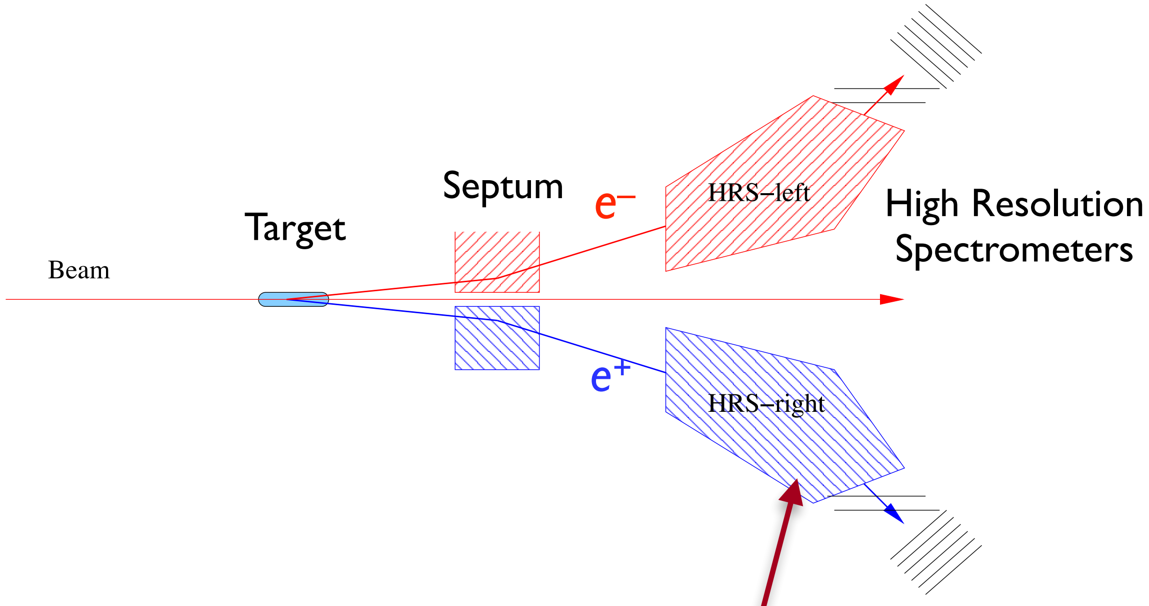
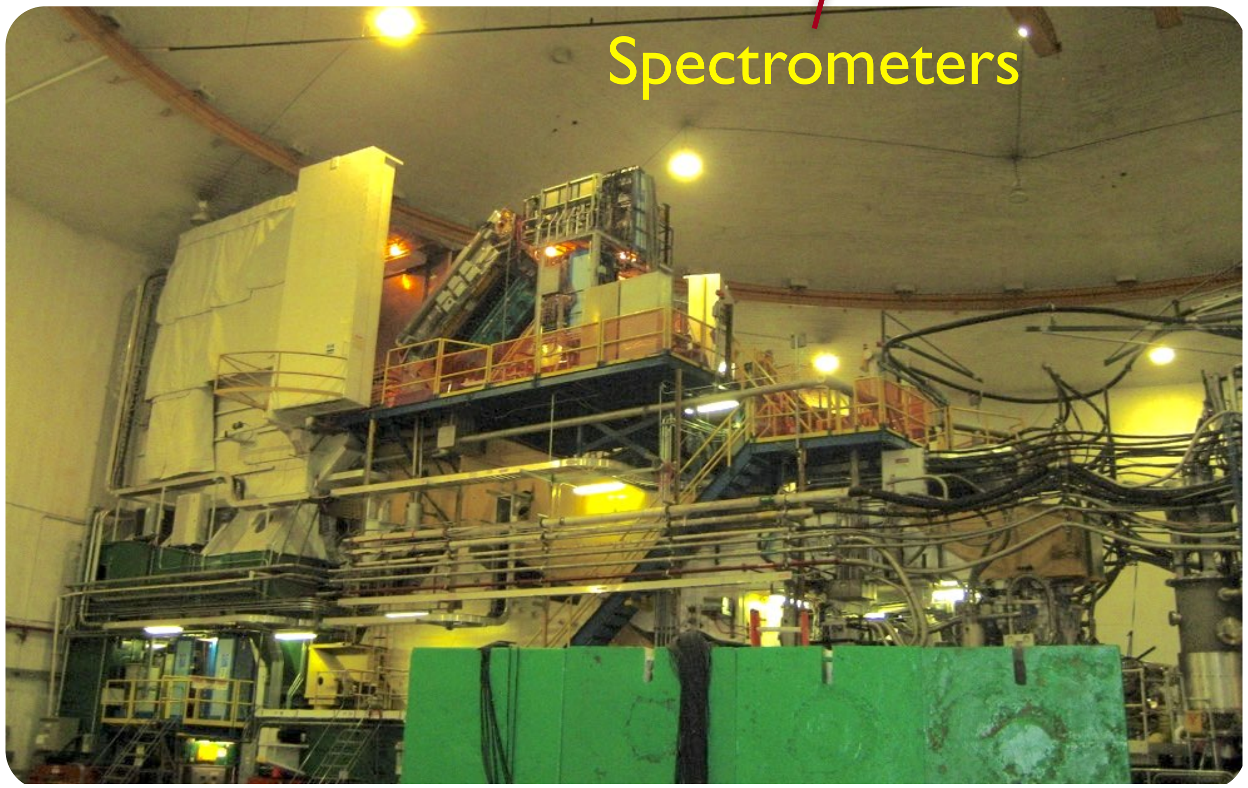


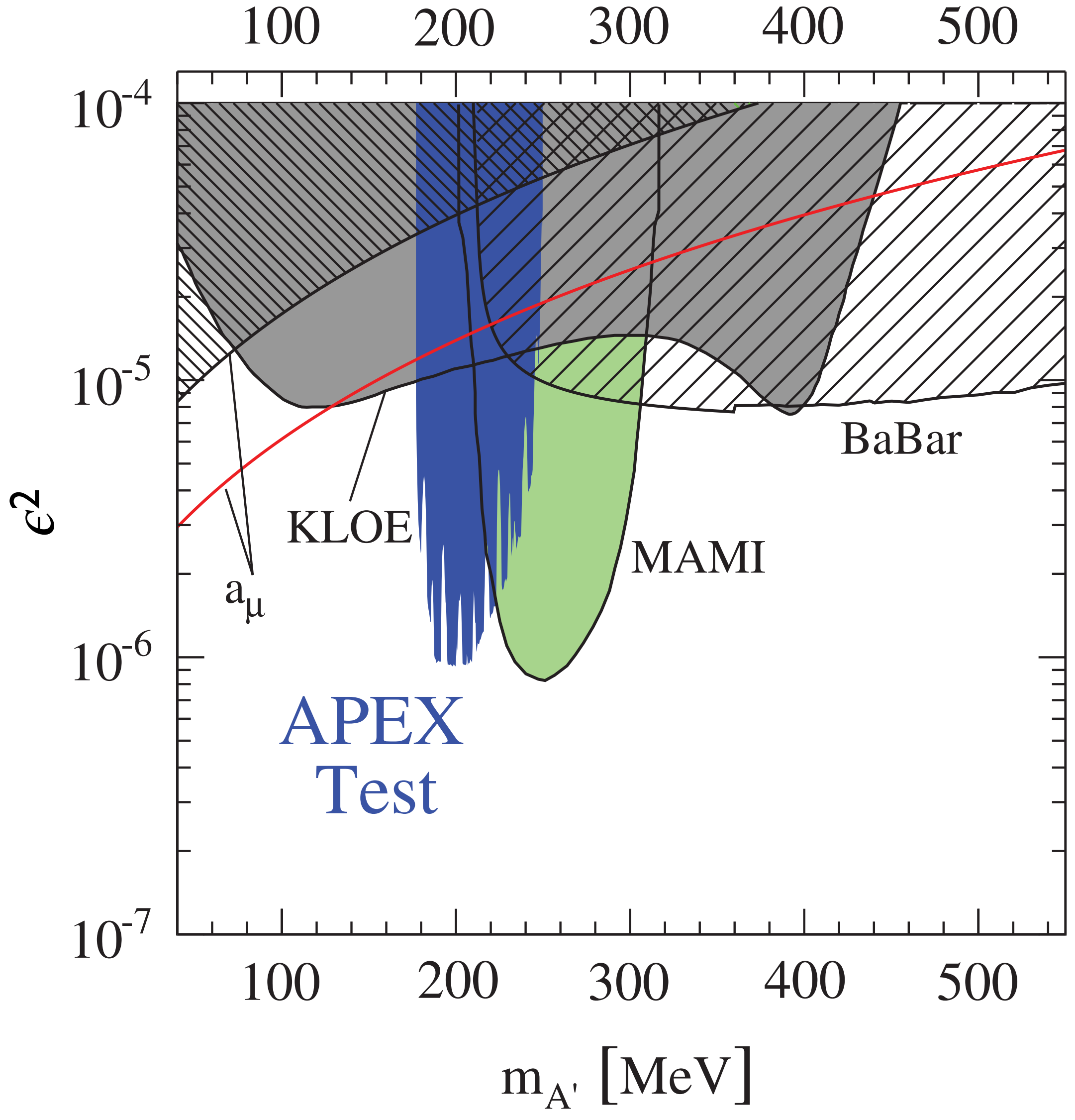
e^- beam + spectrometer: APEX @ JLab CEBAF (2010-?)

Resonance search using Hall A High-Resolution Spectrometers, dark bremsstrahlung production from multi-GeV e^- beam





Test run in 2010: proof of concept and technical feasibility



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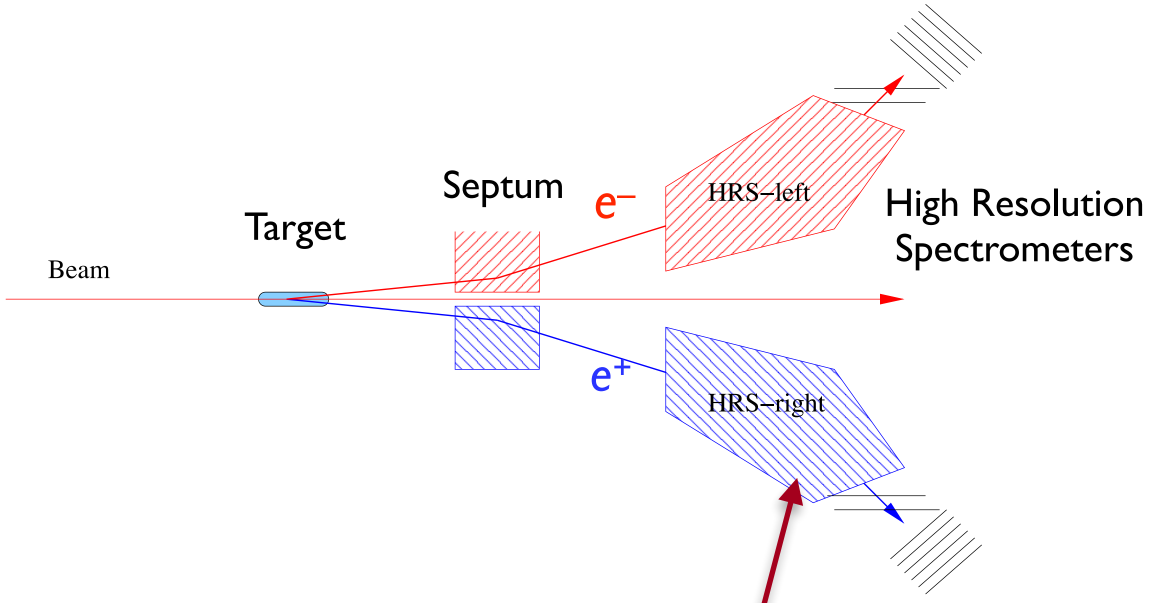
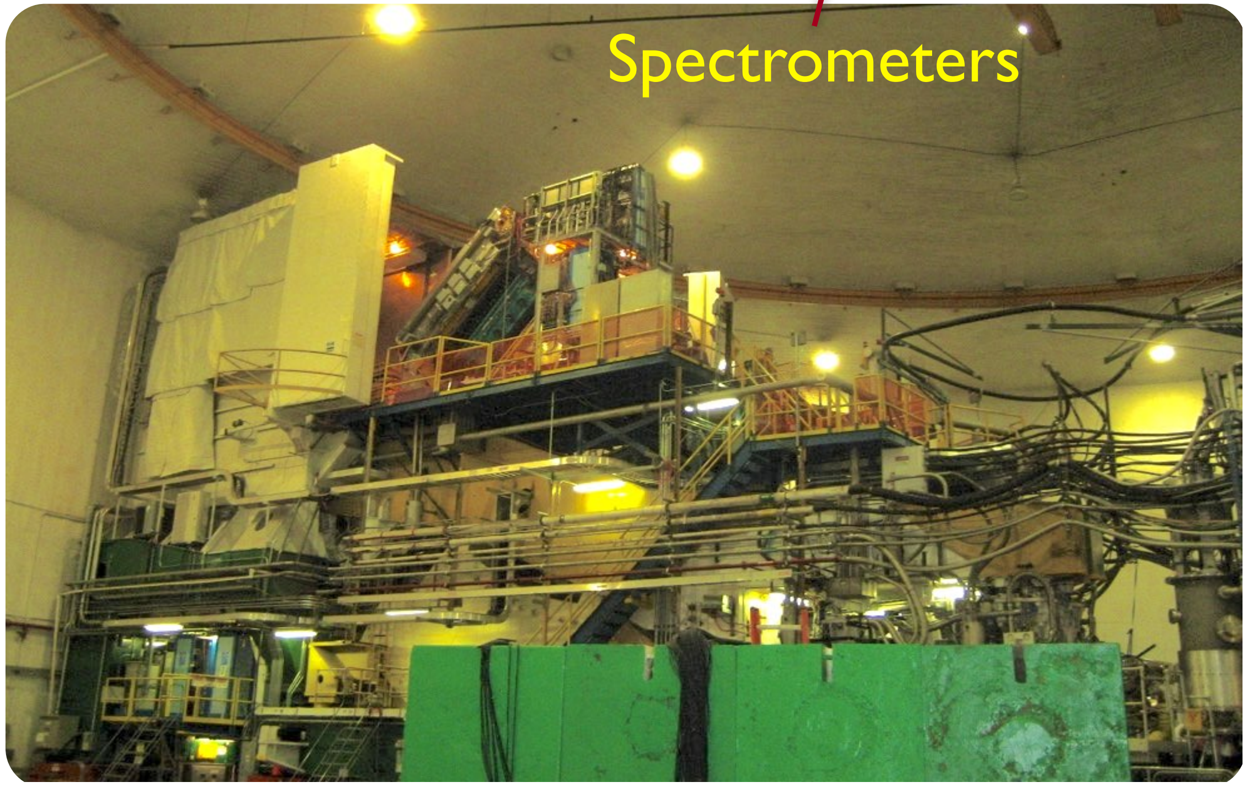
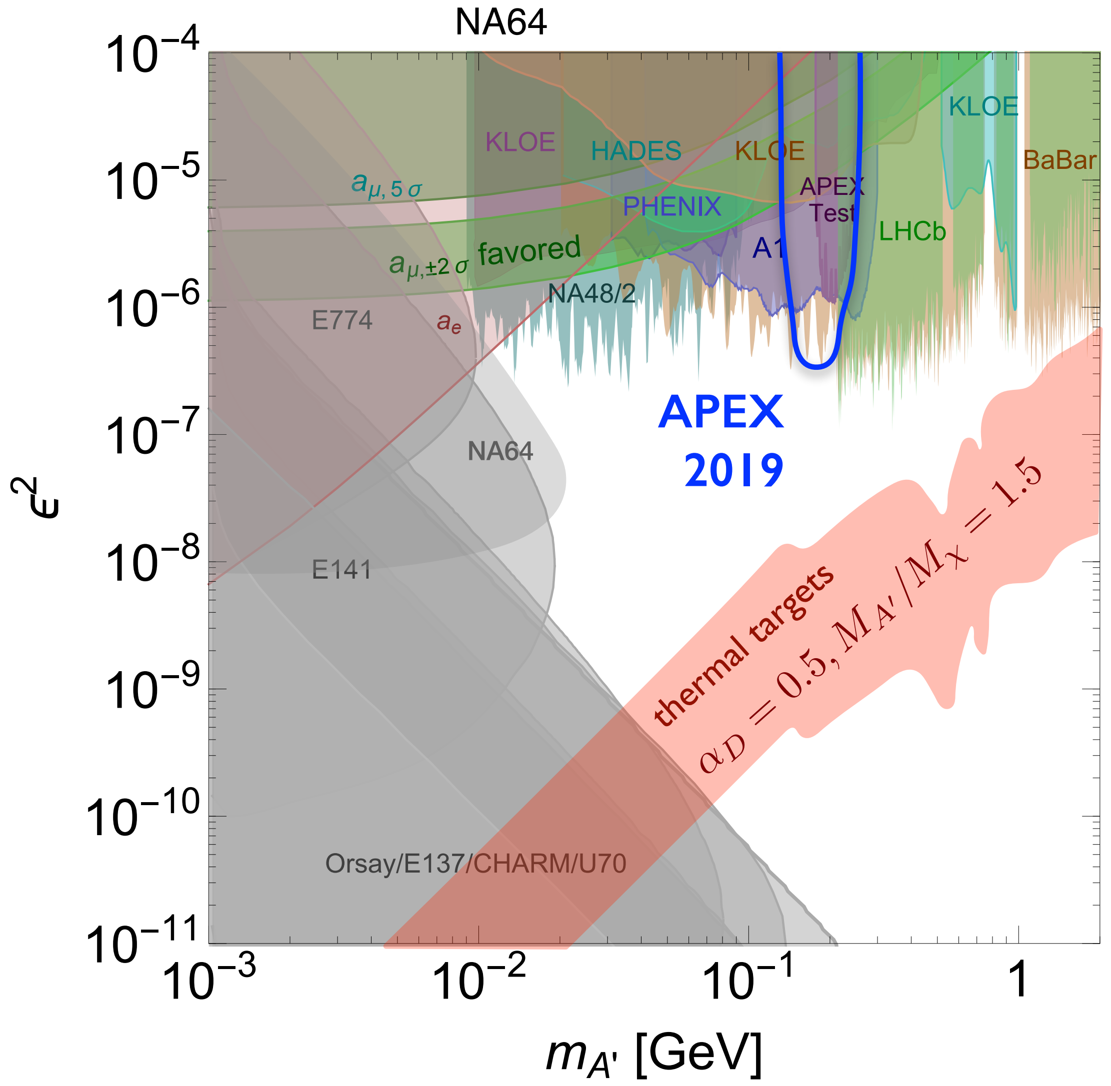




2019 Physics Run *(Jan. - Mar. 2019)*
15 days at E_{beam} = 2.2 GeV



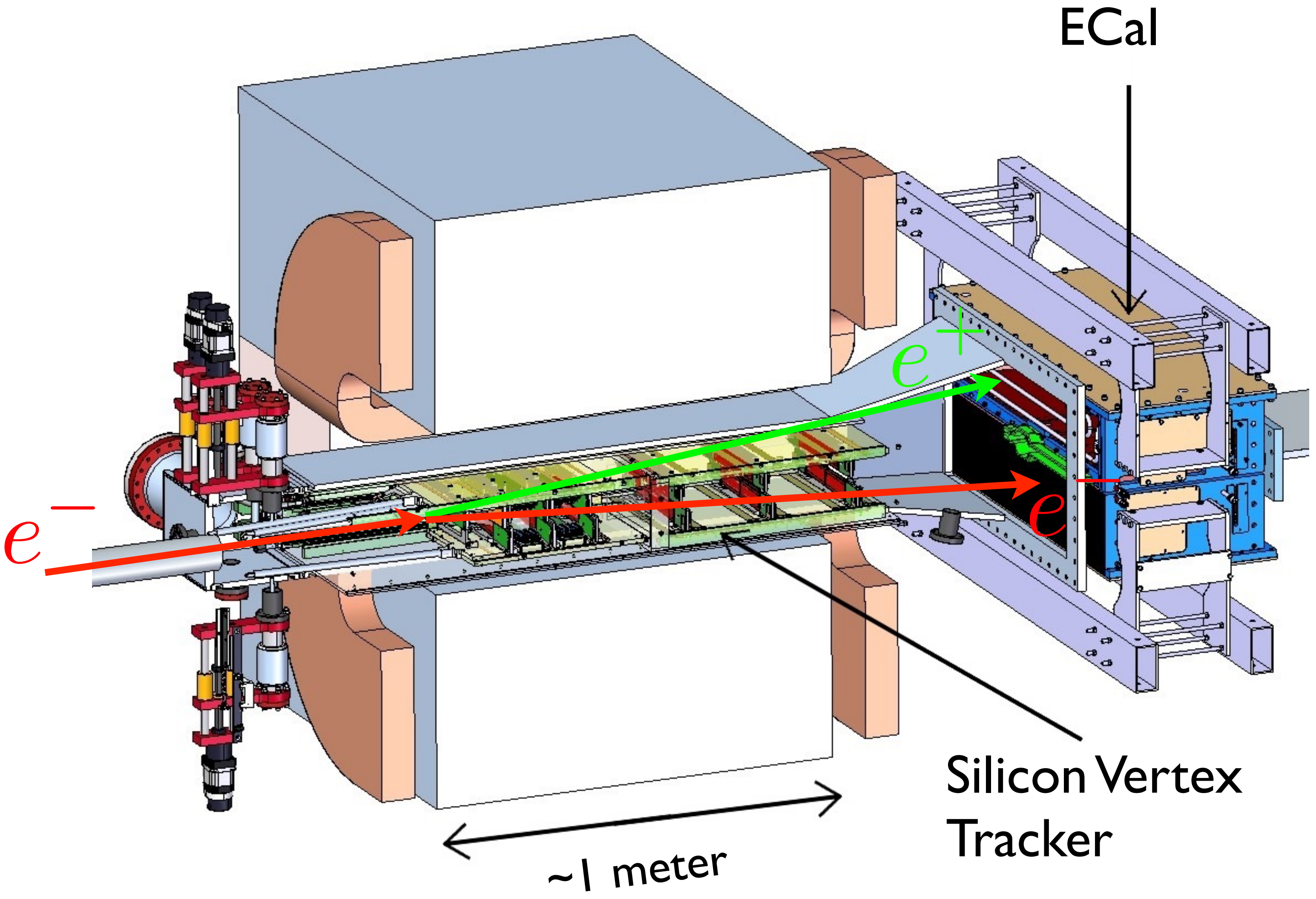
precision calibration and analysis ongoing

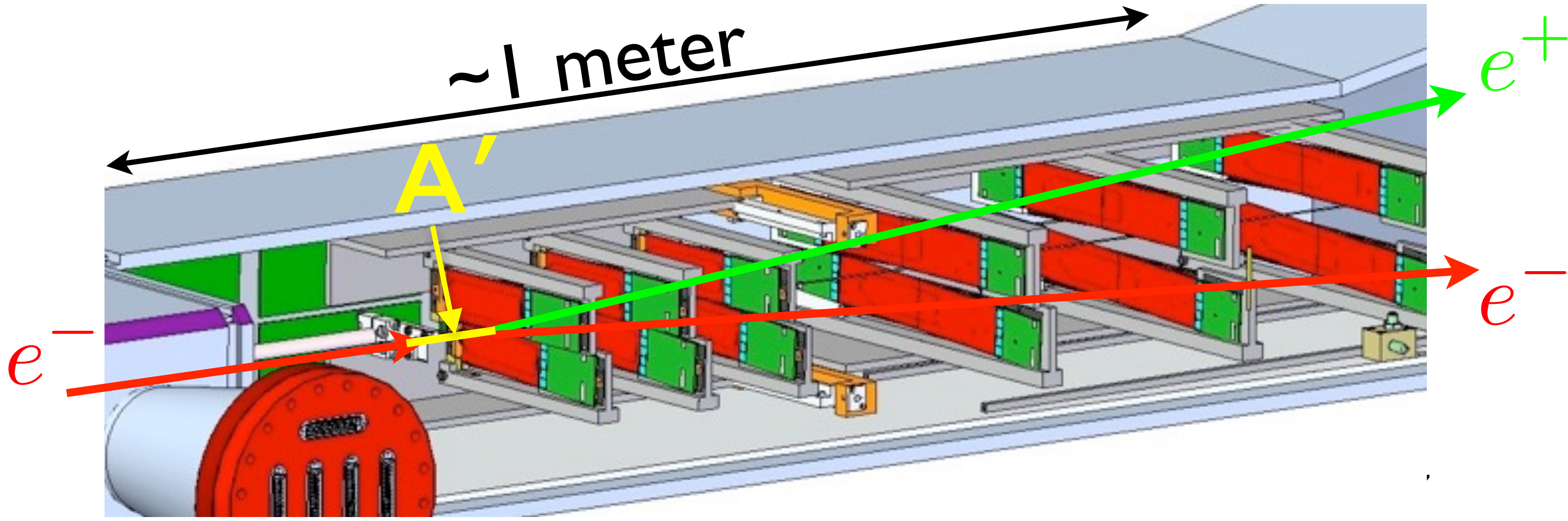
e^- beam + spectrometer w/ vertexing: HPS @ JLab CEBAF (2015-?)

Compact e^+e^- spectrometer, immediately downstream of thin target in multi-GeV beam in Hall B.

- Low-mass, high-rate (>5 MHz/mm^2) silicon tracker (SVT) allows vertexing long-lived A'.
  SVT must suppress SM tridents from target by factor ~10^7
- PbWO$_4$ ECal trigger eliminates 10's MHz scattered single e^-.

Short engineering runs in 2015 (1.7 days) and 2016 (5.4 days)





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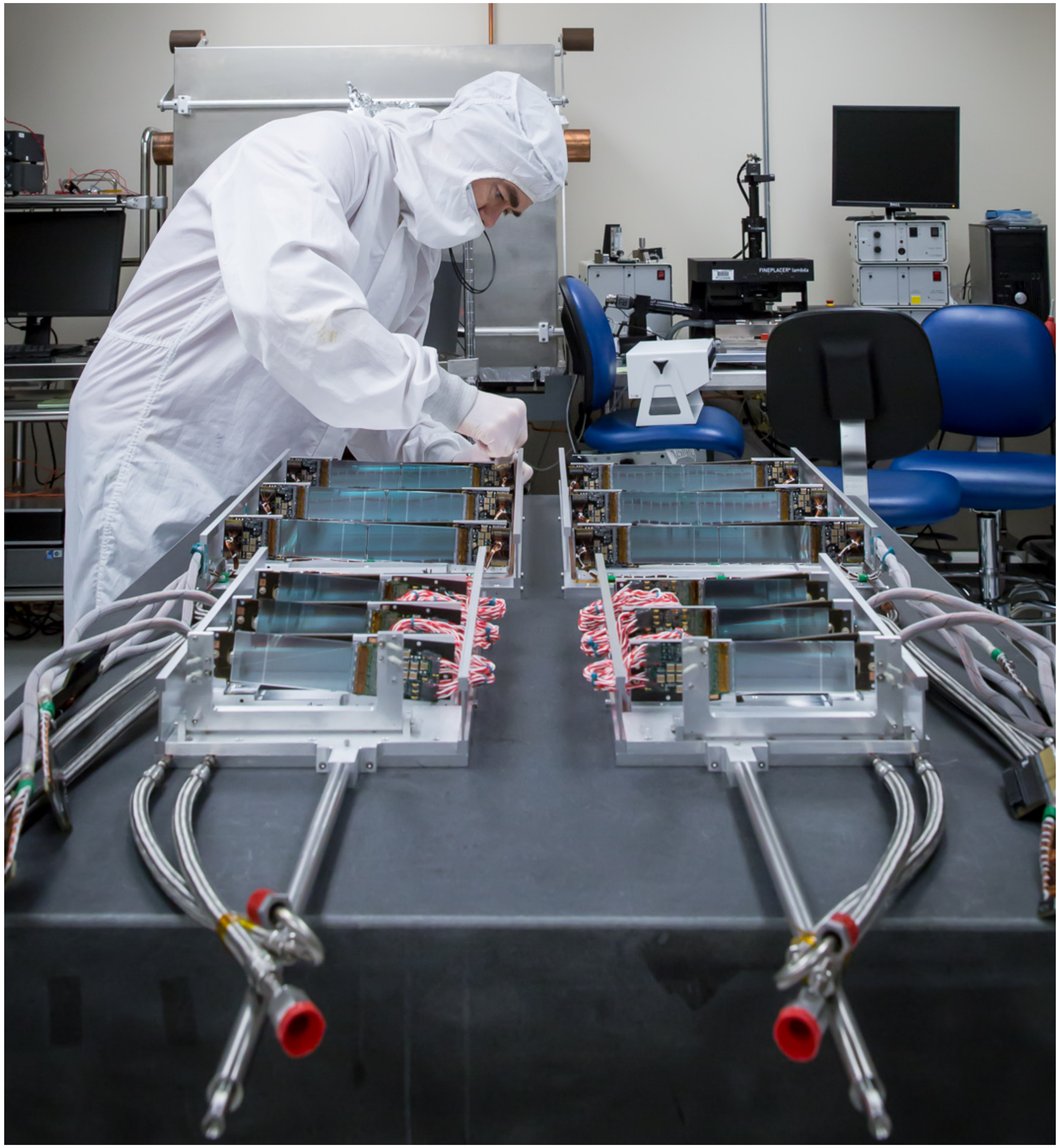

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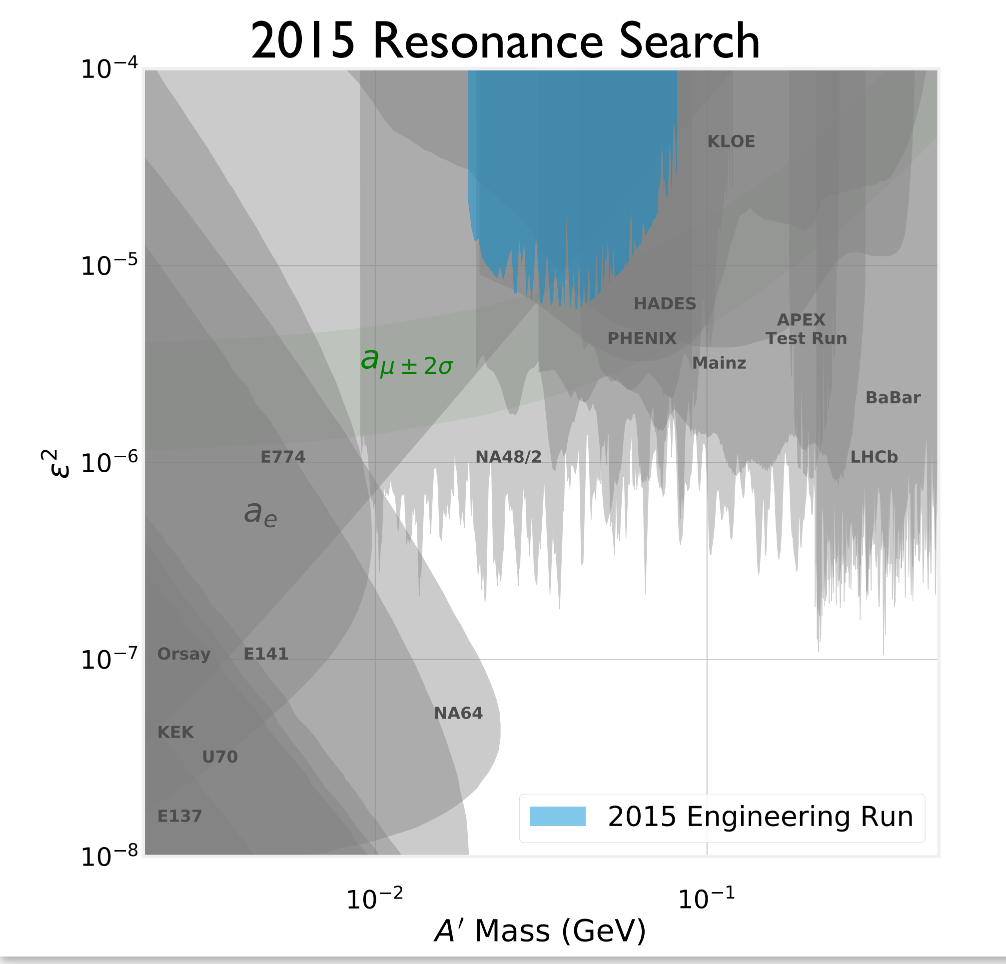
Phys. Rev. D98 (2018), 091101


2015 Resonance Search

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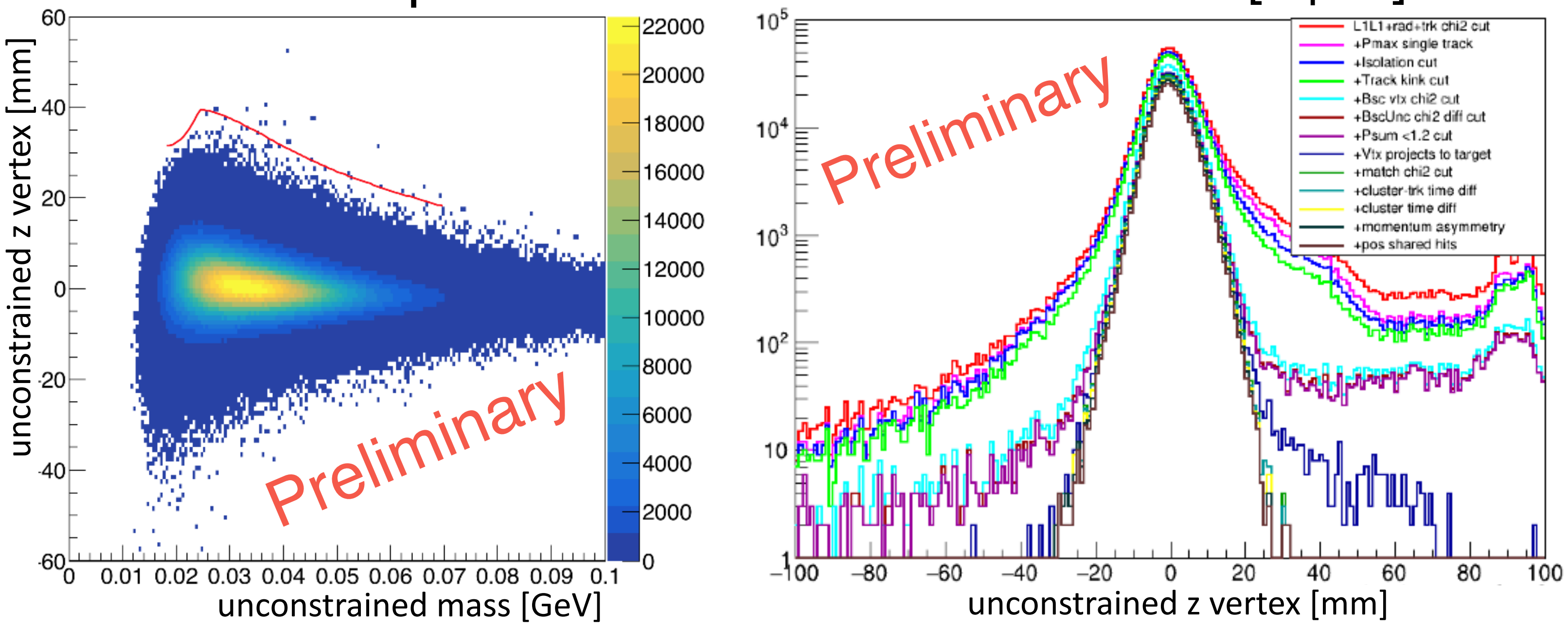
2015 Displaced Vertex Search arXiv:1812.02169 [hep-ex]



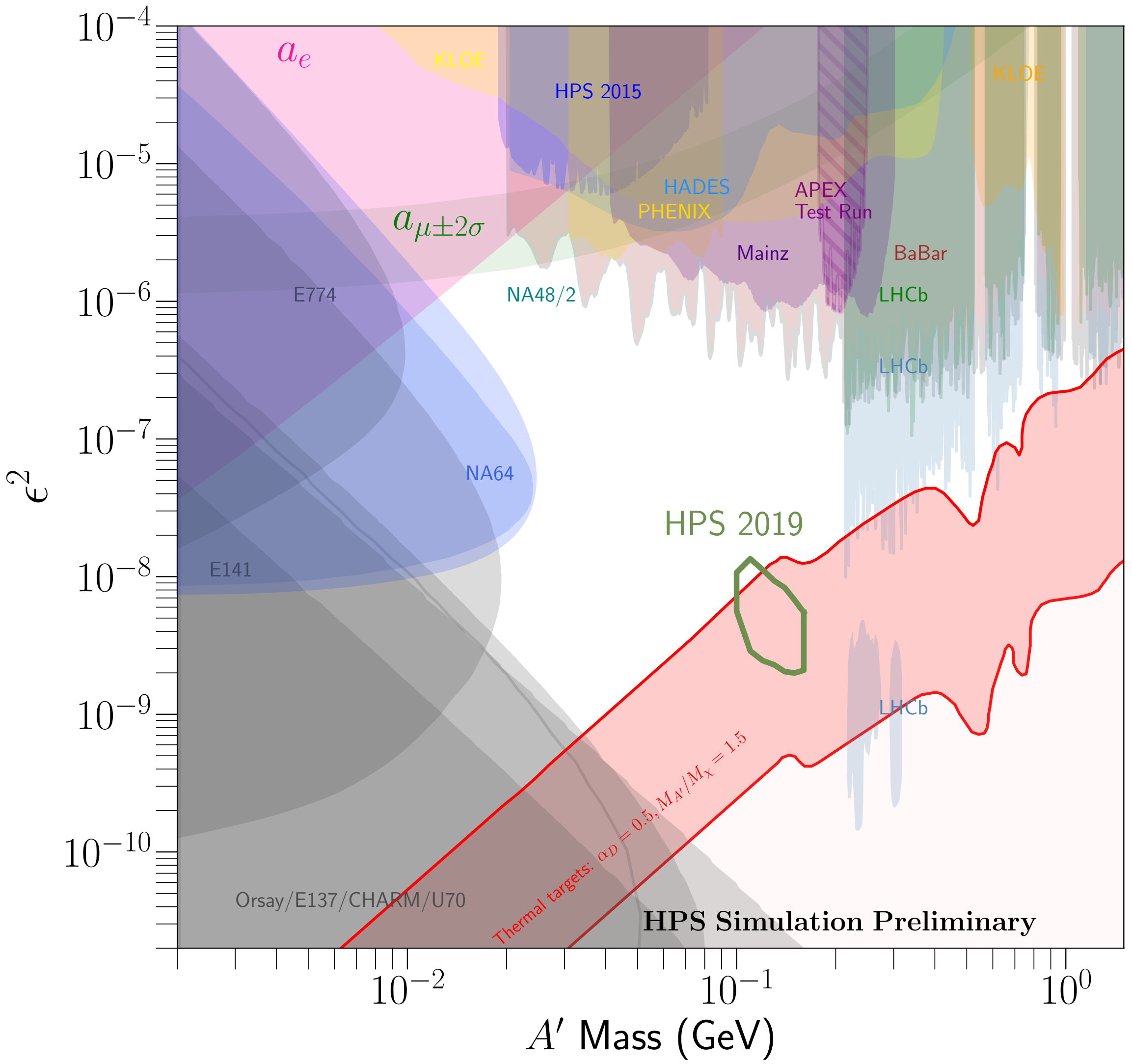
Short engineering runs in 2015 (1.7 days) and 2016 (5.4 days)

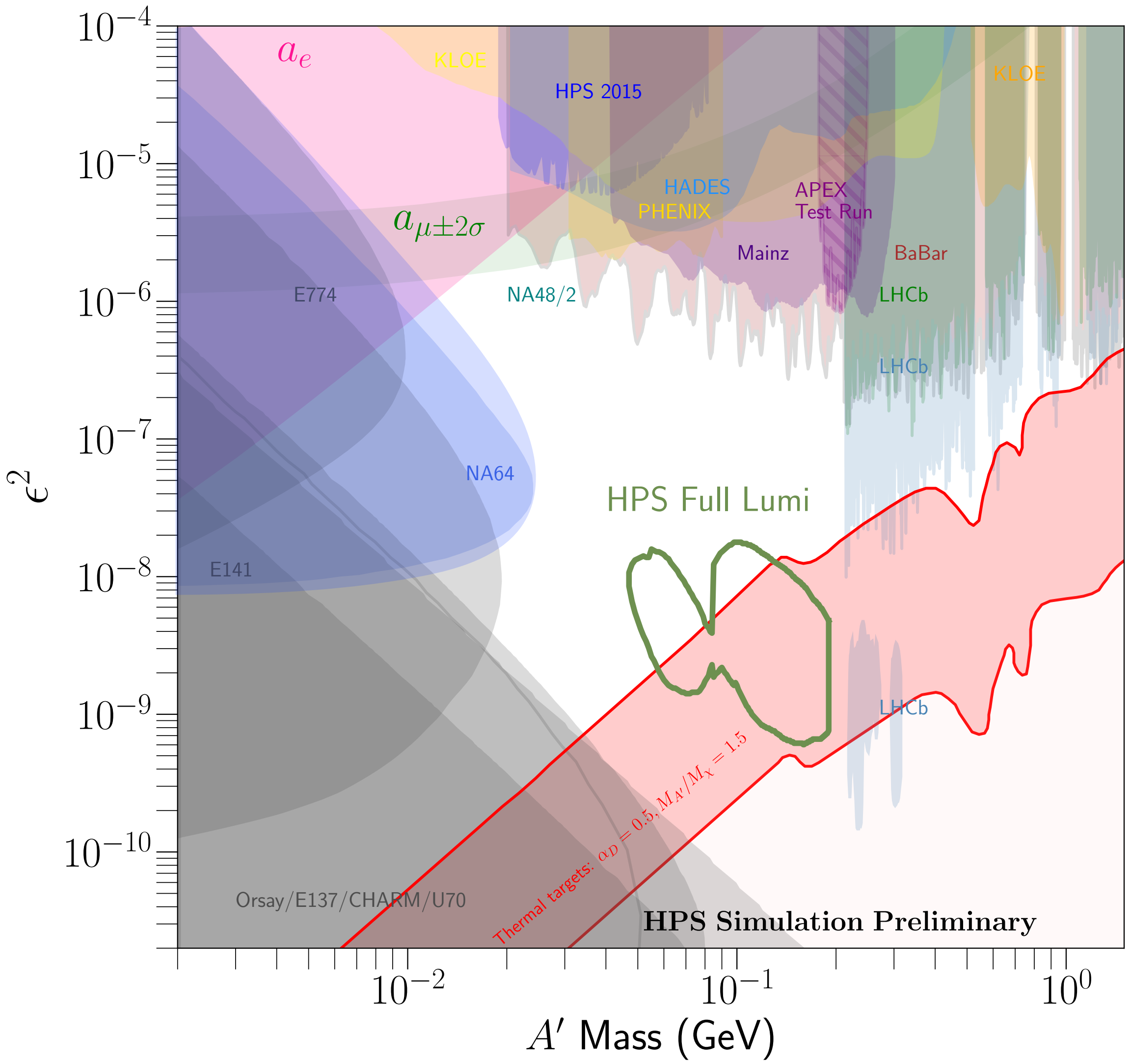
No new sensitivity for minimal dark photons, but analyses proved concept in advance of physics runs.

Preparing publication for 2016 A' results, to be followed by a first result for SIMPs

e- beam + spectrometer w/ vertexing: HPS @ JLab CEBAF (2015-?)

First physics run 6/17 — 9/8/2019 at 4.55 GeV collected ~2 weeks of data.



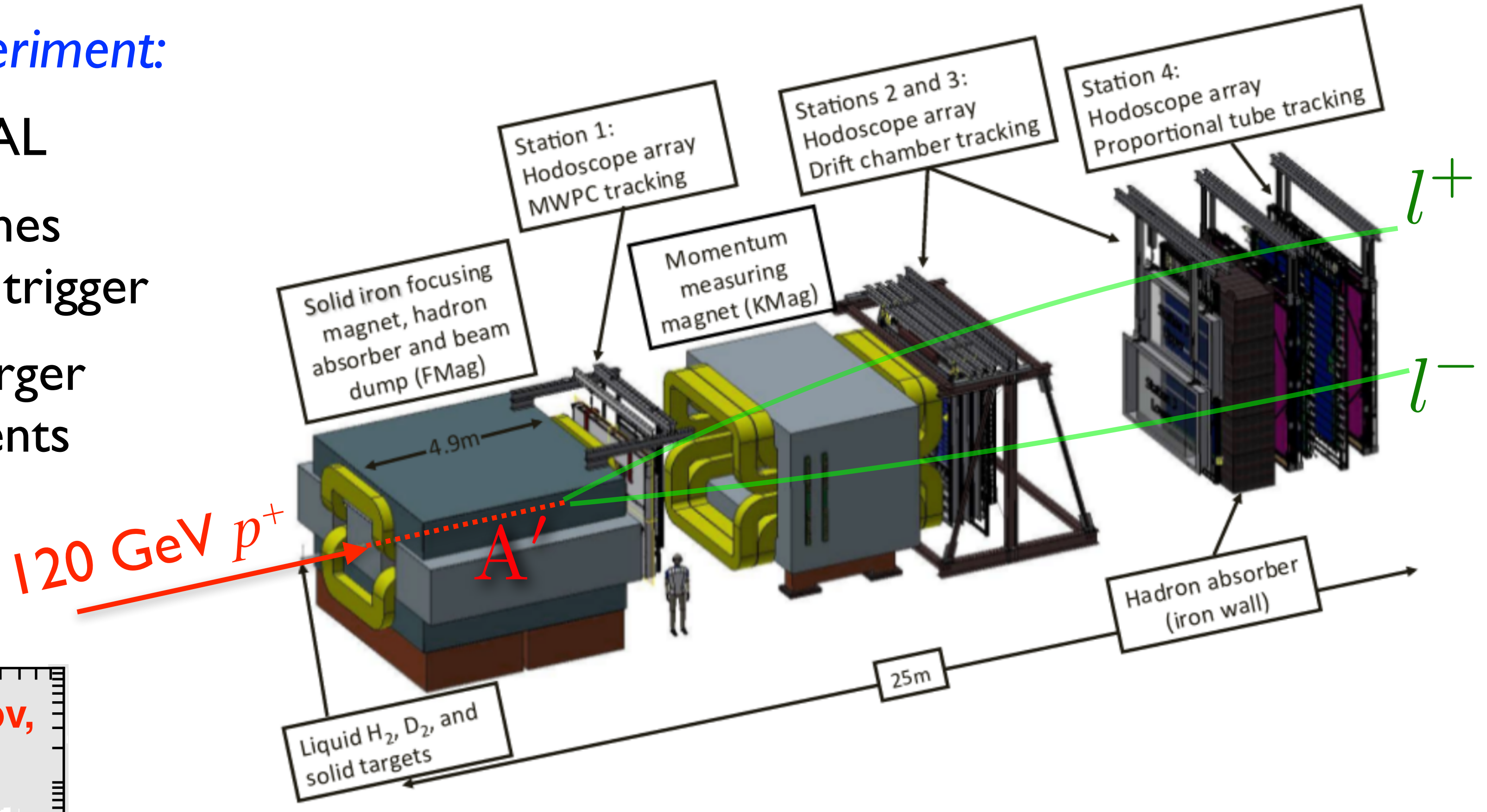


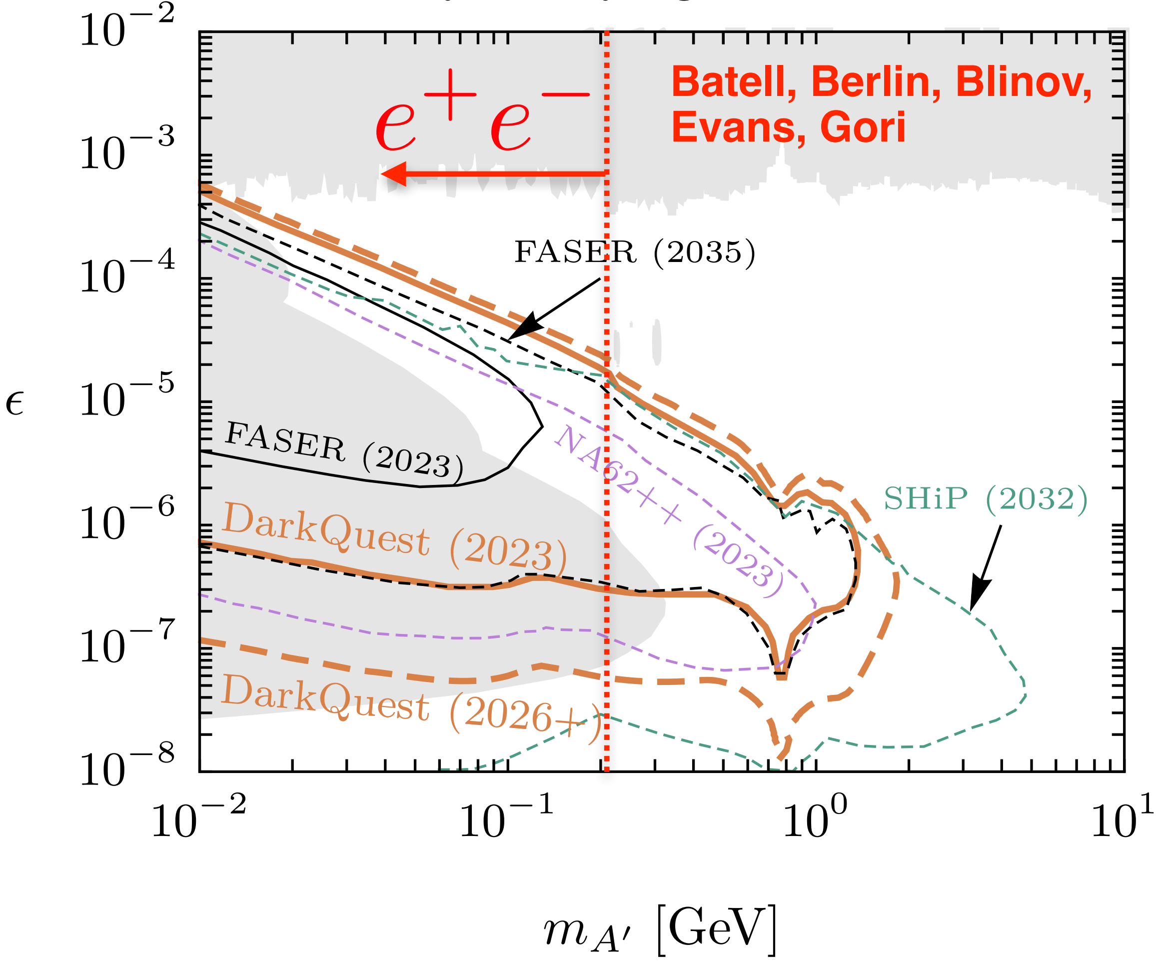
HPS is scheduled for 4 weeks in 2021.
Future run plan for rest of approved time is under review by the JLab PAC.

p^+ beam + shallow dump + spectrometer SeaQuest/DarkQuest/LongQuest @ FNAL (2017-?)

SeaQuest/SpinQuest nuclear physics experiment:

- Fixed target muon spectrometer at FNAL
- Parasitic program of dark photon searches with addition of displaced vertex muon trigger
- Shallow dump + large boost accesses larger couplings than previous dump experiments





Visibly Decaying Dark Photon

DarkQuest proposal:

Adds ECal, improves DAQ/Trigger for operation to 1.4E18 (DQ1) and 1E20 (DQ2) POT

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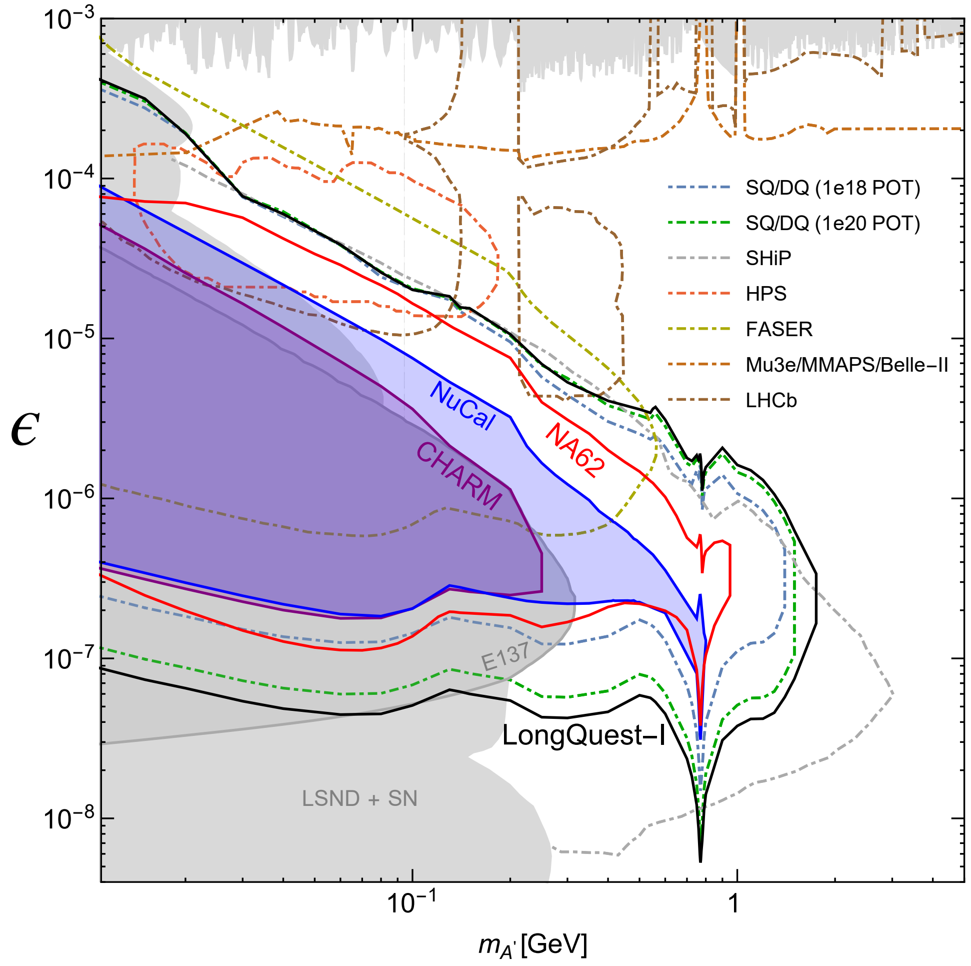

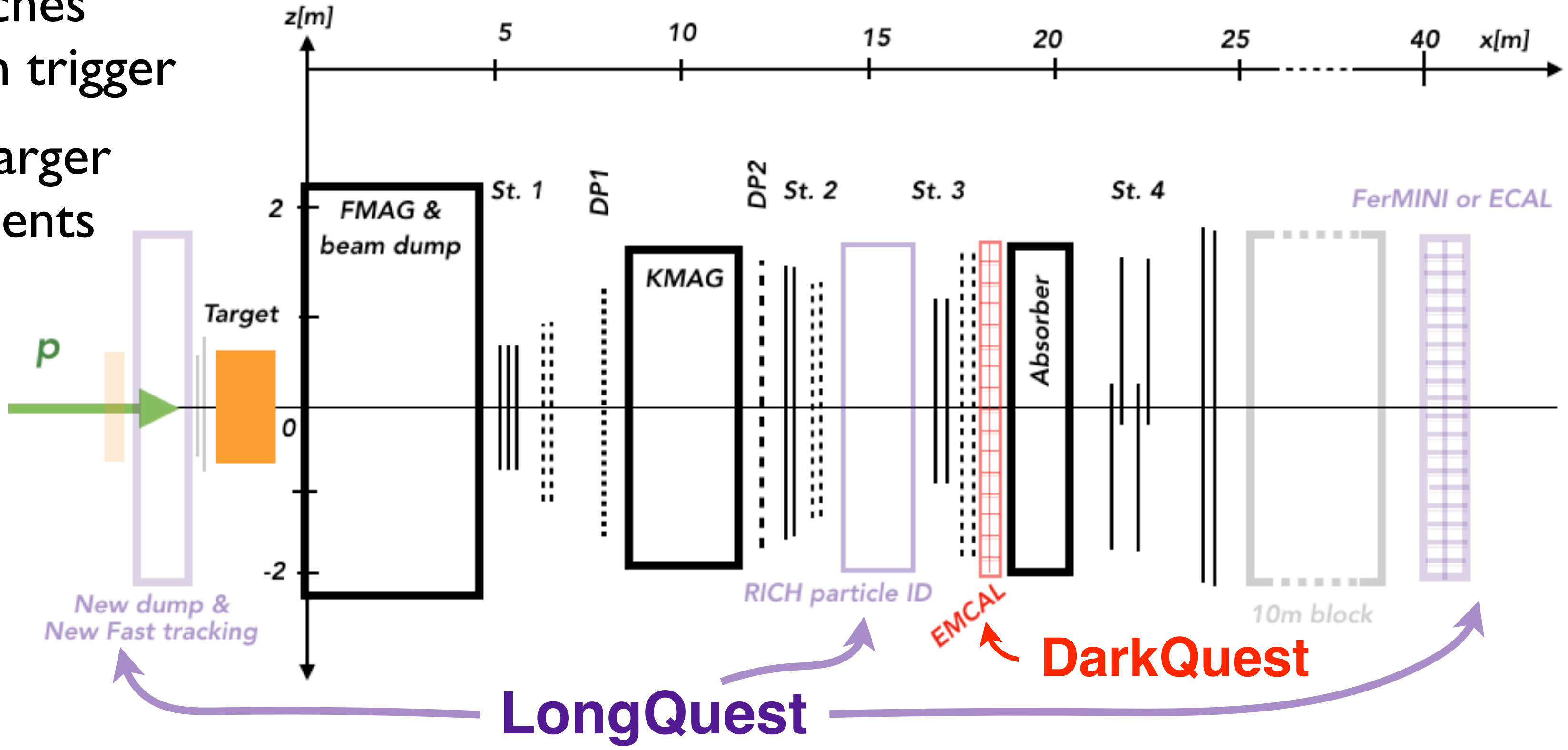

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LongQuest concept:

Extends apparatus to longer baseline to reach yet smaller couplings

p^+ beam + shallow dump + spectrometer SeaQuest/DarkQuest/LongQuest @ FNAL (2017-?)

Like other similar experiments, DarkQuest has broad sensitivity to Dark Sectors:

arXiv:1801.05805 arXiv:1804.00661 arXiv:1908.07525 arXiv:2008.08108

- dark scalars
- strongly interacting massive particles:
  a confining interaction in the dark sector
- inelastic Dark Matter (iDM):
  large mass-splittings in dark states, can
  explain muon (g-2) anomaly.
- heavy neutral leptons

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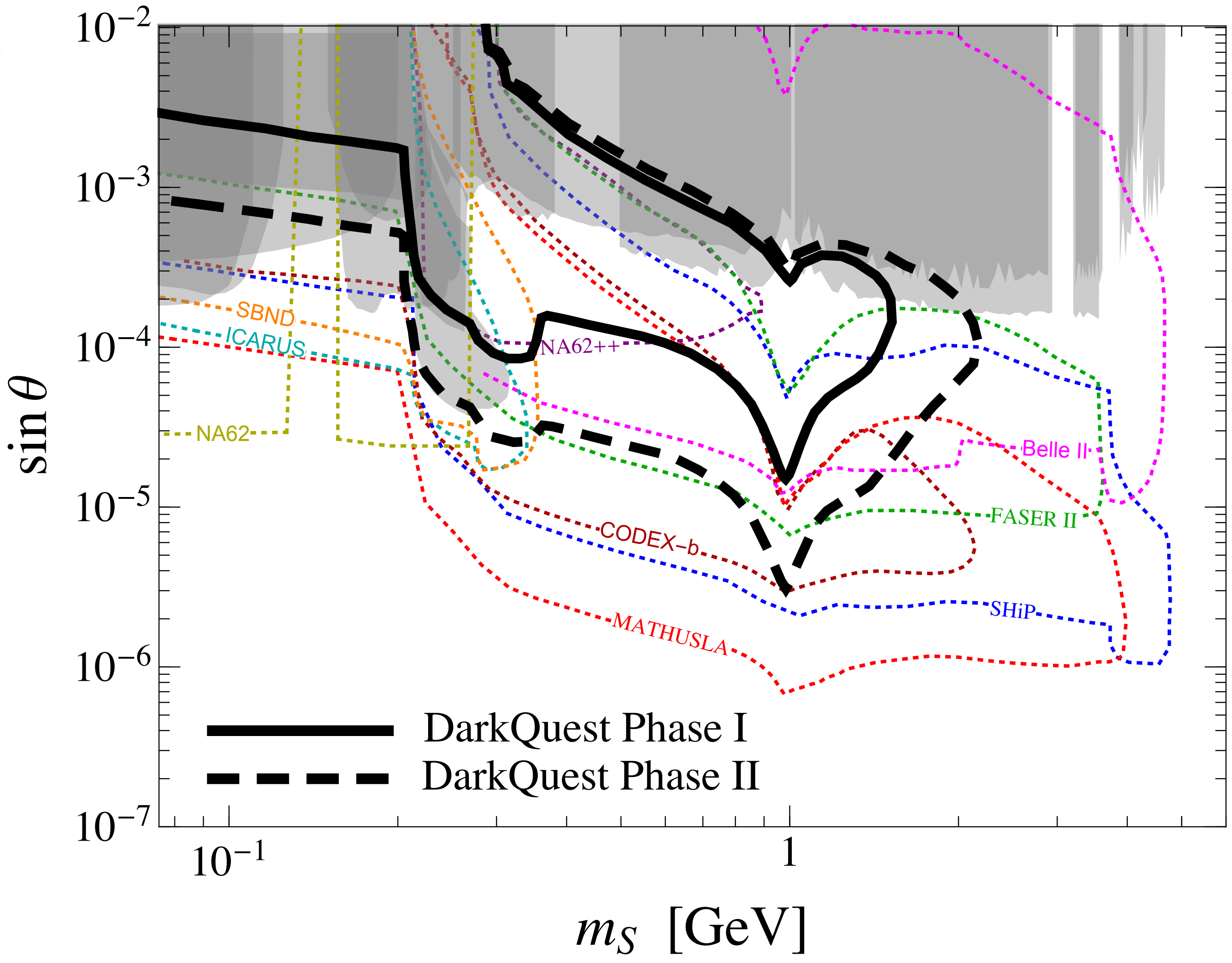

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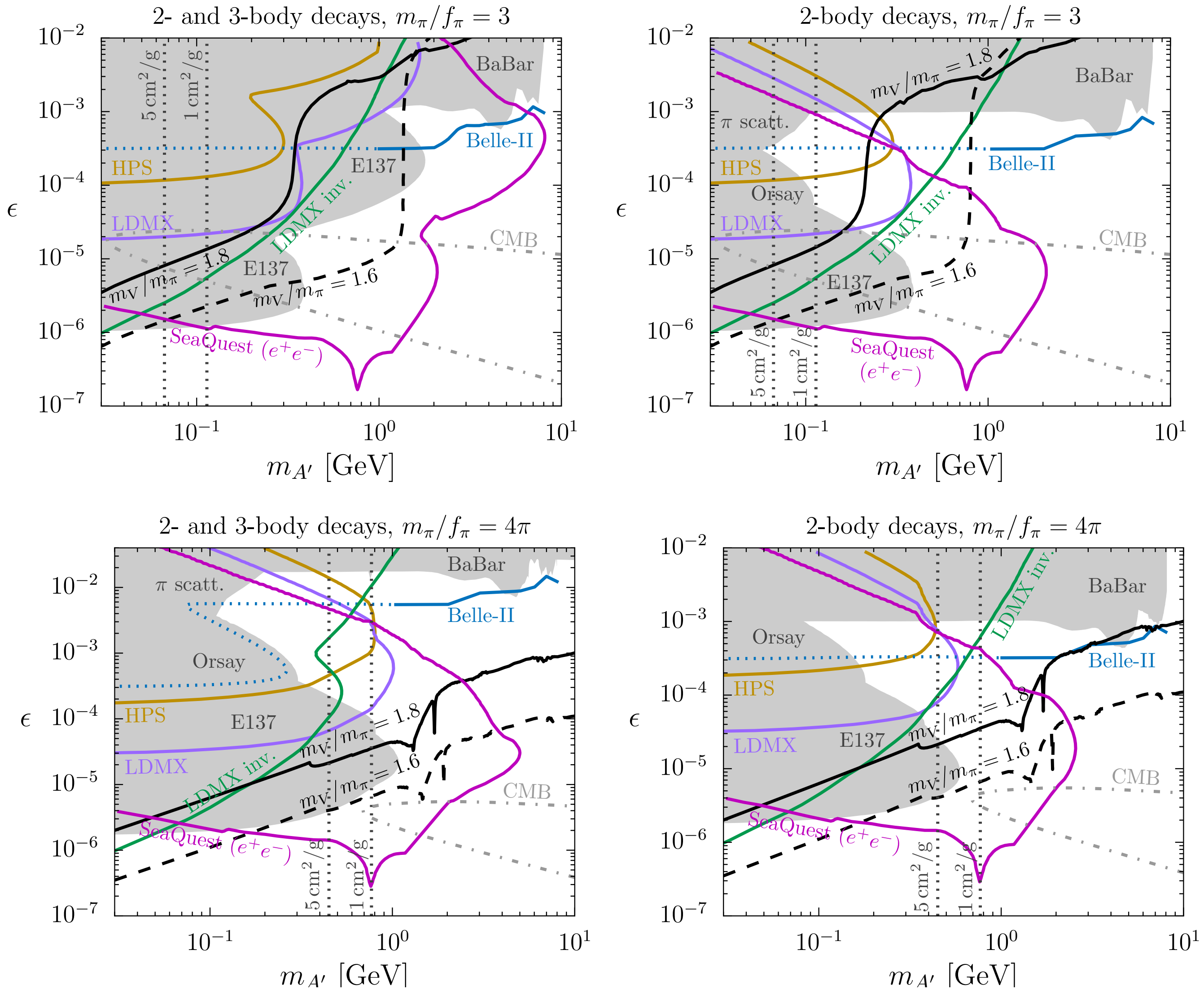

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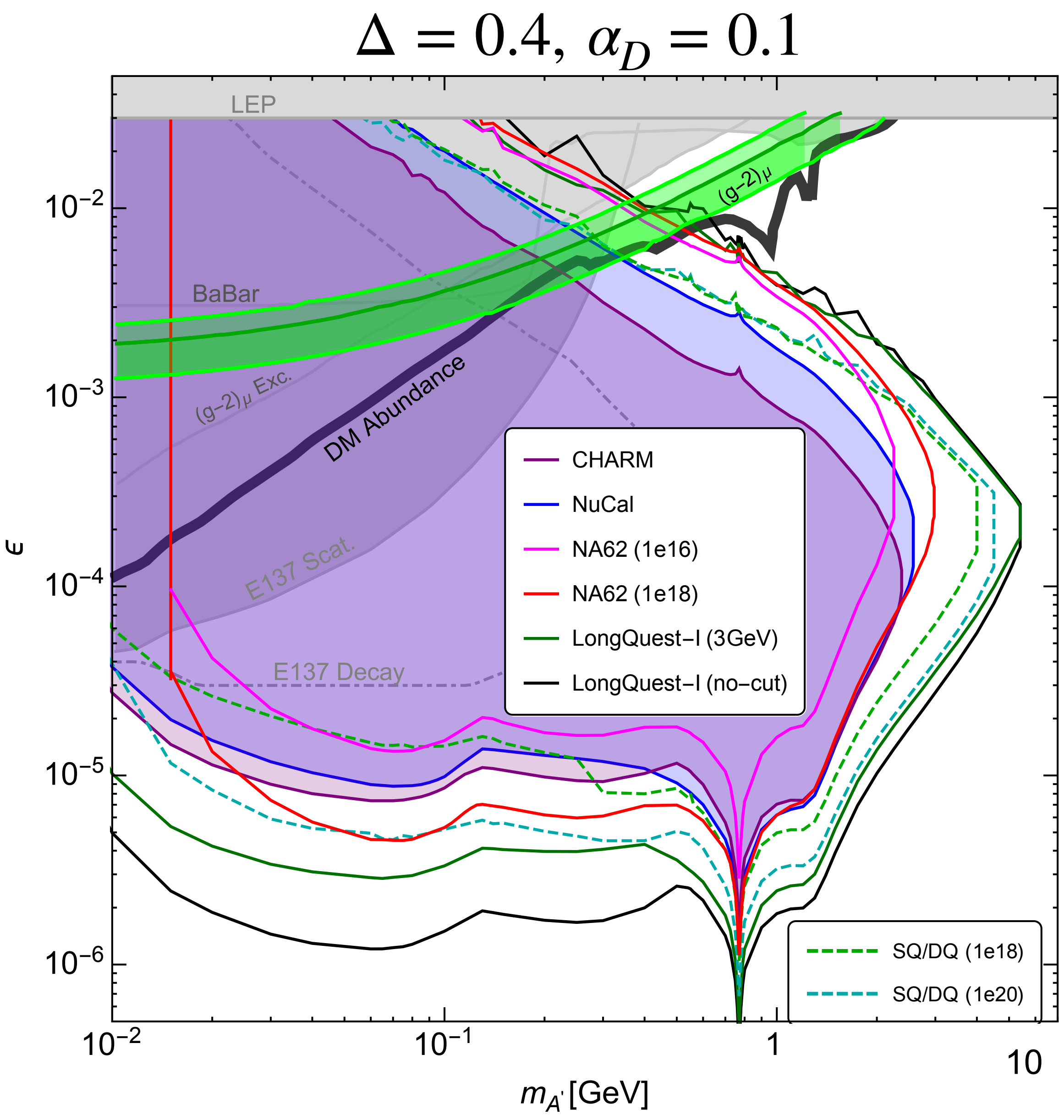

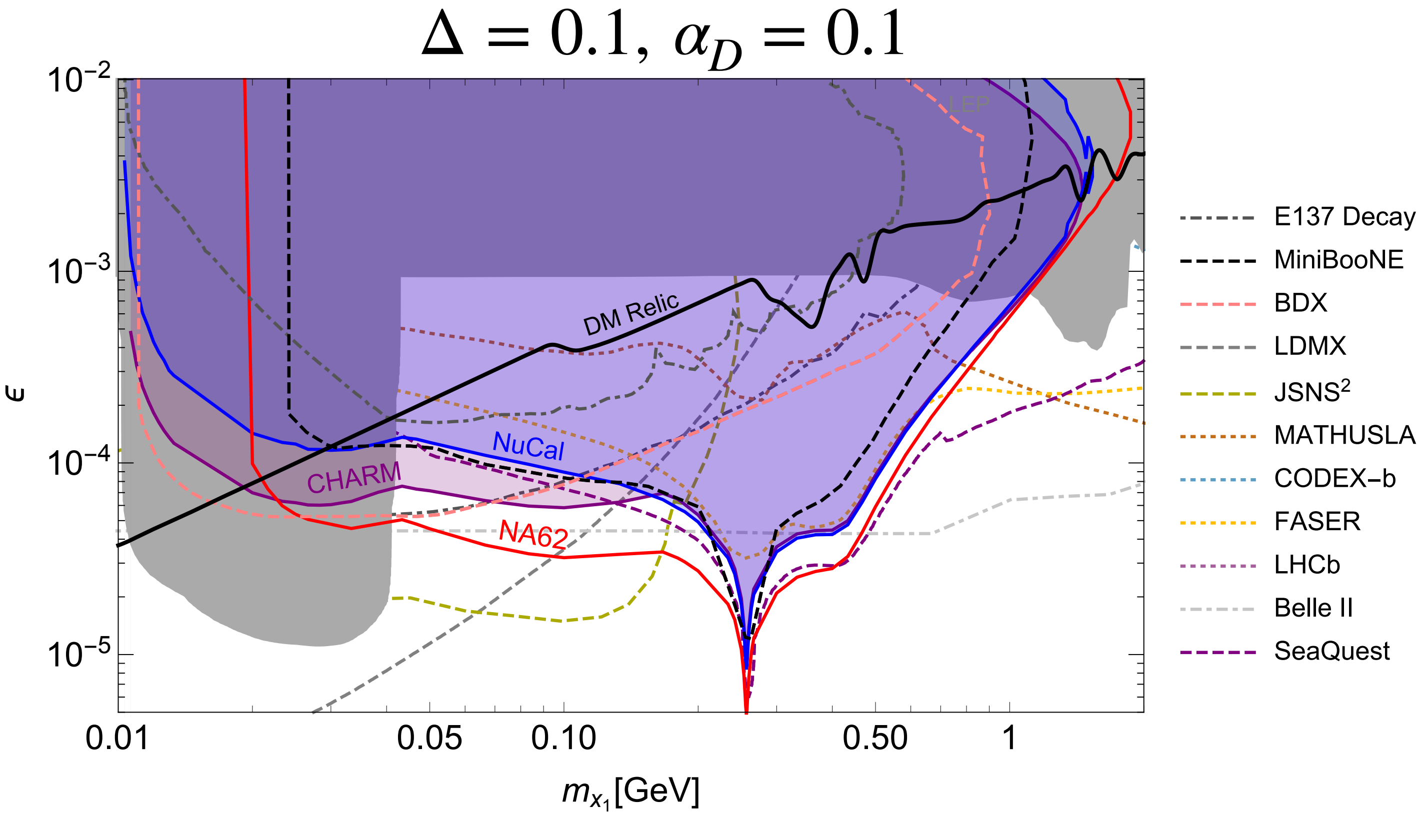

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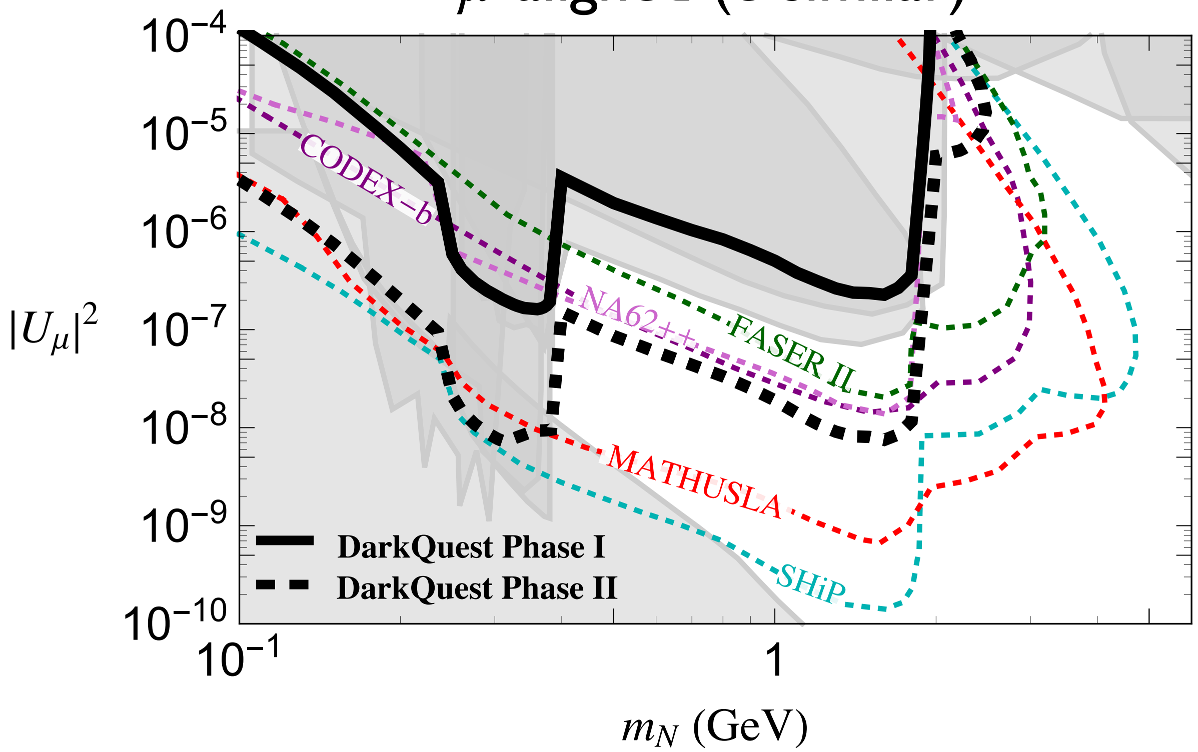
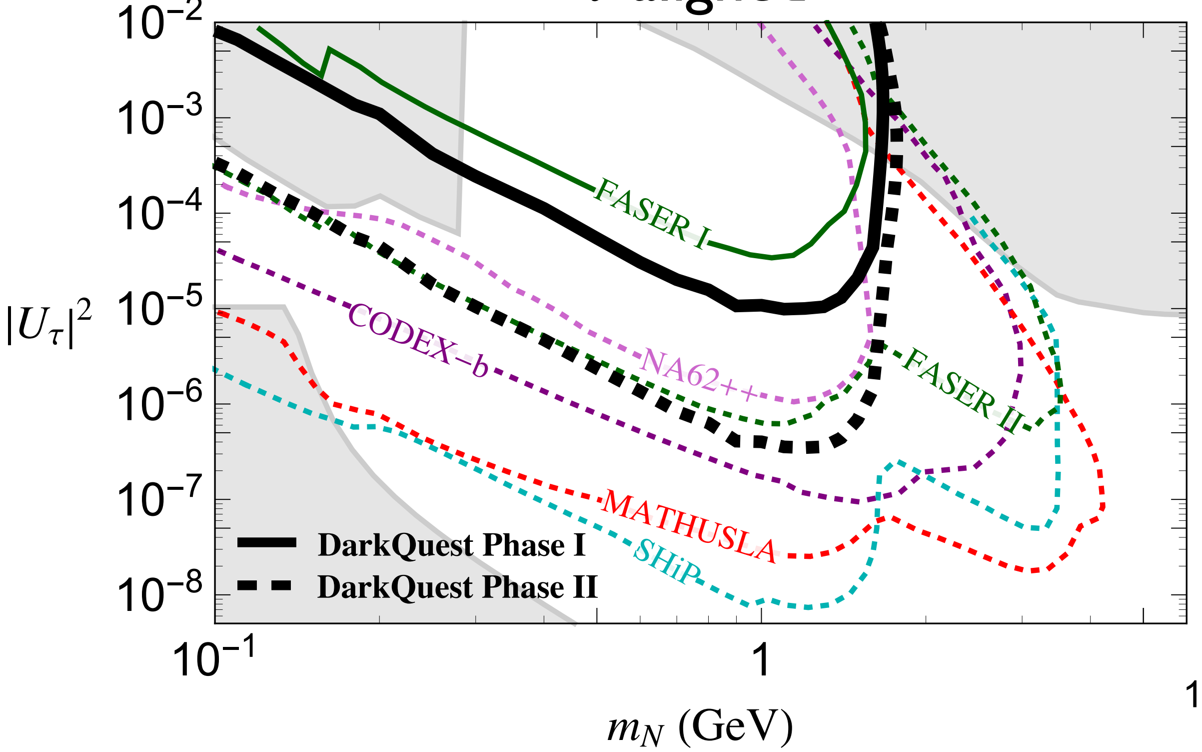
μ-aligned (e similar)



τ-aligned



Millicharges @ FNAL

~massless vector mediators
give rise to millicharged DM

Argoneut:

- 0.24 ton LAr TPC on NUMI beamline
- 10^{20} p^+ @ 120 GeV on graphite target in 2009-2010
- search for projective two-hit events

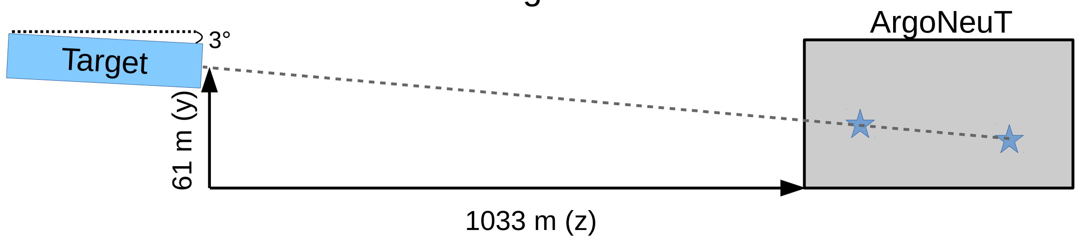
new limits in mass range 0.1-5 GeV

FerMINI proposal:

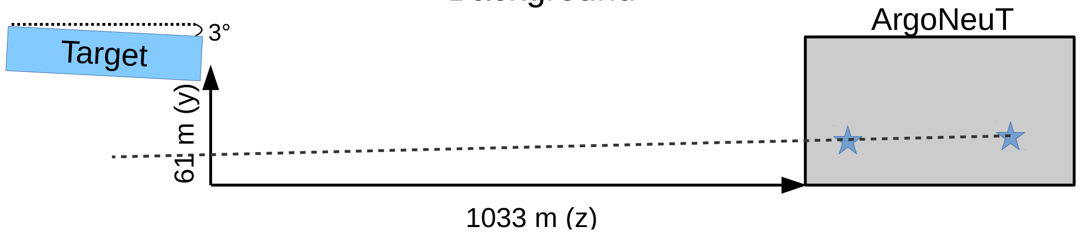
- dedicated plastic scintillator detector, similar to MilliQan, on NUMI beamline
- searches for triple coincidences

complementary to other experiments at lower (LDMX) and higher (MilliQan) masses

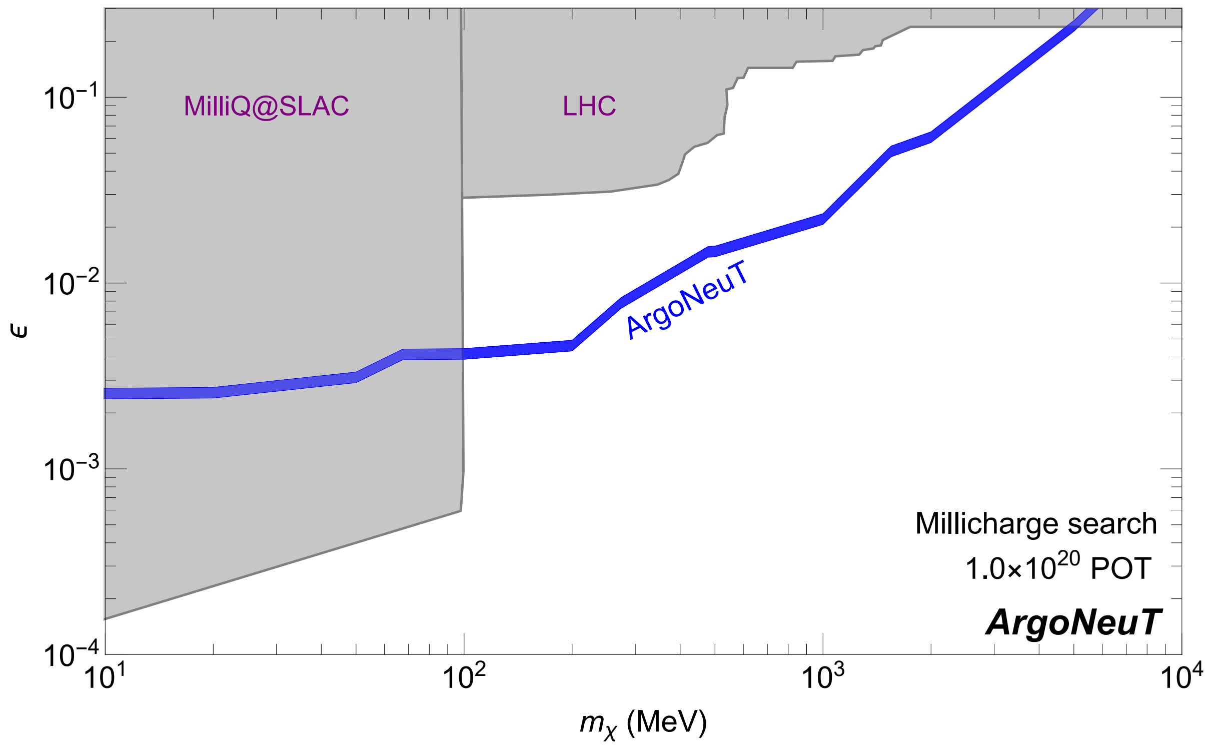
Signal



Background



arXiv:1911.07996



Millicharges @ FNAL

~massless vector mediators give rise to millicharged DM

Argoneut:

- 0.24 ton LAr TPC on NUMI beamline
- 10^{20} p^+ @ 120 GeV on graphite target in 2009-2010
- search for projective two-hit events

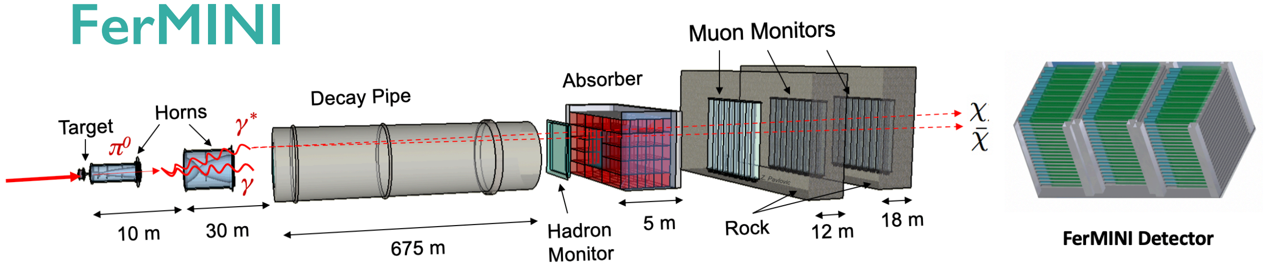
new limits in mass range 0.1-5 GeV

FerMINI proposal:

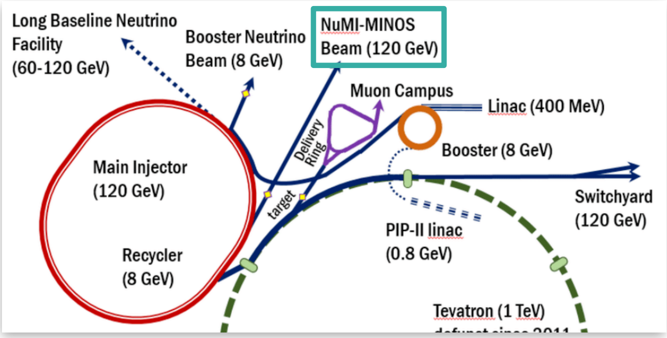
- dedicated plastic scintillator detector, similar to MilliQan, on NUMI beamline
- searches for triple coincidences

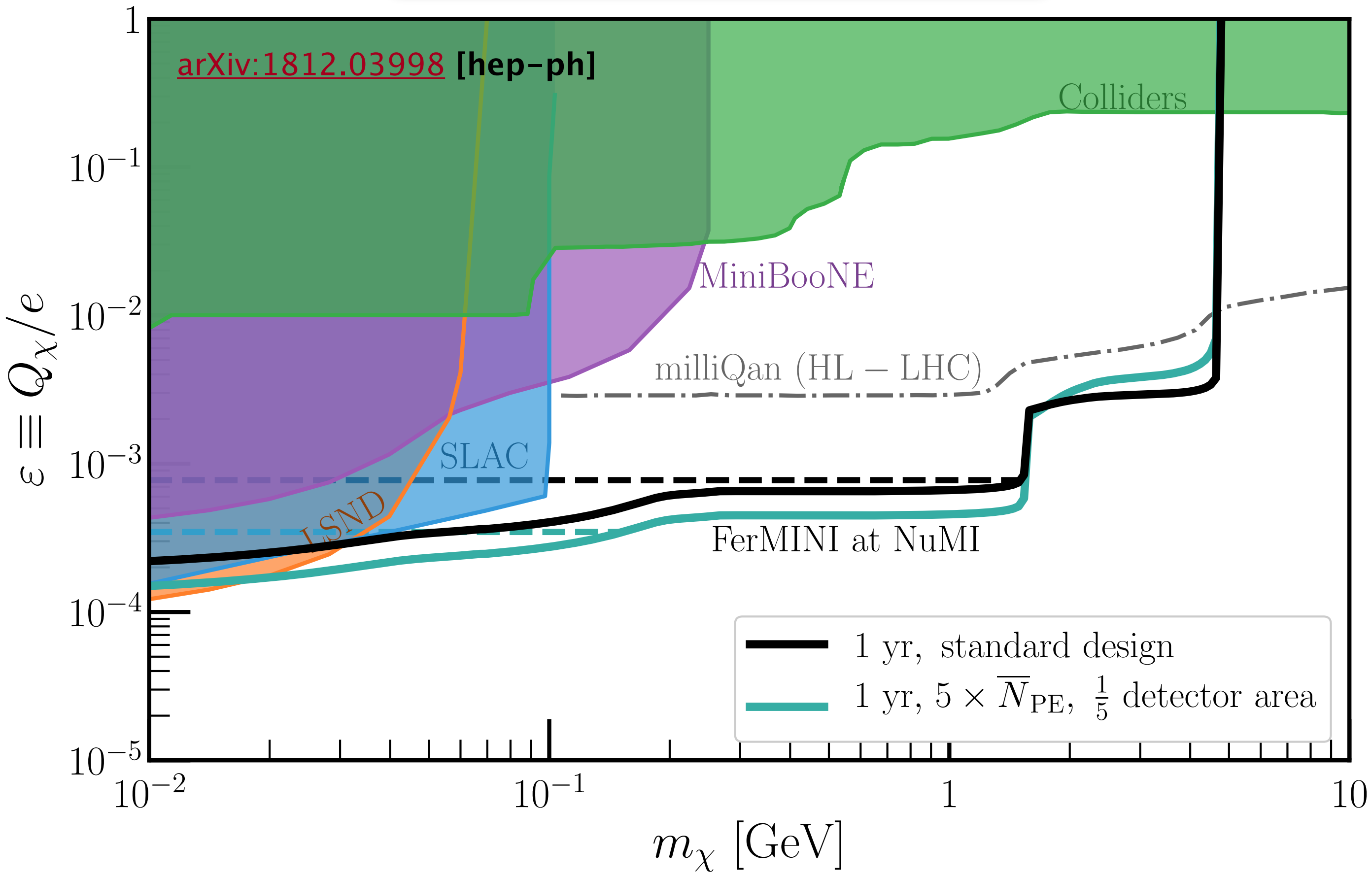
complementary to other experiments at lower (LDMX) and higher (MilliQan) masses

FerMINI



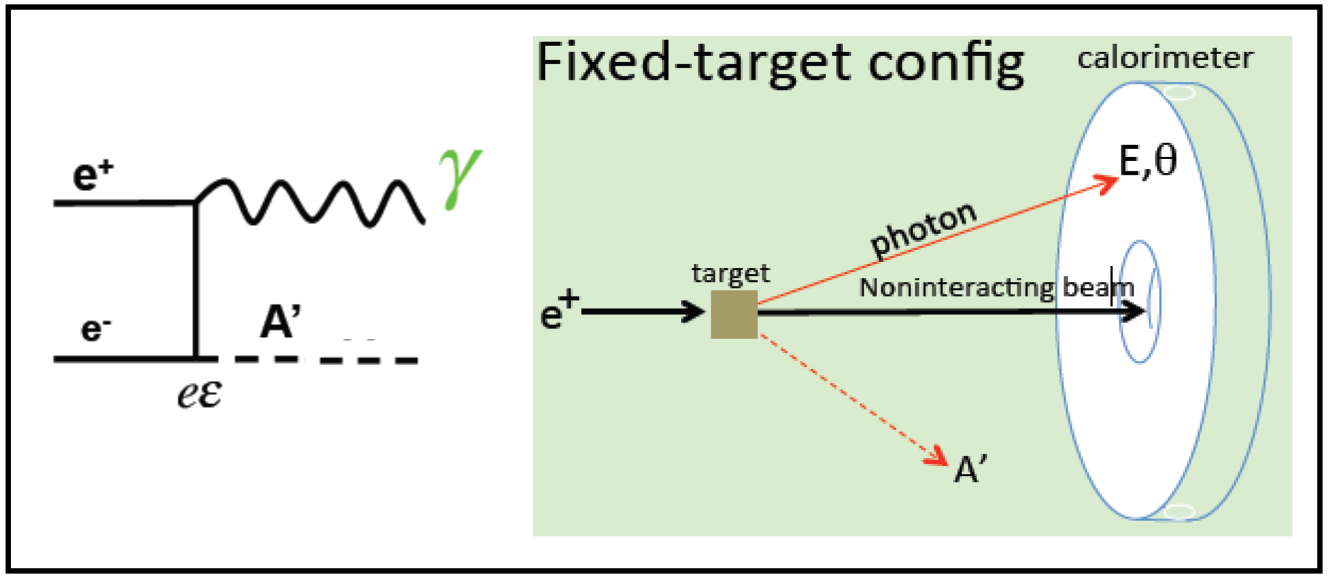
Zarko Pavlovic & Yu-Dai Tsai, Fermilab





e^+ fixed target:
PADME @ JLab (proposal)

*Reconstruction of mass without measurement of decay products. Sensitive to both visible and invisible decays of **on-shell** mediators.*



$$M^2_{\mathrm{rec}} = 2m_e\left(E_+ - E_\gamma(1 + \frac{E_+}{2m_e}\theta^2_\gamma)\right)$$

Most components suitable for CEBAF energies

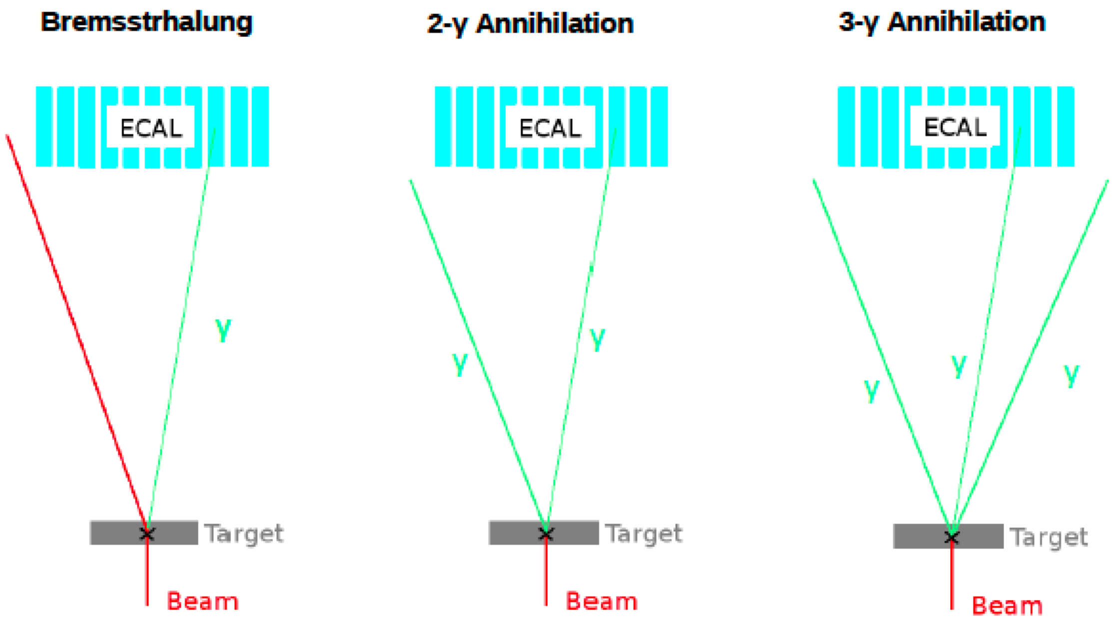
- Target
- Calorimeter
- Veto System

DAQ requires changes for CW beam

Reach limited mostly by CM energy $\sim \sqrt{E_{\mathrm{beam}}}$
(at JLab CEBAF $\sqrt{11\ \mathrm{GeV}} = 106\ \mathrm{MeV}$*)*

High energy positron beams not available yet at JLab

Key backgrounds:



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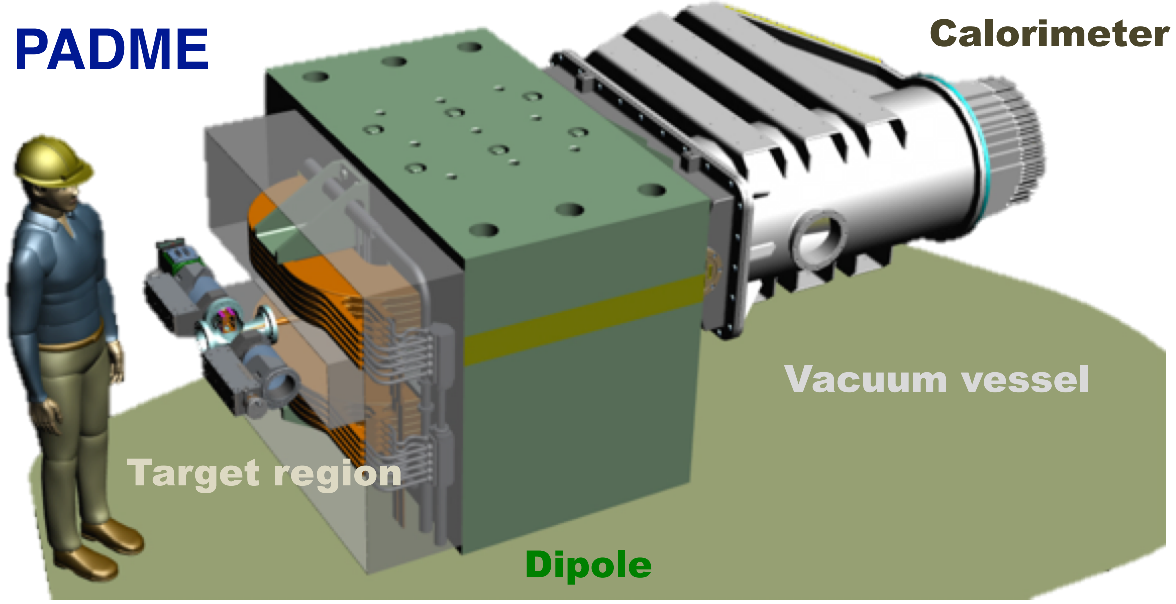
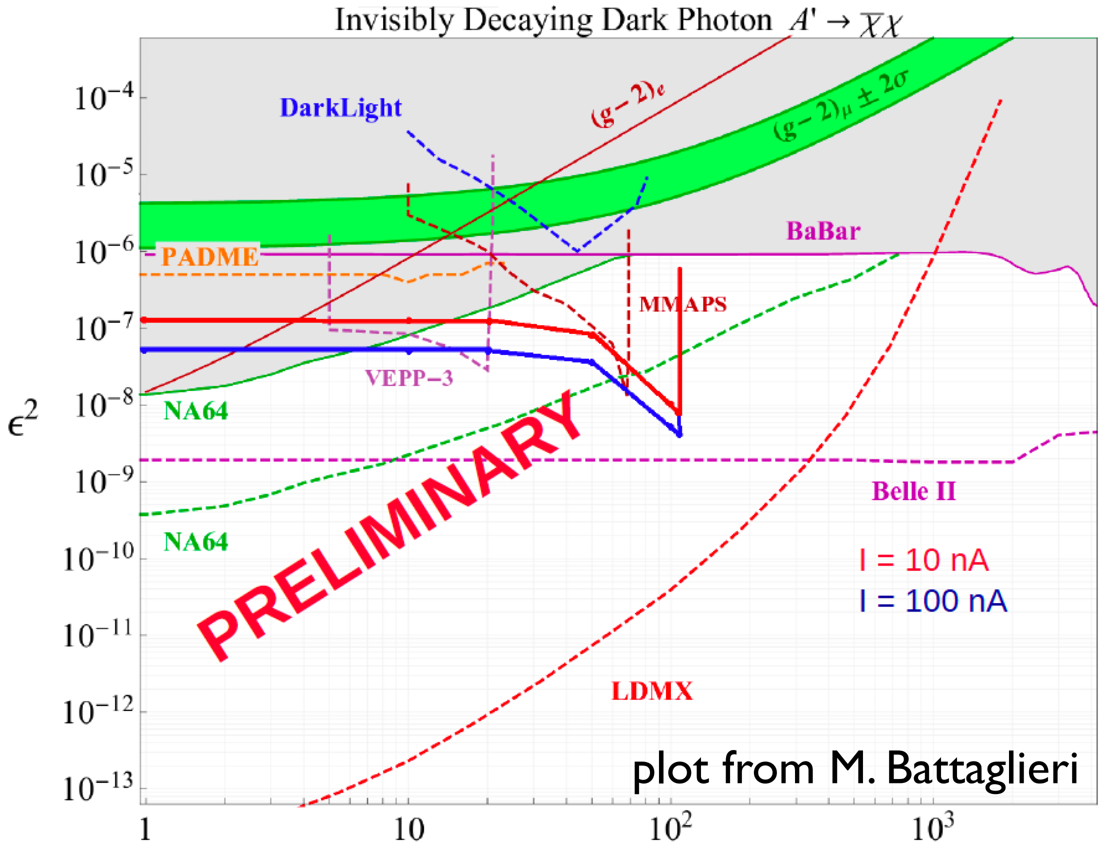
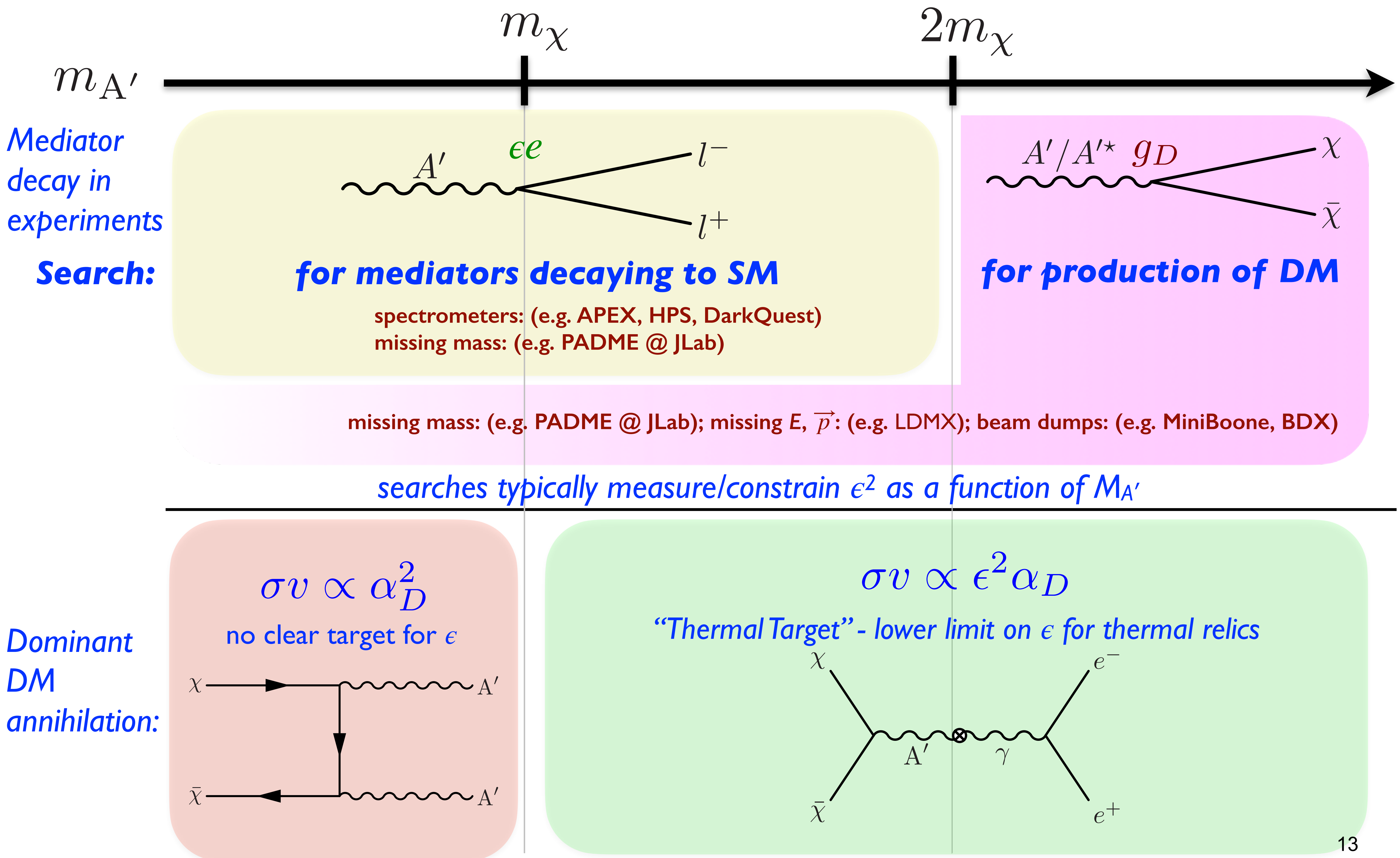




plot from M. Battaglieri

Mass Hierarchy Determines Search Strategy & Interpretation



Mediator decay in experiments

Search: ***for mediators decaying to SM***

spectrometers: (e.g. APEX, HPS, DarkQuest)
missing mass: (e.g. PADME @ JLab)

for production of DM

missing mass: (e.g. PADME @ JLab); missing *E*, $\vec{p}$: (e.g. LDMX); beam dumps: (e.g. MiniBoone, BDX)

searches typically measure/constrain ϵ^2 as a function of $M_{A'}$

Dominant DM annihilation:

$$\sigma v \propto \alpha_D^2$$

no clear target for ϵ

$$\sigma v \propto \epsilon^2 \alpha_D$$

"Thermal Target" - lower limit on ϵ for thermal relics

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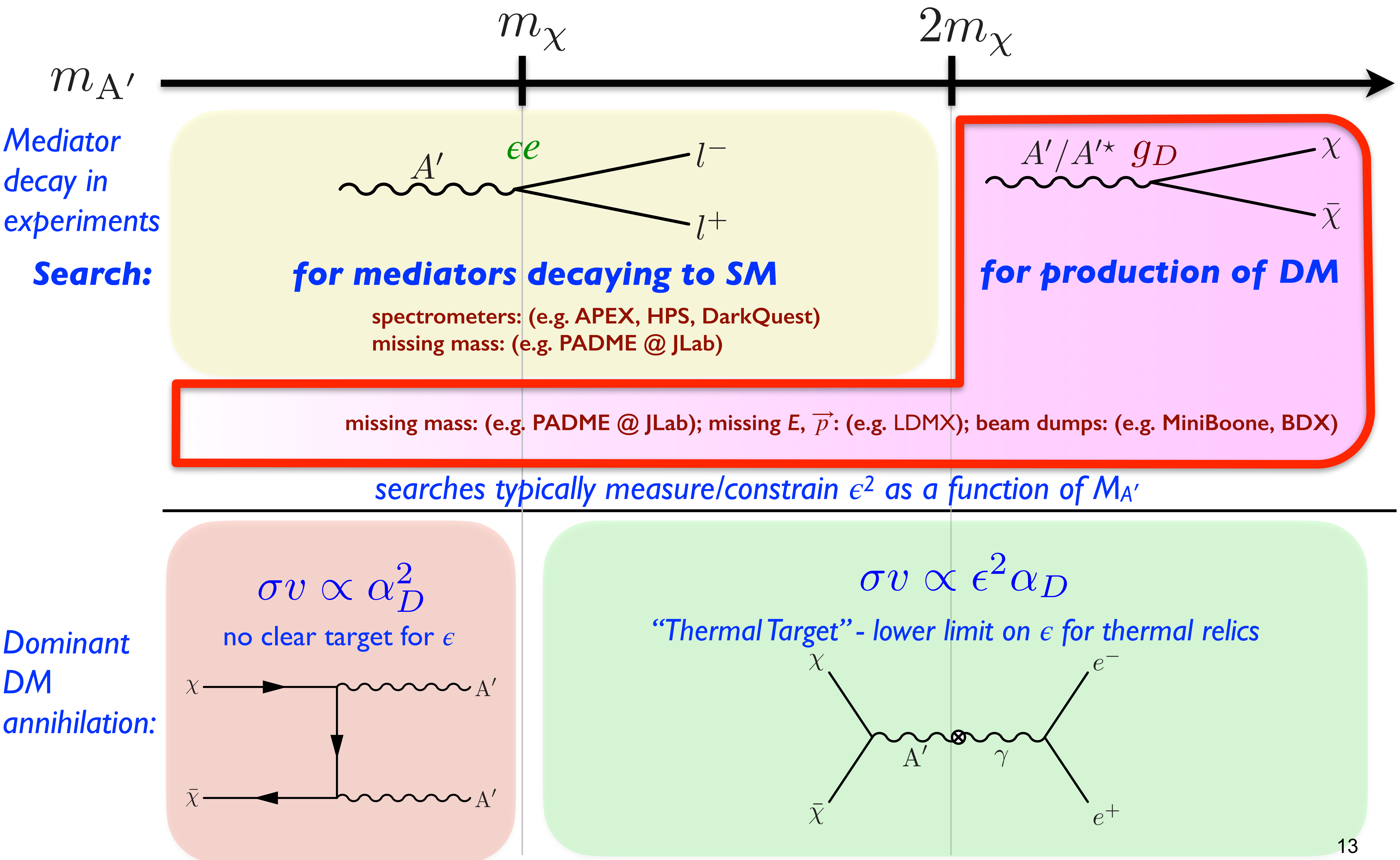

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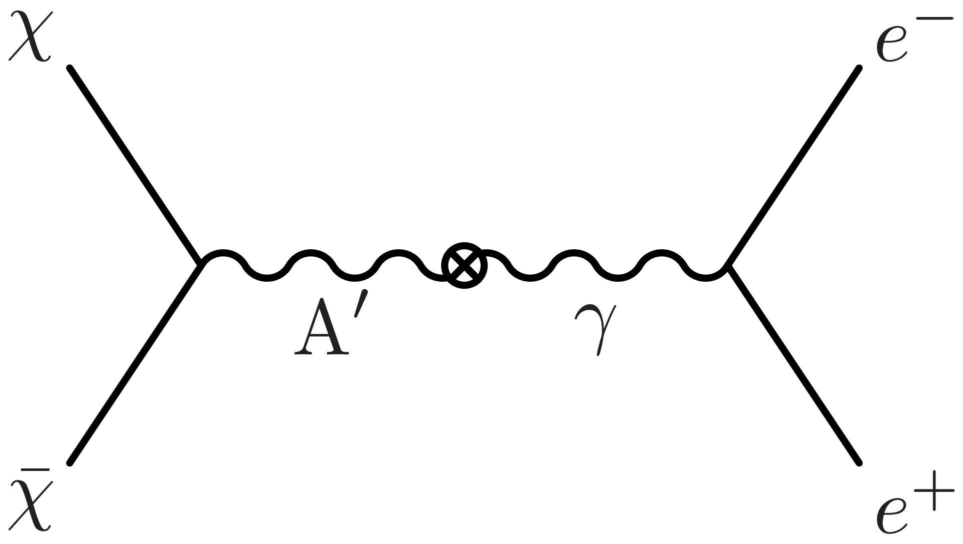
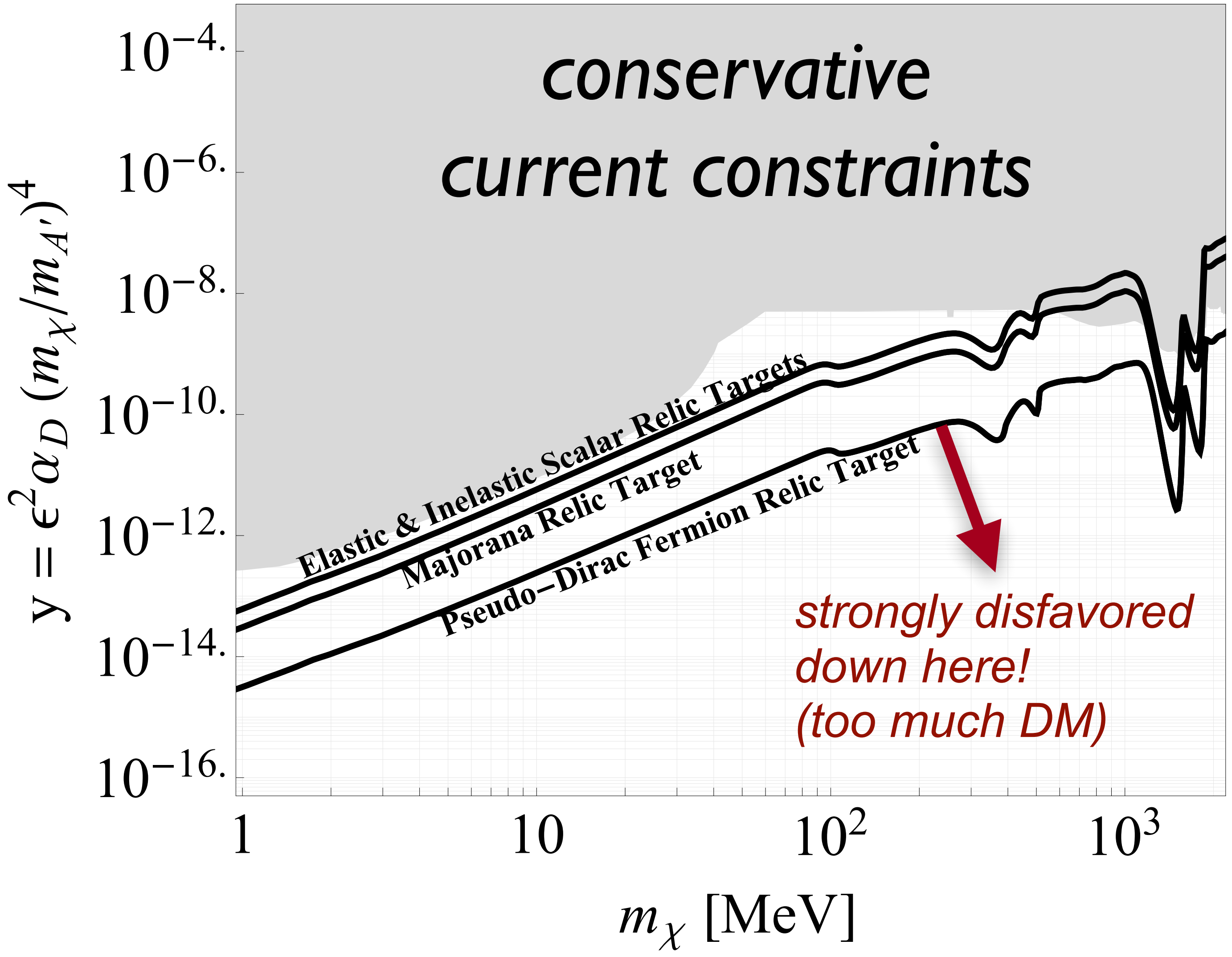
Searches for Production of Light Dark Matter

Want parameter space more natural for DM searches



$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

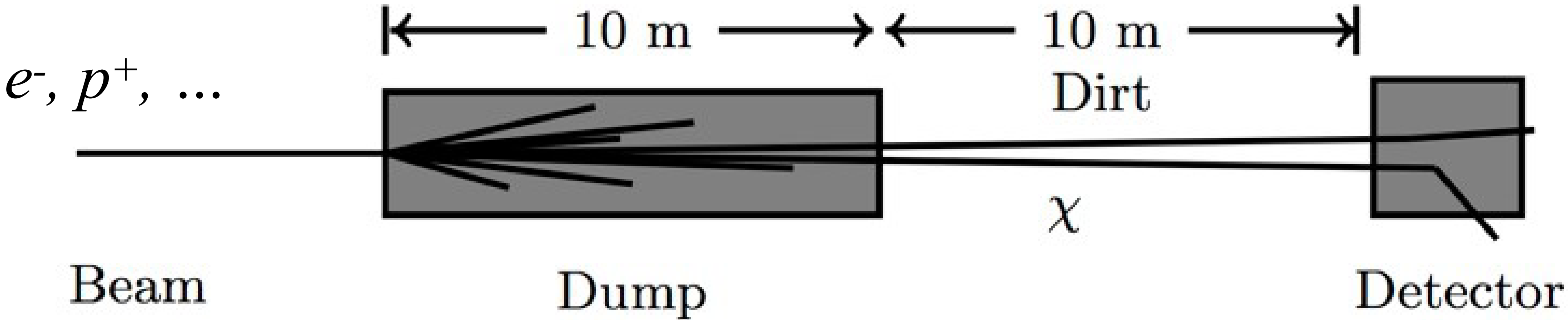


conservative current constraints

strongly disfavored down here! (too much DM)

Choose conservative values of α_D, $M_{A'}/M_\chi$ for converting $(M_{A'},\epsilon) \Longrightarrow (M_\chi,y)$

Beam Dumps



Boosted $A' \to \chi\bar{\chi}$ makes a dark matter beam!

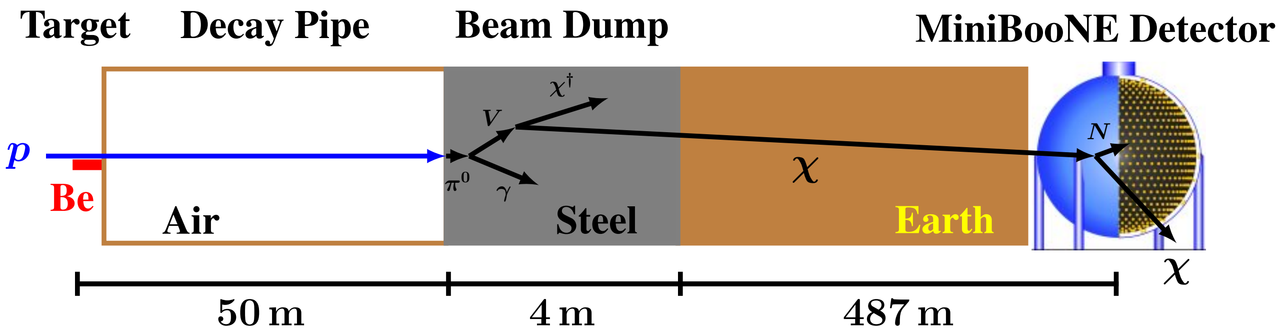
- relatively low rates, few and simple backgrounds
- potential to investigate DM-SM interactions w/ different detector materials
- can often operate parasitically with intense beams using existing facilities
  - neutrino program @ FNAL (p^+ beam dump)
  - coherent ν-N scattering program @ ORNL, LANL (p^+ beam dump)
  - nuclear physics program @ JLab CEBAF (e^- beam dump)

MiniBoone @ FNAL

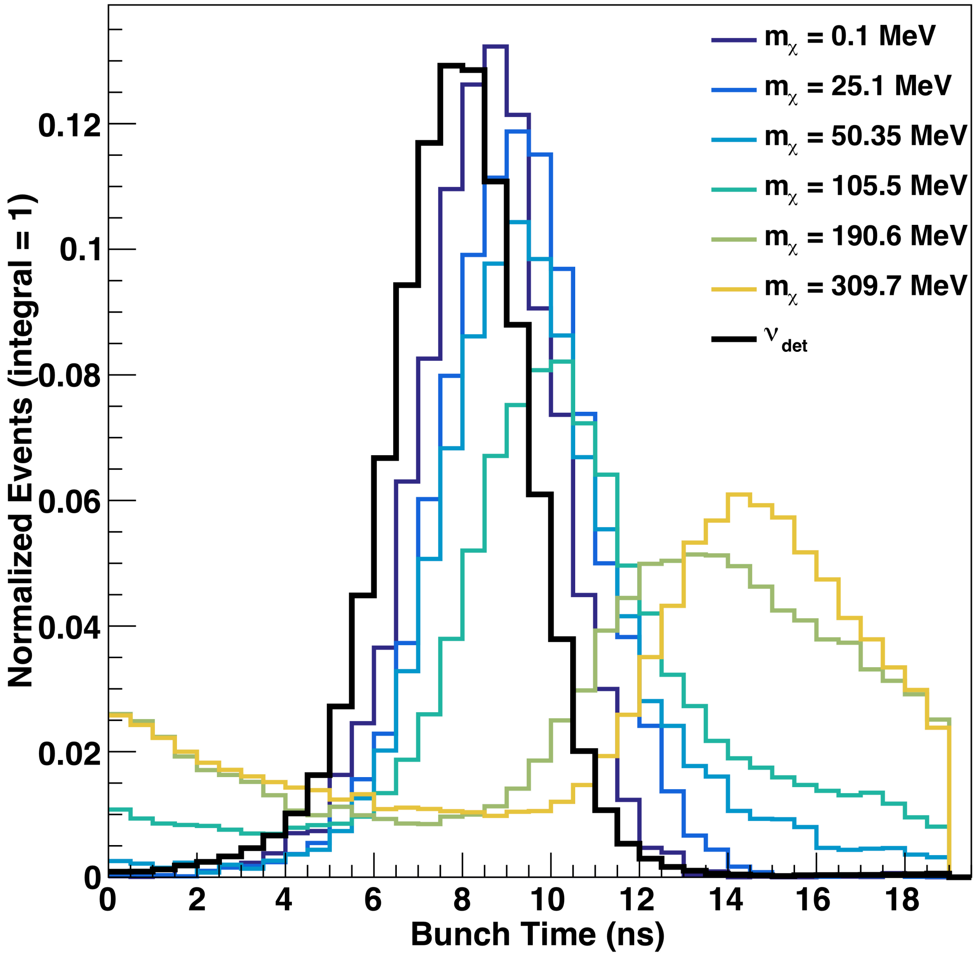
8 GeV protons on iron dump; 800 ton mineral oil detector

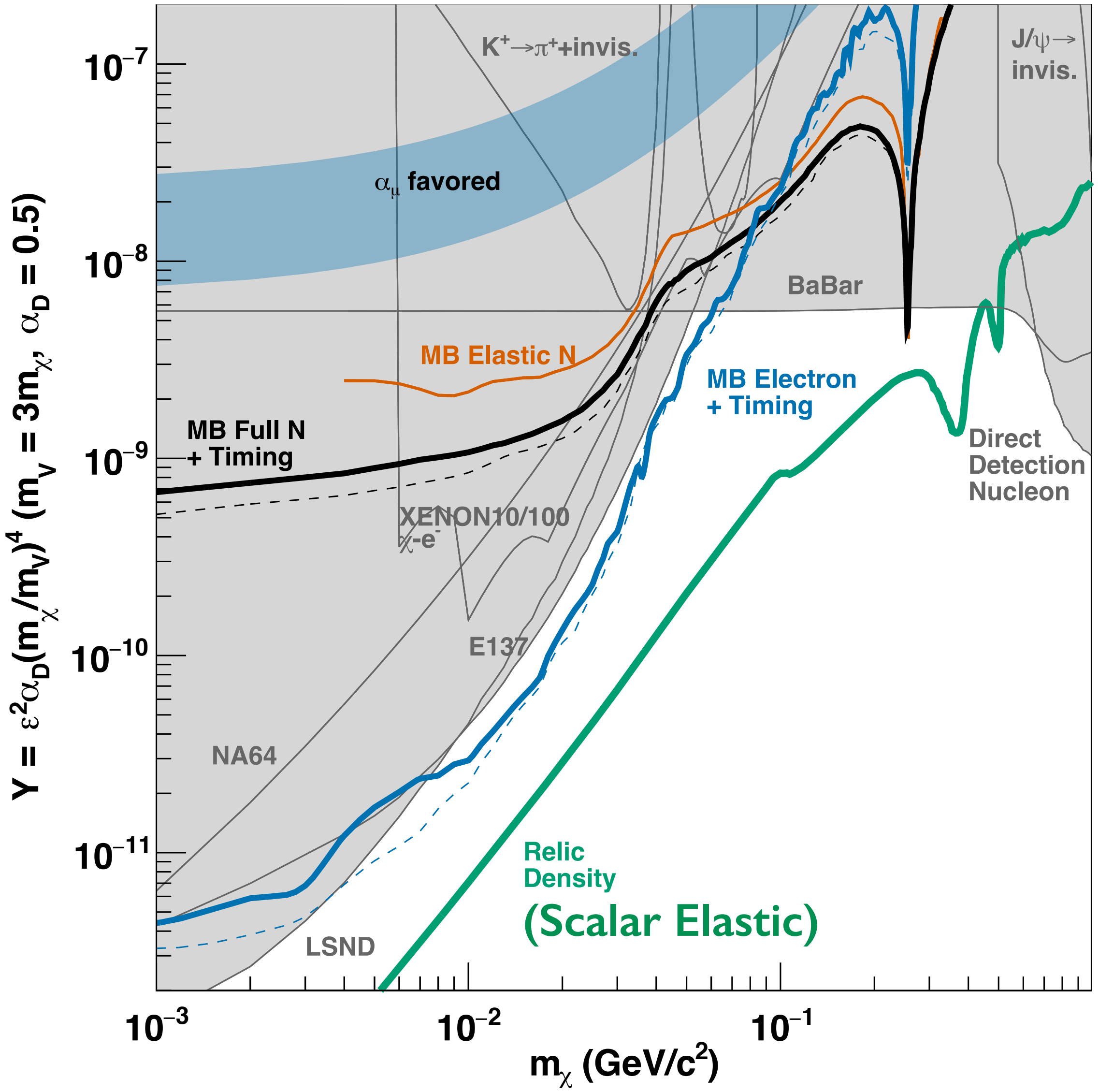
- Improved analysis of 10-month dedicated beam-dump run in 2013-2014 with 1.9×10^{20} protons adds analysis of electron recoils
- Time-of-flight helps distinguish from neutrino backgrounds at higher masses

Demonstrates capabilities of infrastructure for neutrino program to search for light DM



arXiv:1807.06137 [hep-ex]



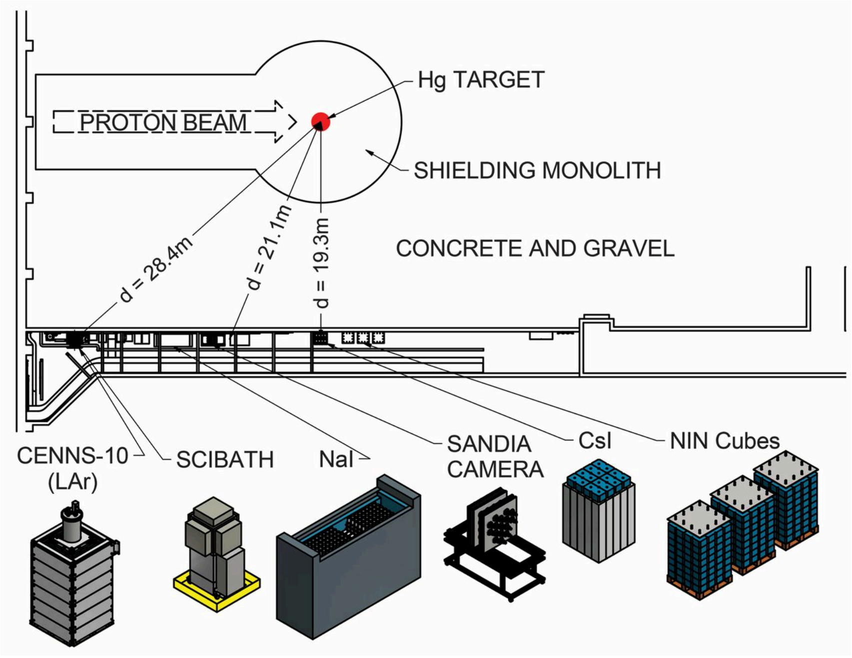


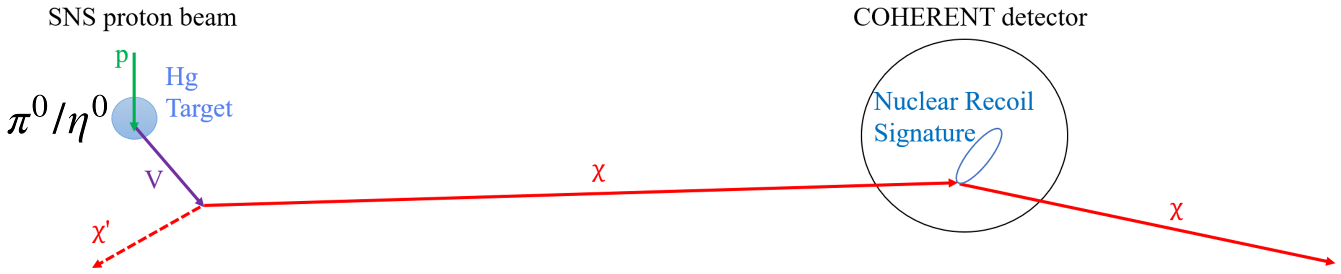
COHERENT @ Oak Ridge National Lab

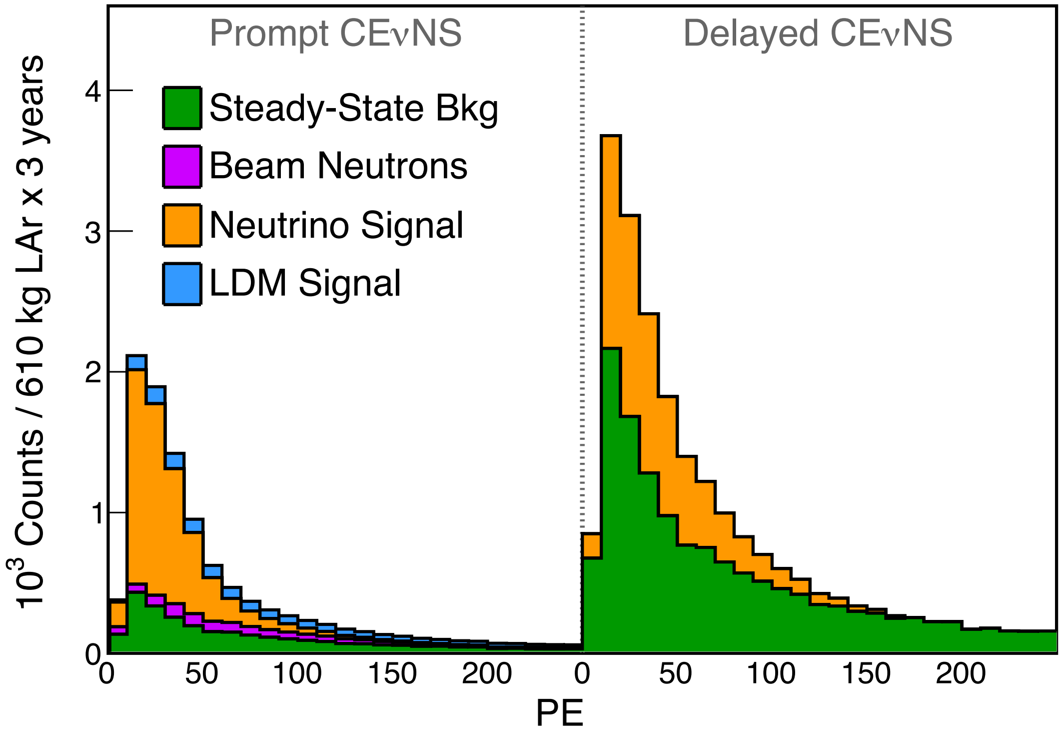
Designed to study Coherent Elastic Neutrino Nucleus Scattering (CEνNS) w/ first observation in 2017

- 1 GeV proton beam on mercury target: suite of off-axis detectors measure CEνNS N-dependence
- Preliminary result for sub-GeV DM in 2017 demonstrated concept
- CEνNS is a key background for DM search: prompt timing used to reduce backgrounds

Sensitivity study for planned 750 kg LAr detector







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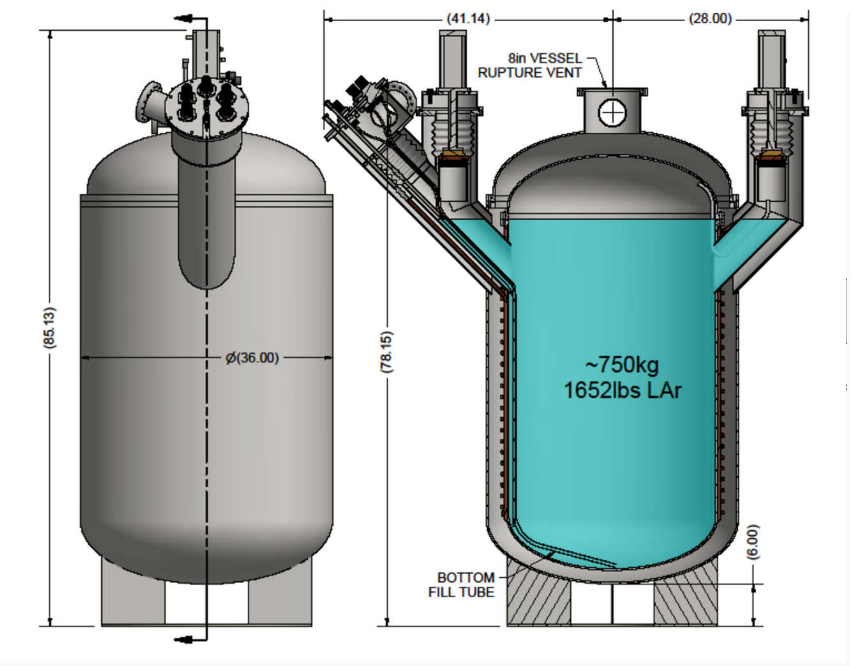
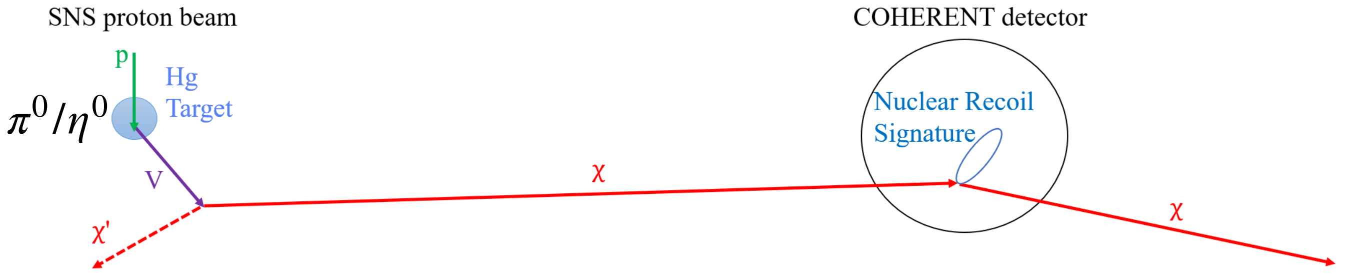
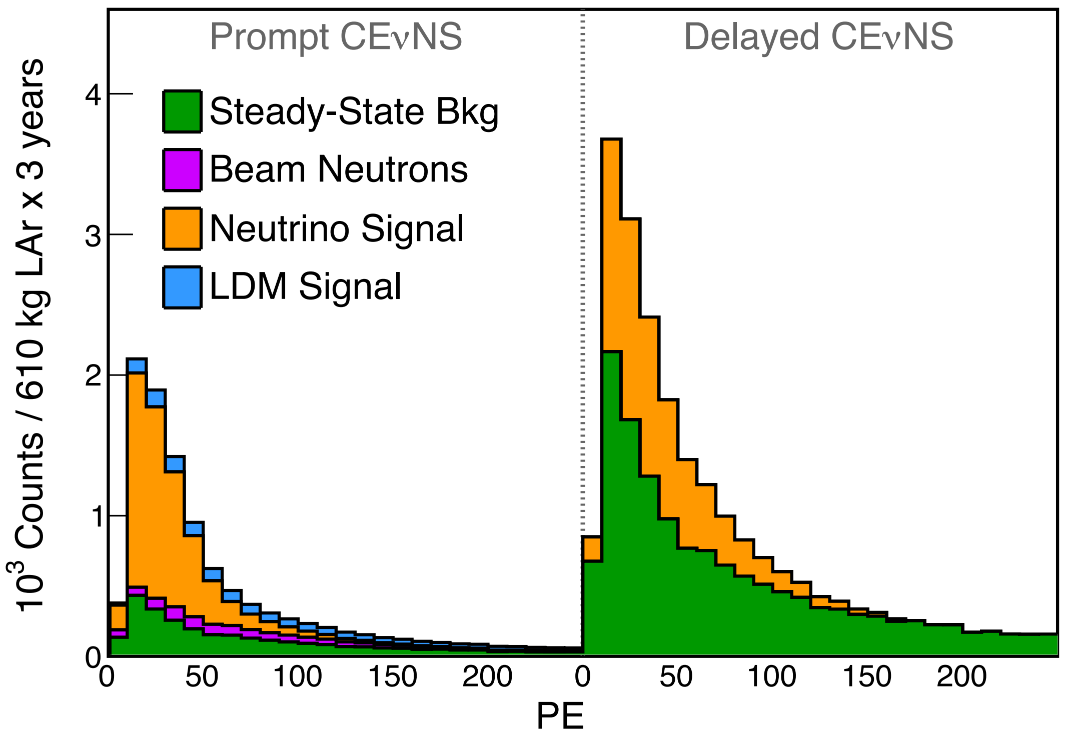
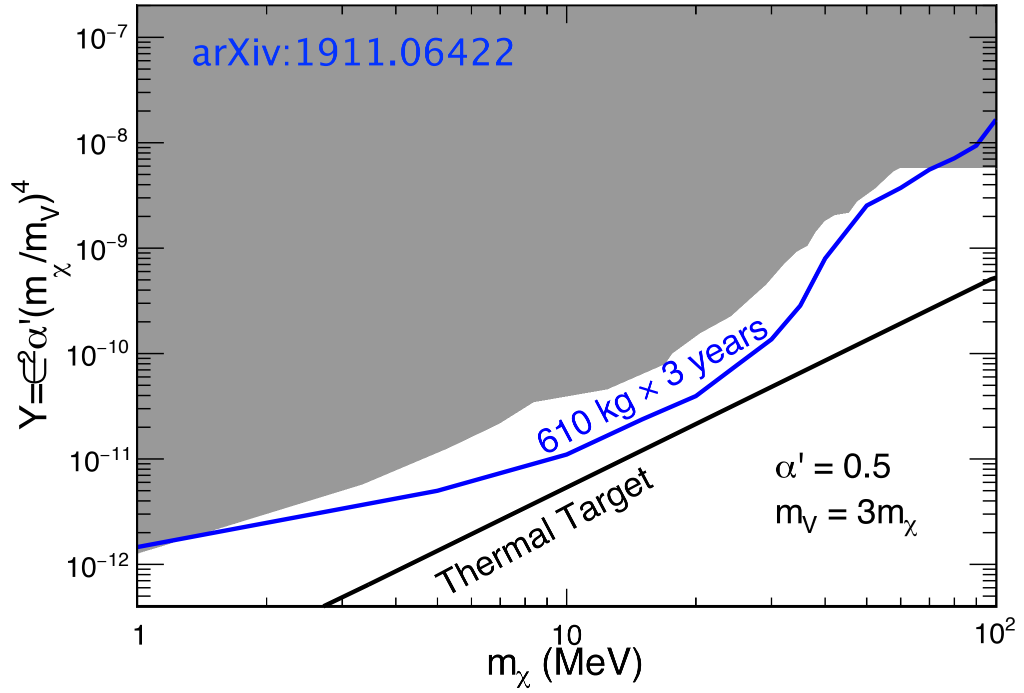






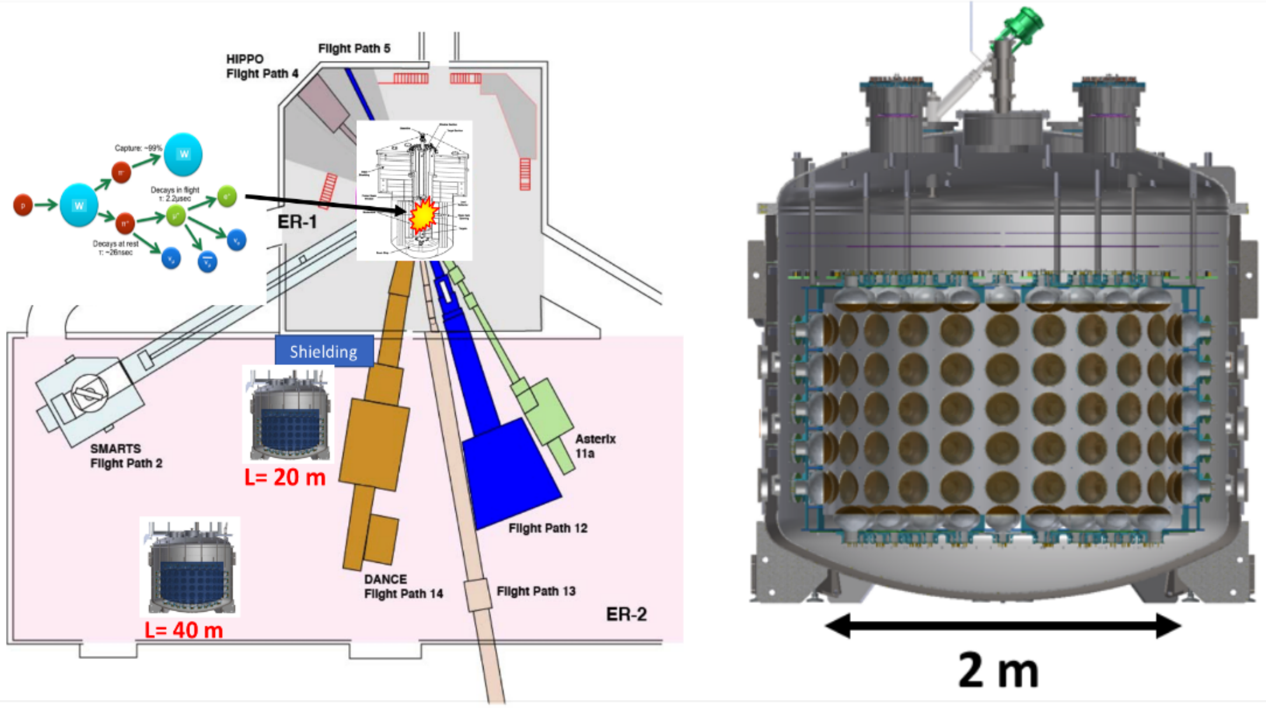


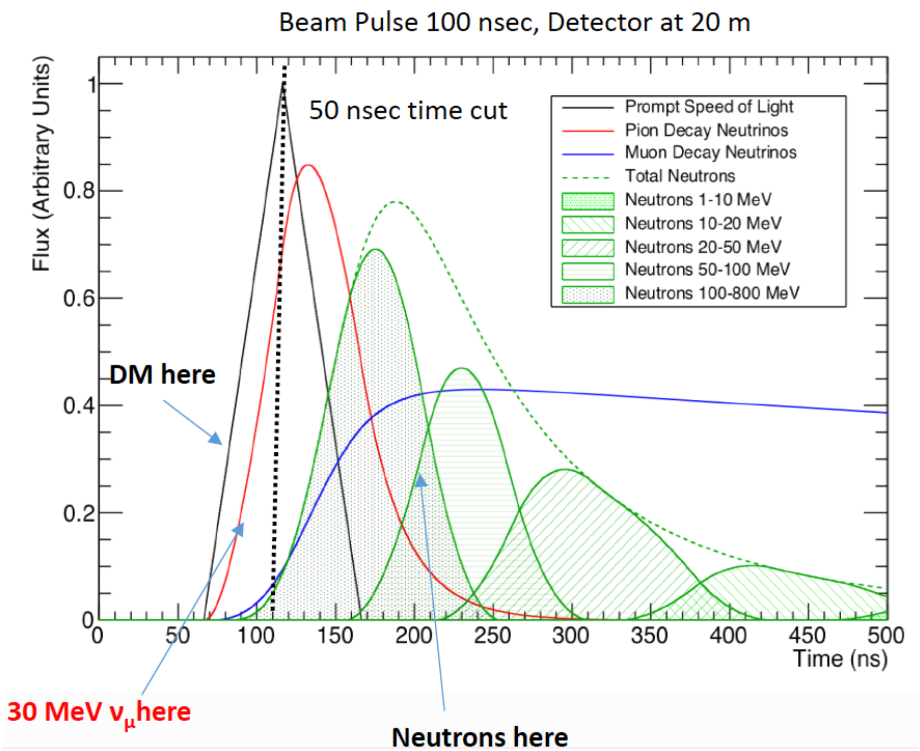
Coherent Captain-Mills (CCM) @ LANL

Designed to study CEνNS and search for eV-scale sterile neutrinos

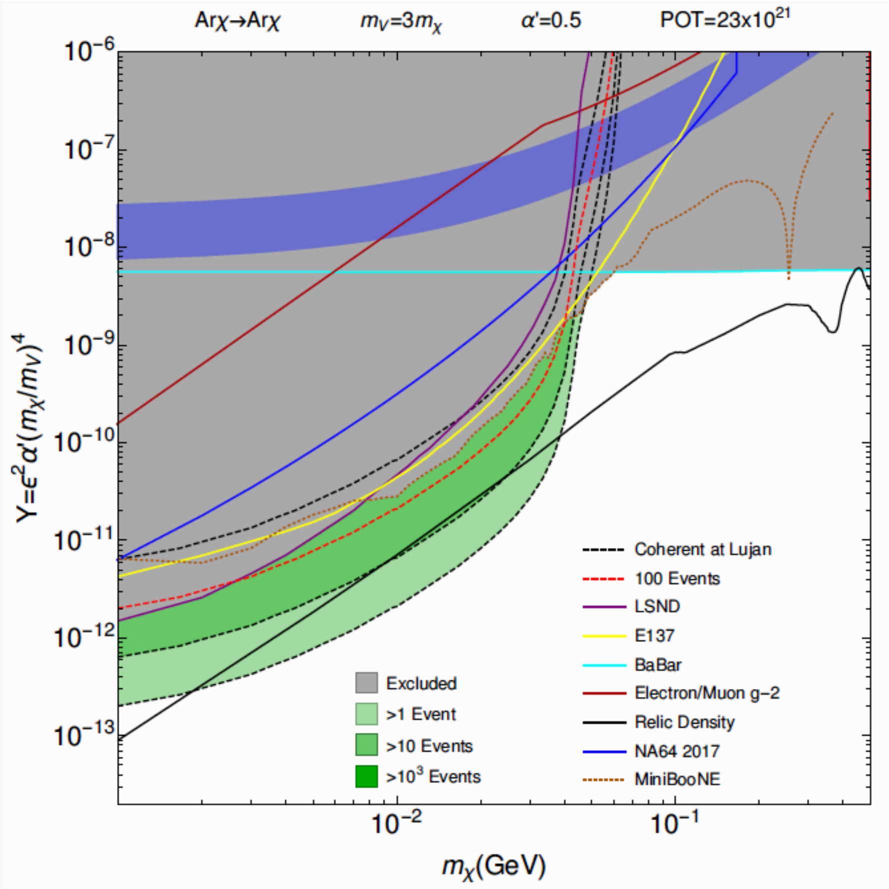
- 800 MeV proton beam on tungsten target
- pair of 10-ton LAr detectors
- similar use of timing to reject delayed backgrounds from neutrons and neutrinos

Good sensitivity if low backgrounds achieved





Figures from R. Van De Water & P. deNiverville



Beam Dump eXperiment (BDX) @ JLab CEBAF

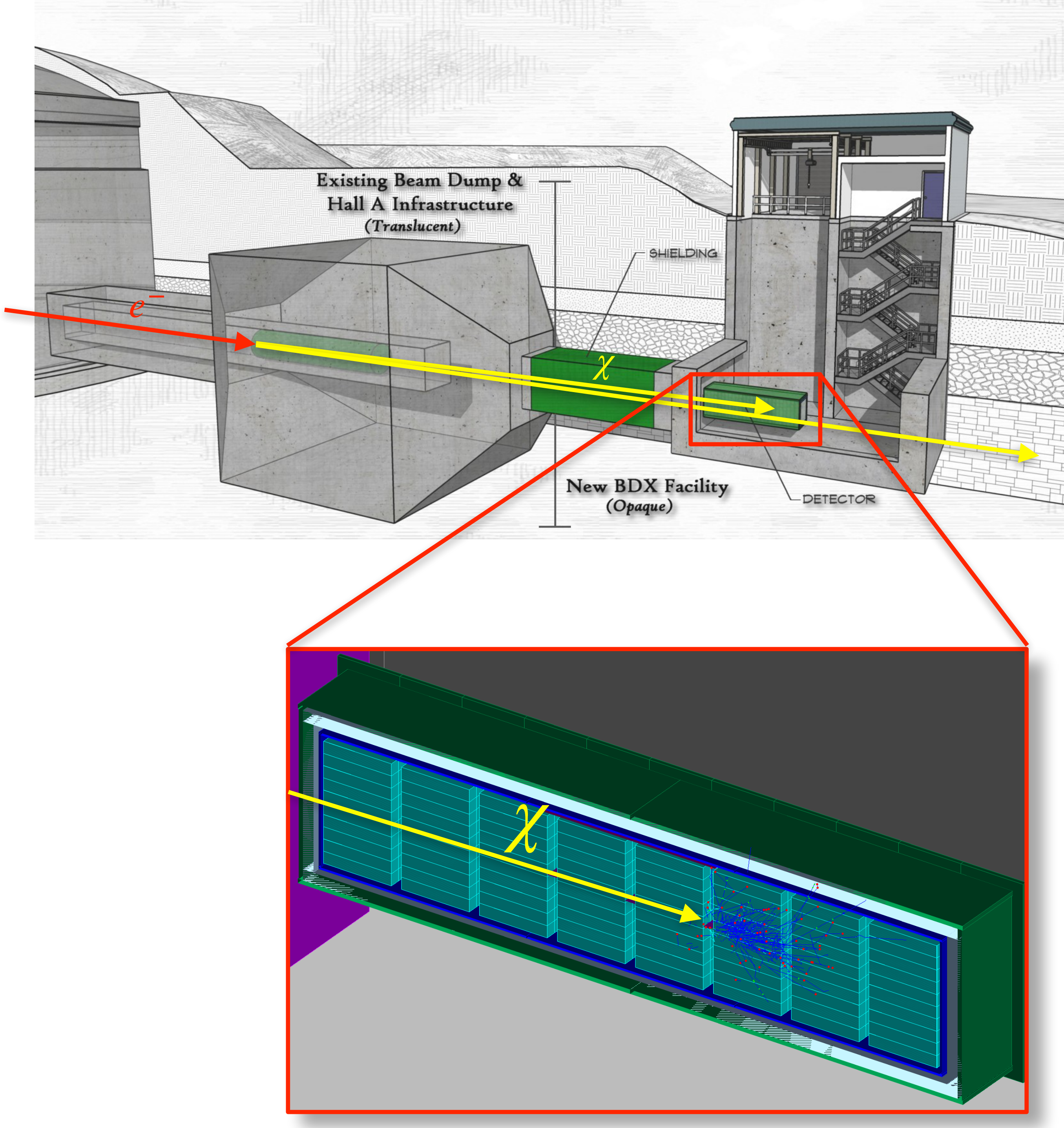
Proposal to run parasitic DM detector behind high-current dump at JLab in new experimental facility

- 2-11 GeV electrons, ~few×10^{21}/year
- CsI detector w/ SiPM readout, cosmic veto
- CW beam: neutrino backgrounds not reducible with timing

Achieves similar sensitivity to proton beam dumps

Test detector, BDX-HODO deployed in pair of wells installed verifies expected backgrounds

BDX-MINI, operated in same location collected 2.1×10^{21} EOT from Dec. 2019 - Mar. 2020 producing first results.



figures from M. Battaglieri

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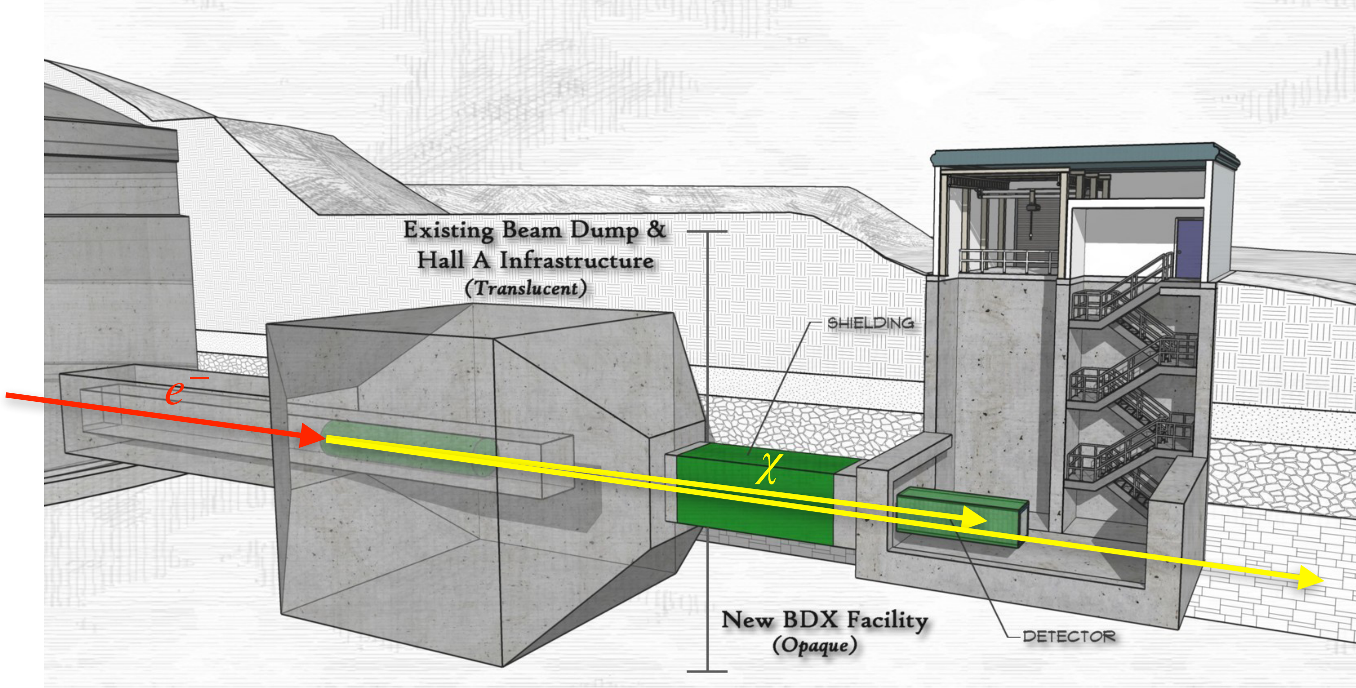

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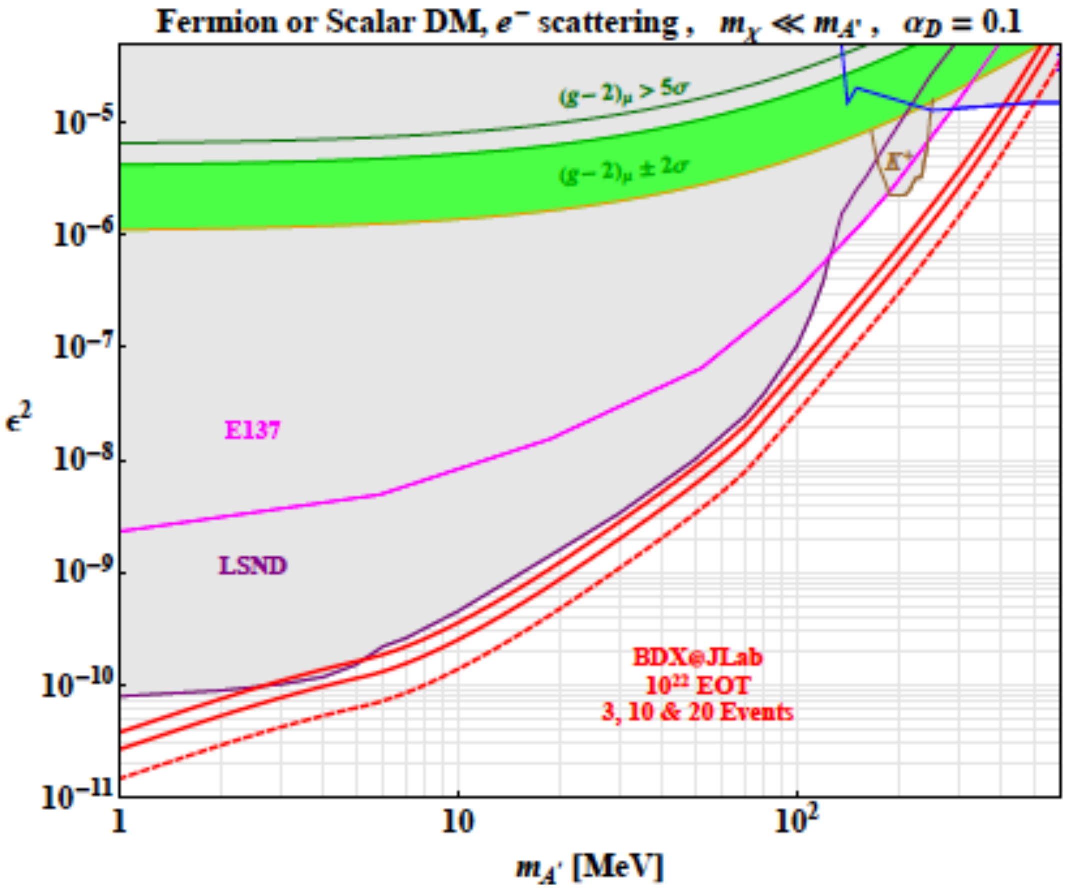

figures from M. Battaglieri

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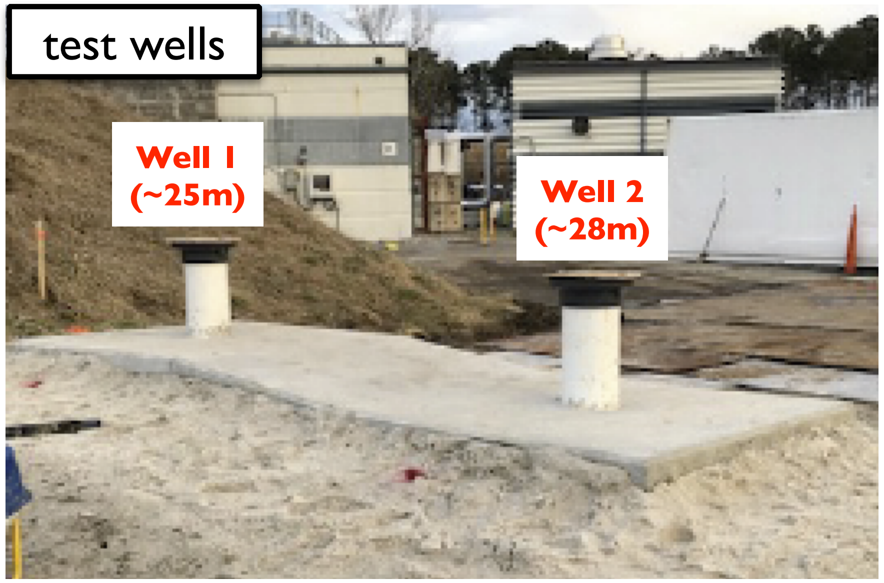

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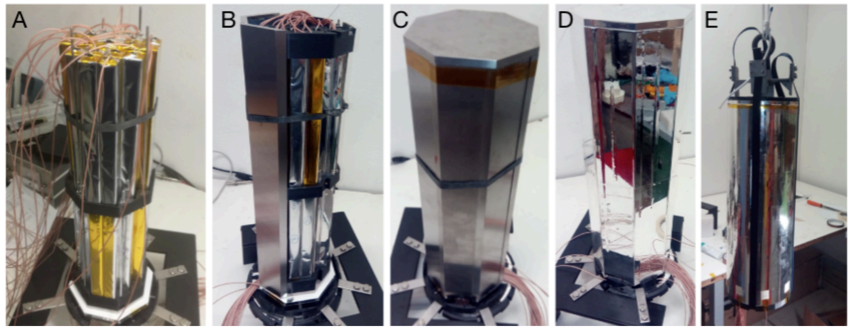
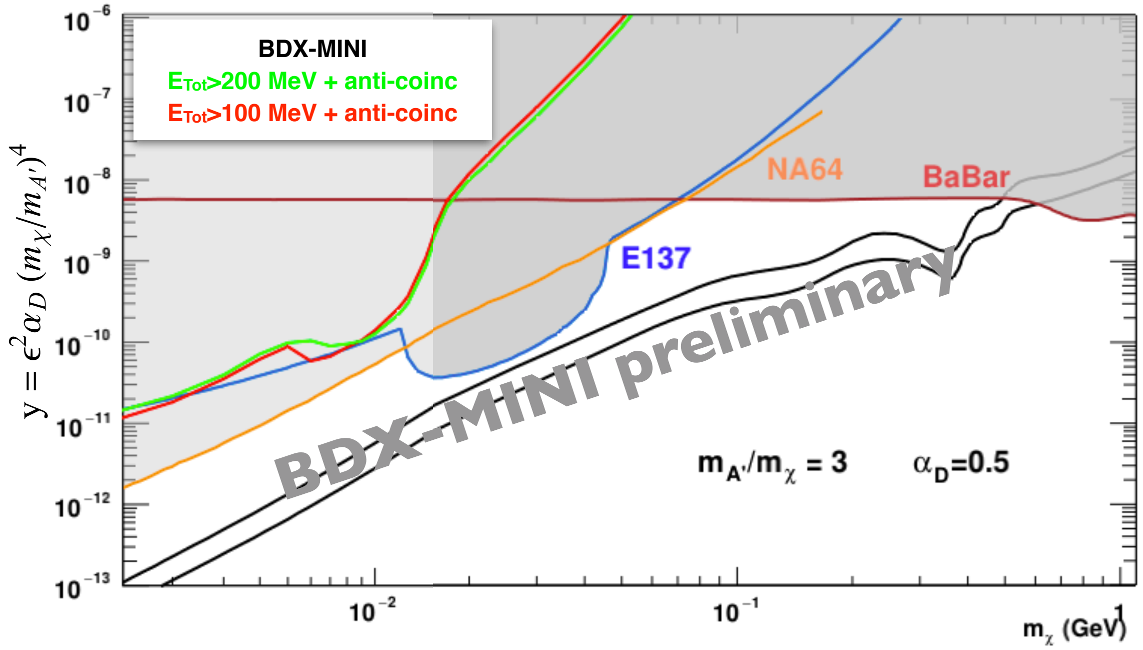
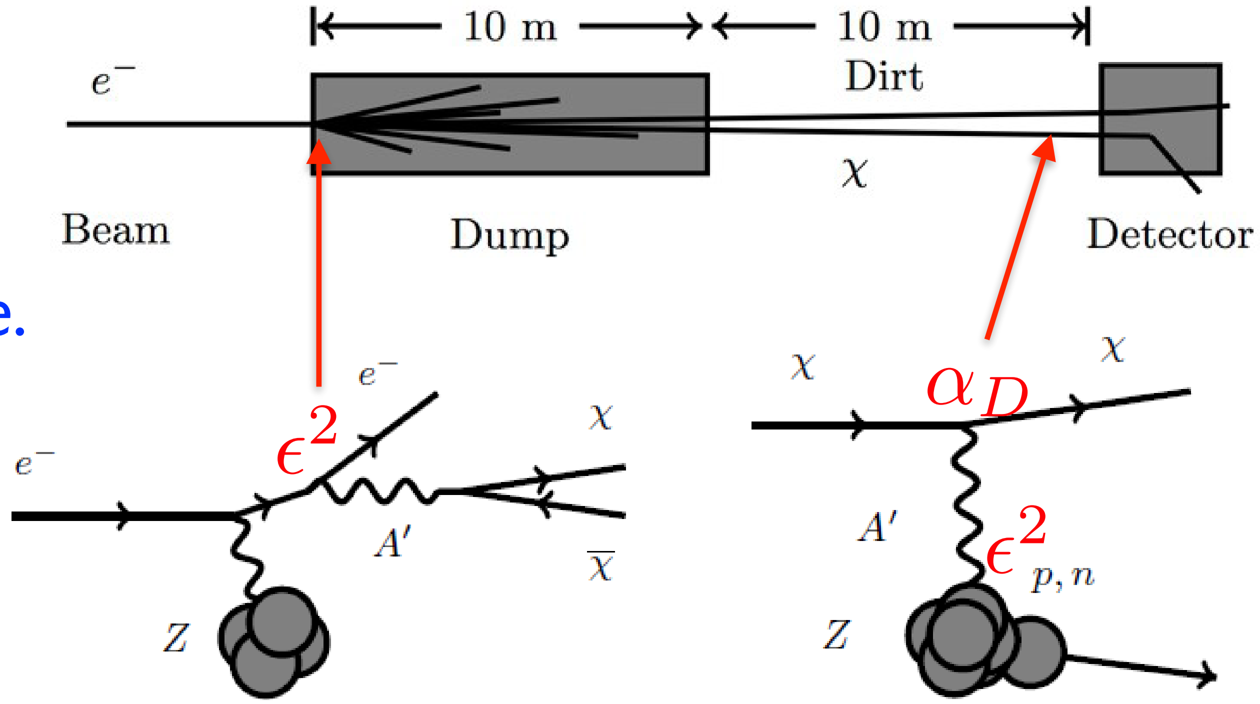




figures from M. Battaglieri

Beam Dump Limitations

Next generation beam dumps cover only scalar target with expected yields, where neutrino backgrounds are already a challenge.

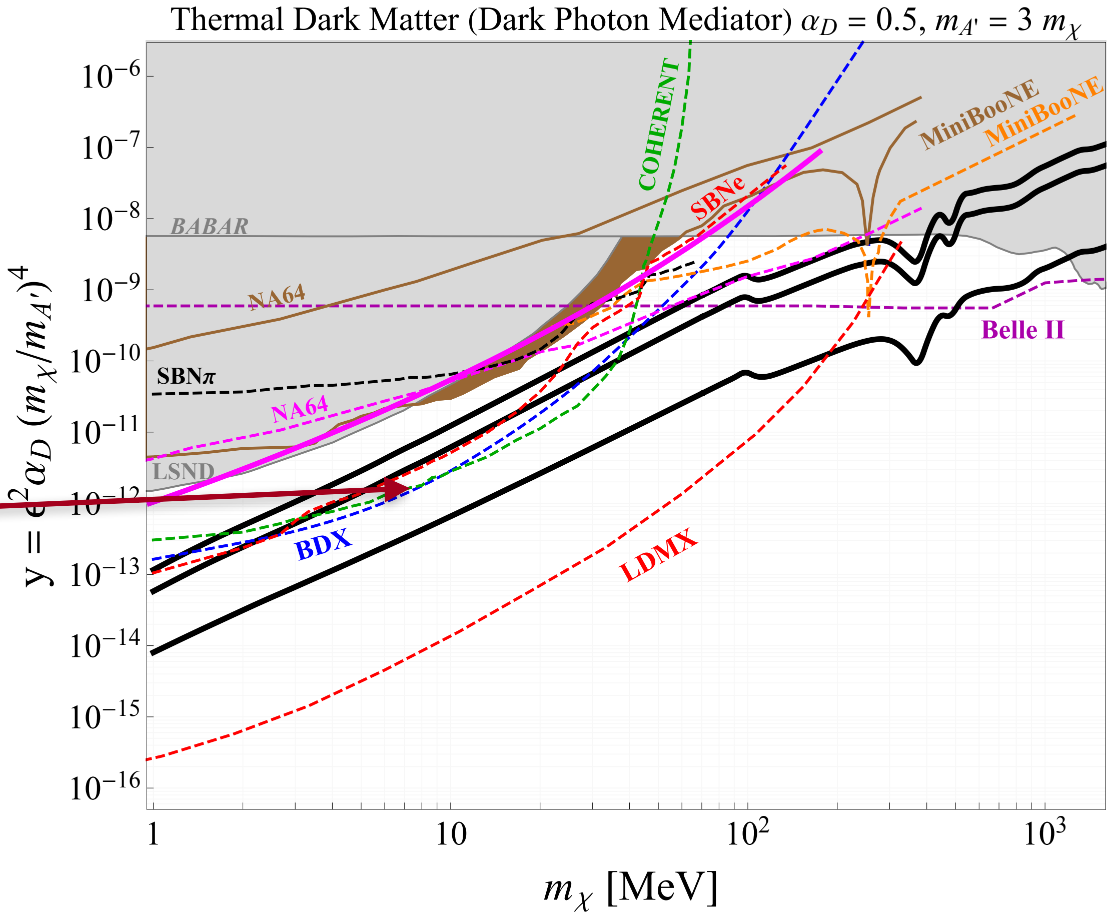


Signal yield scales as $\alpha_D\epsilon^4$

$\Longrightarrow$ reach in y α $(\#\mathrm{EOT})^{1/2}$ *(no background)*

$\Longrightarrow$ reach in y α $(\#\mathrm{EOT})^{1/4}$ *(w/ background)*

Reaching all thermal targets convincingly with beam dumps looks very difficult.

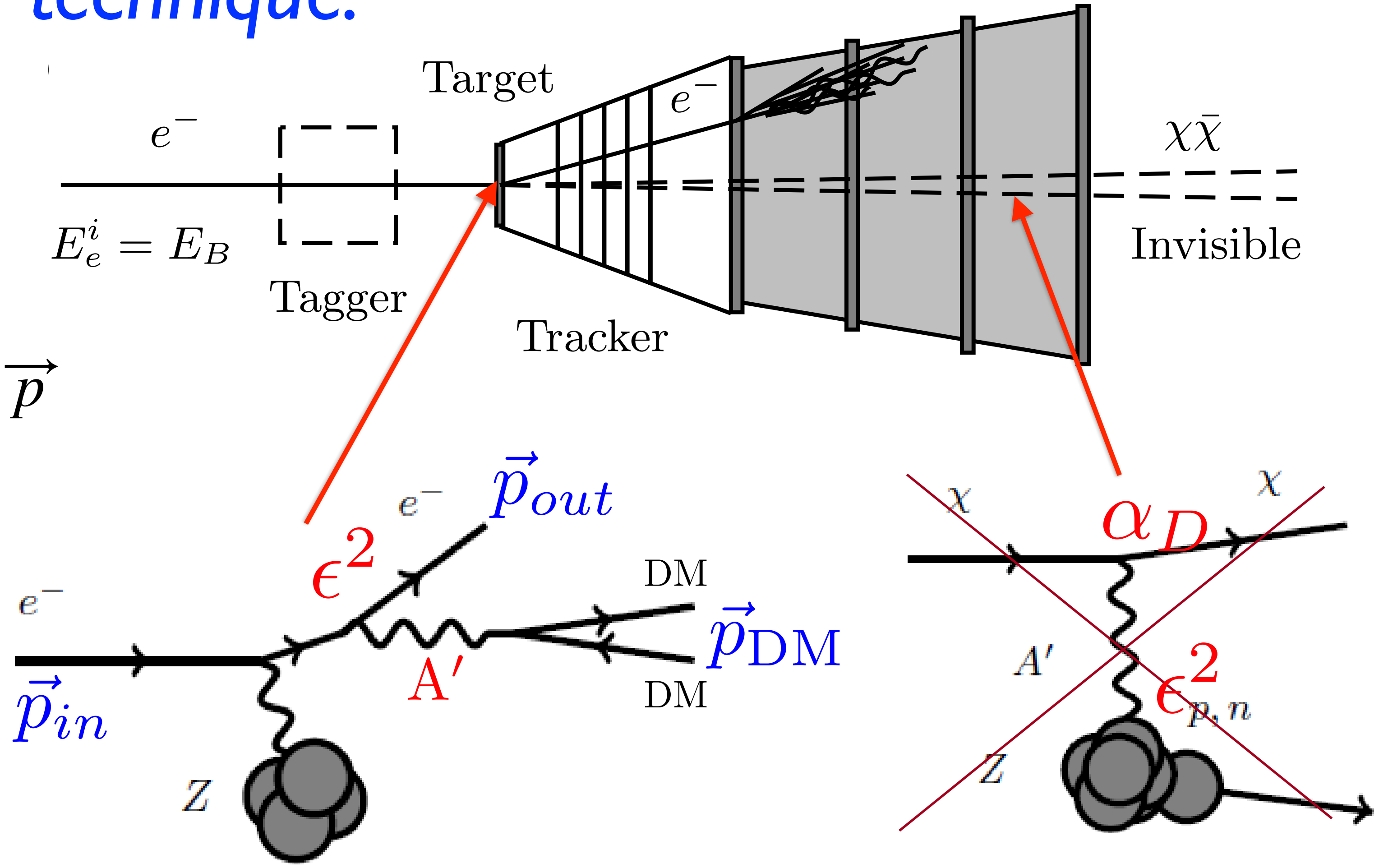


How to Discover Something (nearly) Invisible?

Missing energy/momentum technique:

- one electron at a time, to uniquely associate e$^-_{\text{out}}$ with e$^-_{\text{in}}$ (only leptons are clean enough)
- look for events with large ΔE or $\Delta \vec{p}$
- no other products of reaction (something invisible produced)

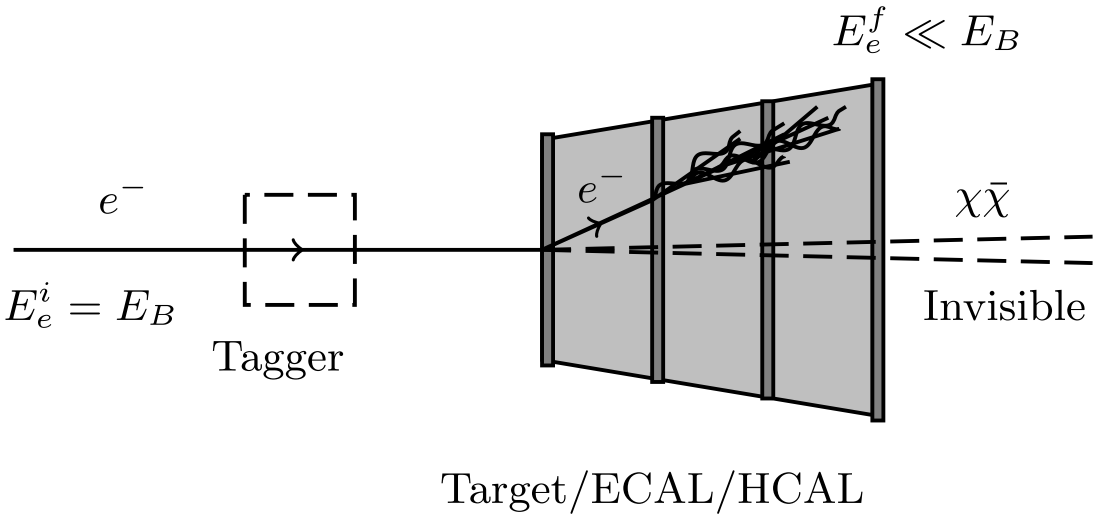
$$N \propto \epsilon^2$$



$$\vec{p}_{\text{in}} = \vec{p}_{\text{out}} + \vec{p}_{\text{DM}}$$

Much better sensitivity than beam dumps with relatively small event yields.

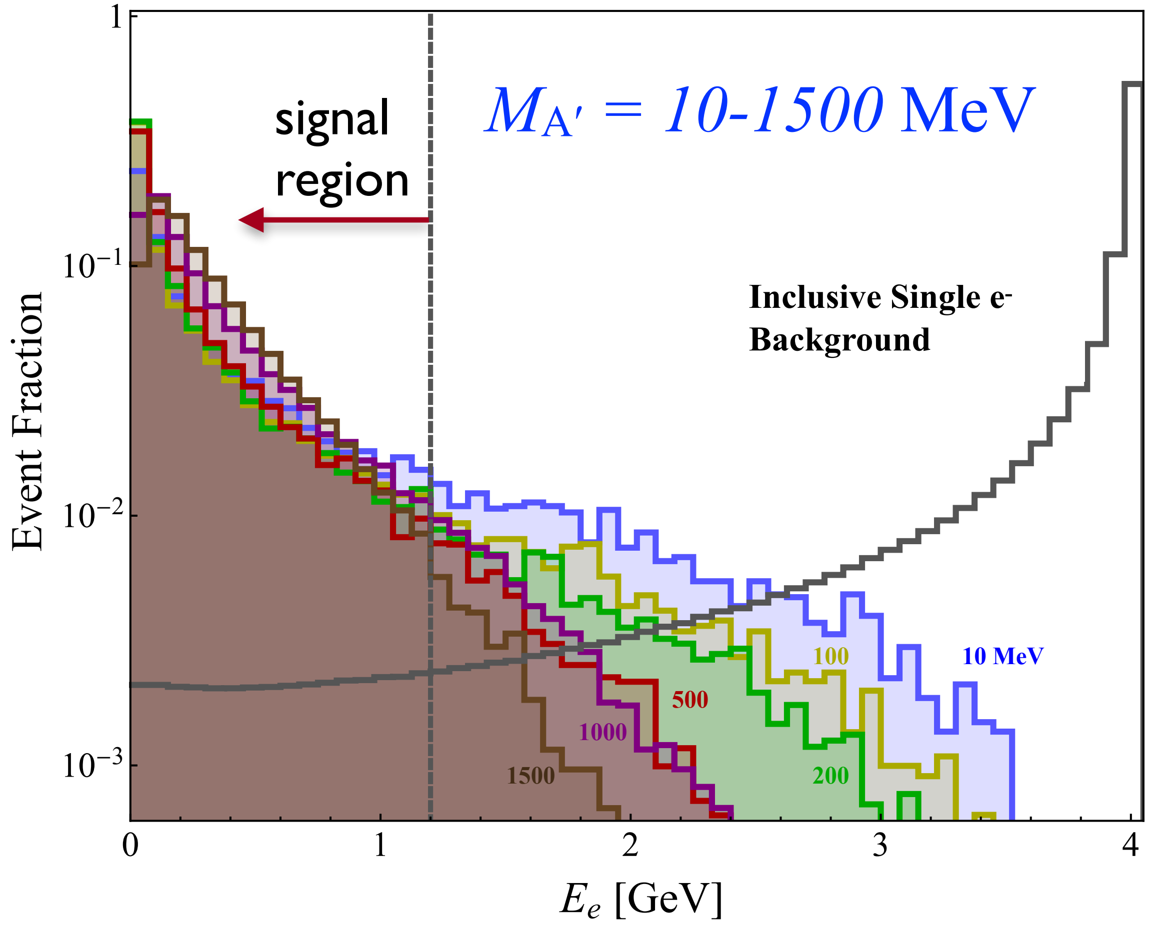
Missing *Energy* vs. Missing *Momentum*



Missing energy experiments…

- *have a thick (active) target for higher yields*
- *have only one signal discriminator*
- *have no way to probe mediator physics*
- *are challenged by backgrounds beyond 10^{14} EOT that require e-γ particle ID*

recoil energy distributions, 4 GeV e^- on 10% X_0 target



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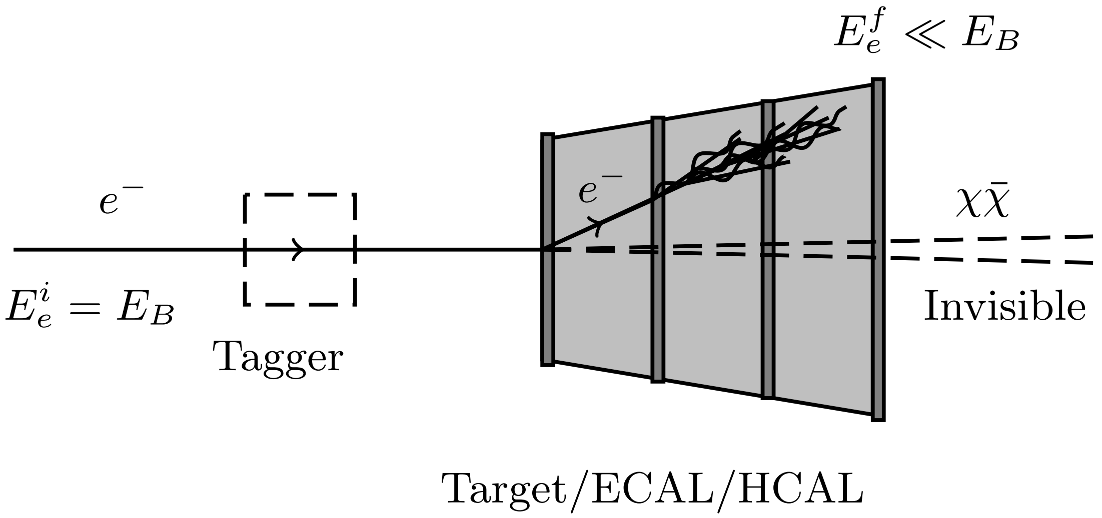

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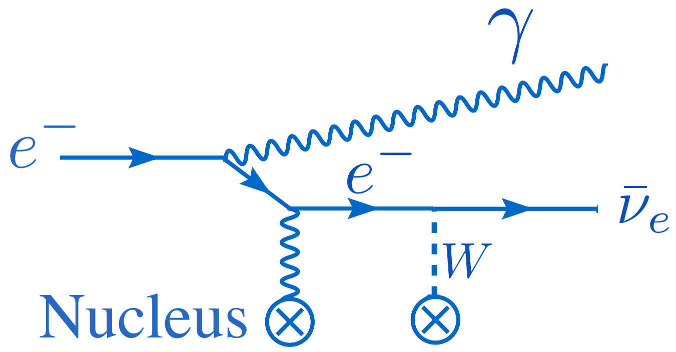

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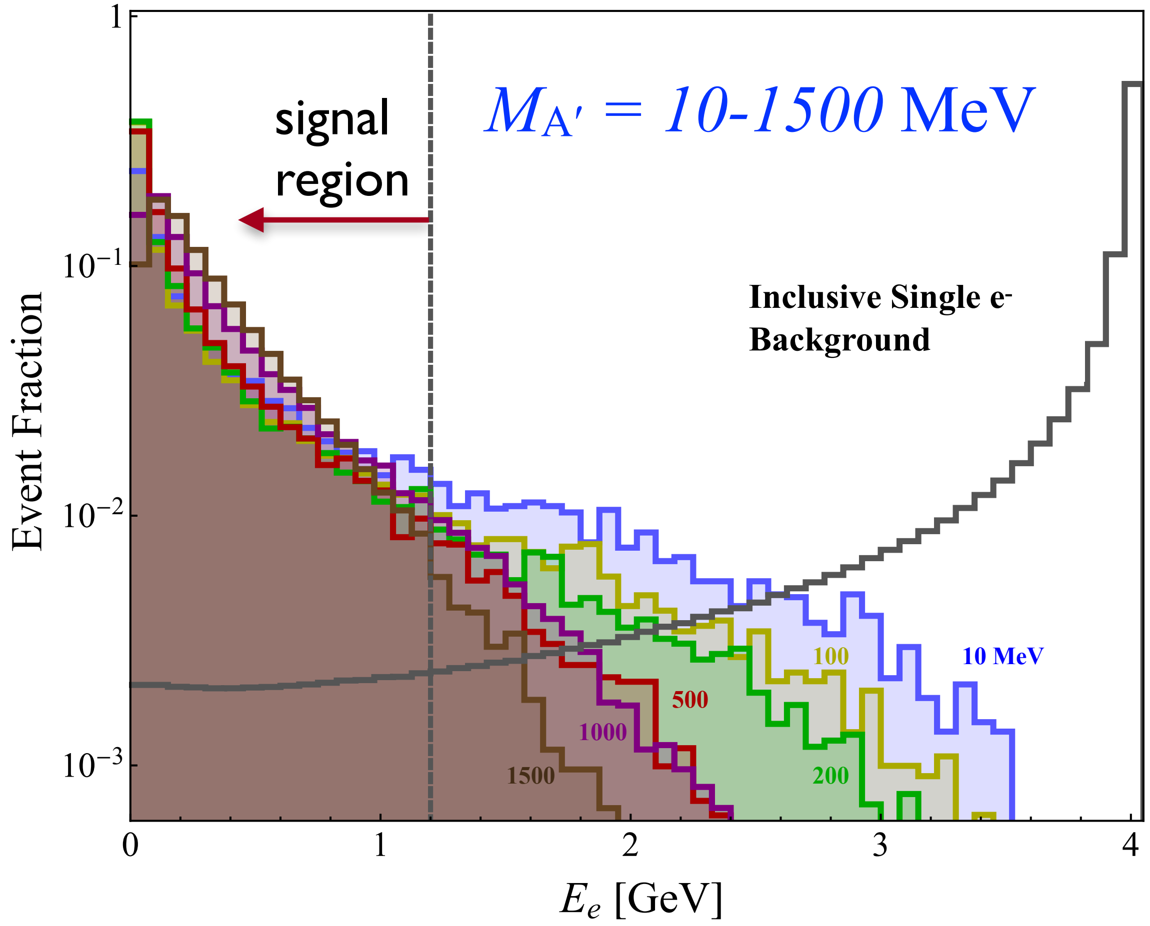

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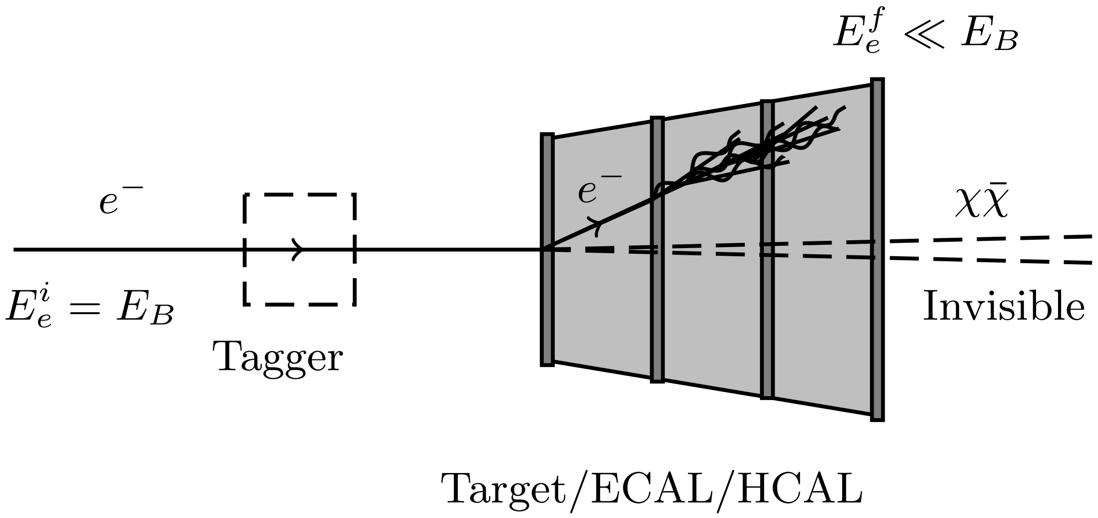
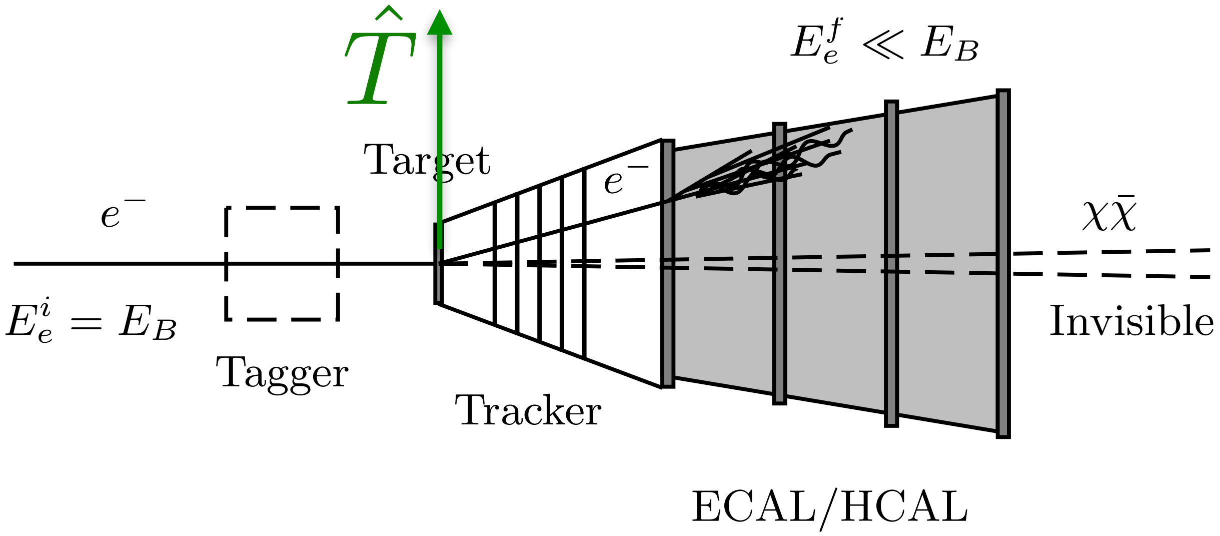
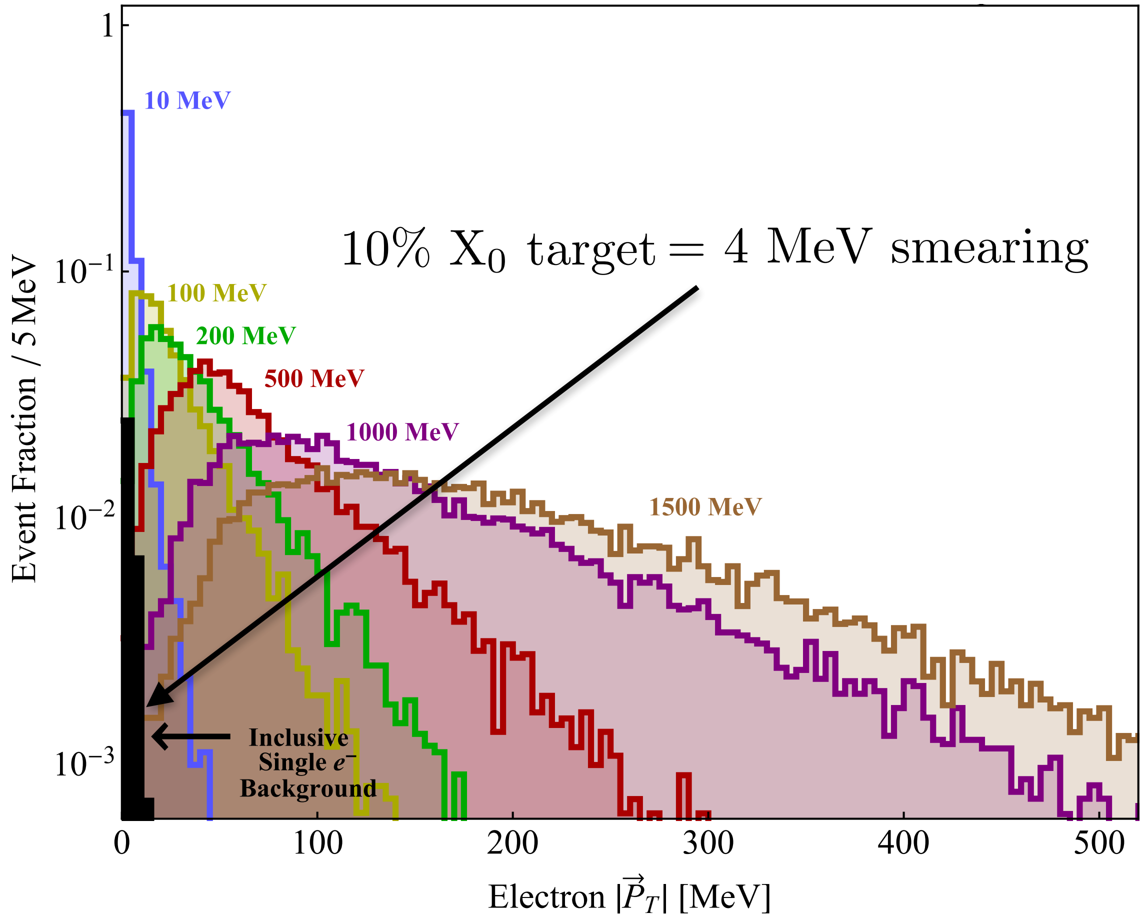




recoil p_T distributions, 4 GeV e^- on 10% X_0 target



Missing momentum experiments…

- also have Δp_T as a signal discriminator
- have Δp_T as a signal *identifier*, sensitive to $m_{A'}$
- have tracking for e-γ particle ID so that no irreducible backgrounds beyond 10^{16} EOT.
- *include a missing energy experiment: thin-target missing momentum experiments can also perform a missing energy analysis*

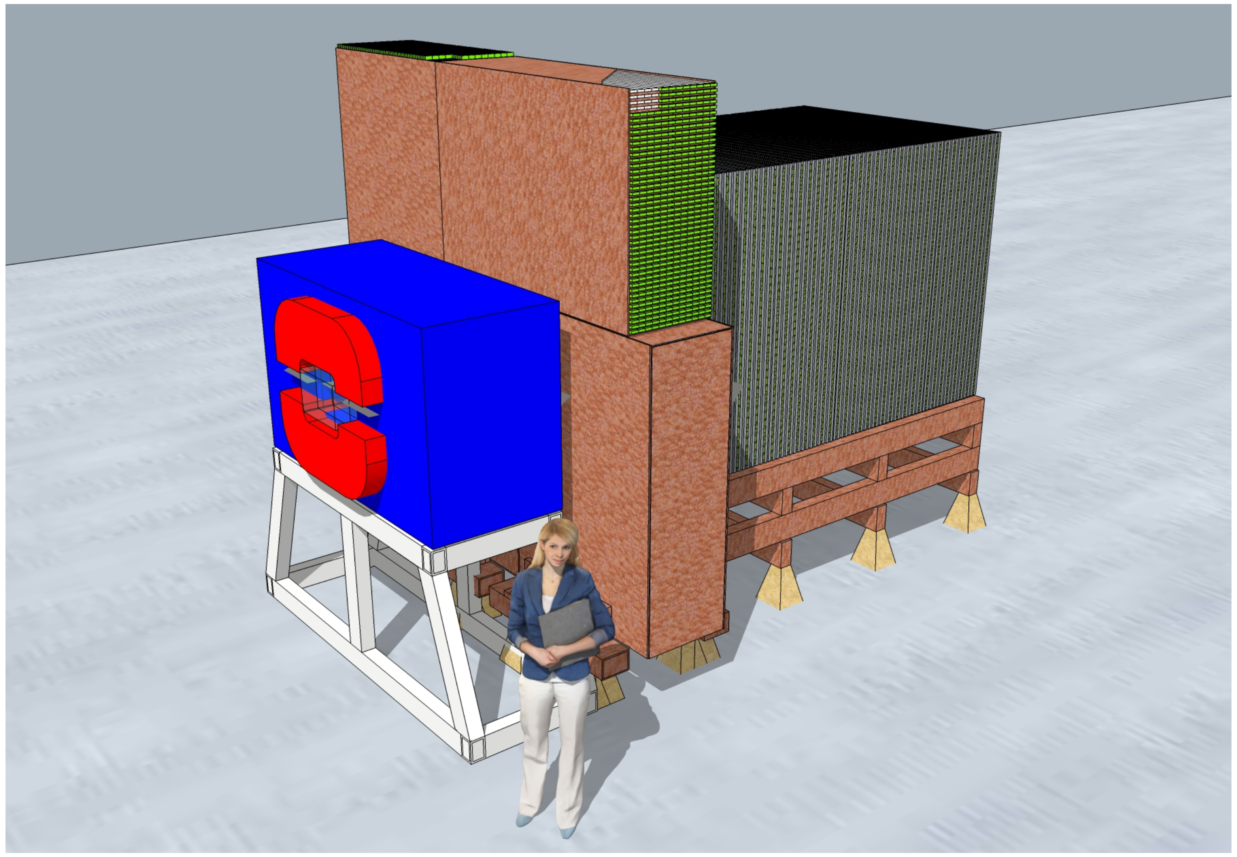
The LDMX Experiment at SLAC

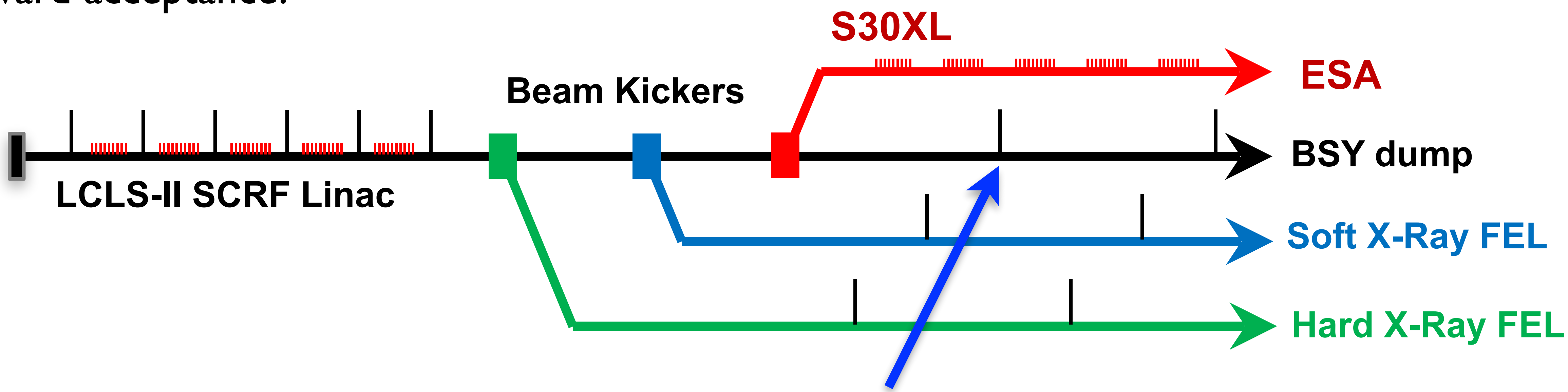
missing momentum experiment for $\gtrsim 10^{16}\ e^-$

HPS-like compact layout, tracking from HPS, ECal from CMS upgrade and HCal from Mu2e

planned operation in End Station A at SLAC using LCLS-II drive beam delivered through the Sector 30 Transfer Line (***L***inac to ***E***nd ***S***tation ***A***).

In addition to missing momentum, also sensitivity to visible signatures with thin target and hermetic forward acceptance.





LCLS-II will send ~2.5×10^{21} electrons/year to the dump: other opportunites?

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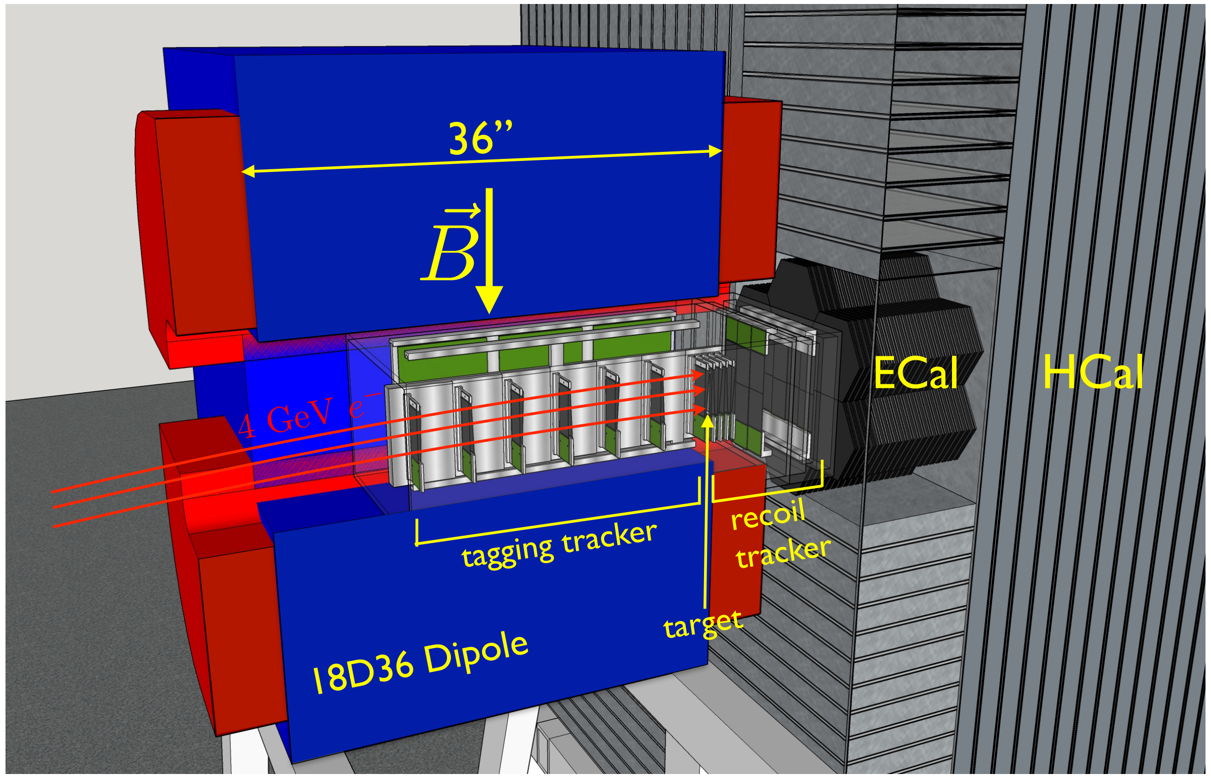
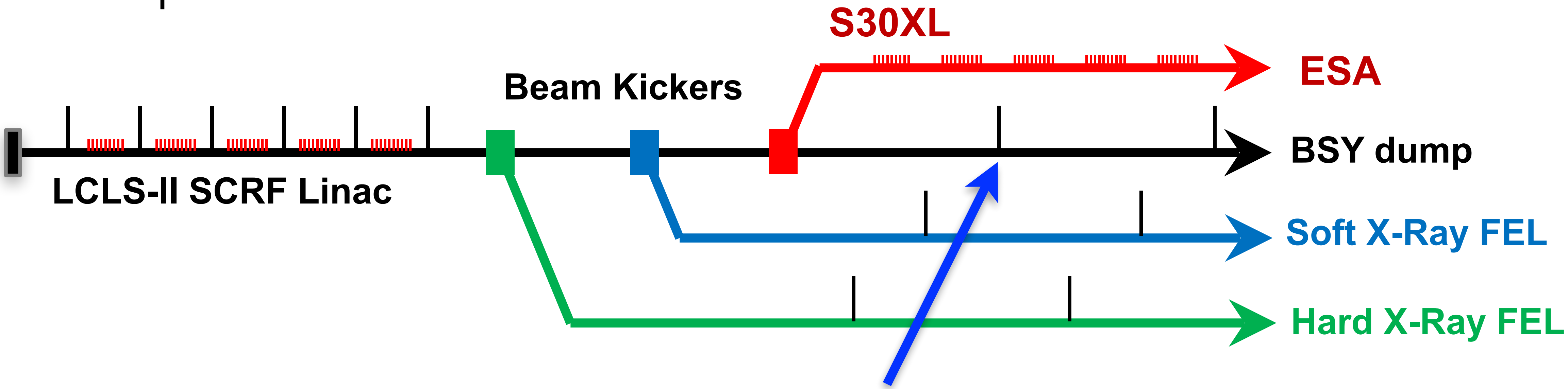




S30XL

ESA

Beam Kickers

BSY dump

LCLS-II SCRF Linac

Soft X-Ray FEL

Hard X-Ray FEL

LCLS-II will send ~2.5×10²¹ electrons/year to the dump: other opportunites?

LDMX Sensitivity to A'-mediated Freeze-out DM

Key backgrounds are e^- + low multiplicity:

$$e^- \to e^- + \text{hard } \gamma$$
$$\gamma \to \mu^+\mu^-$$
$$\gamma \to \text{hadrons}$$

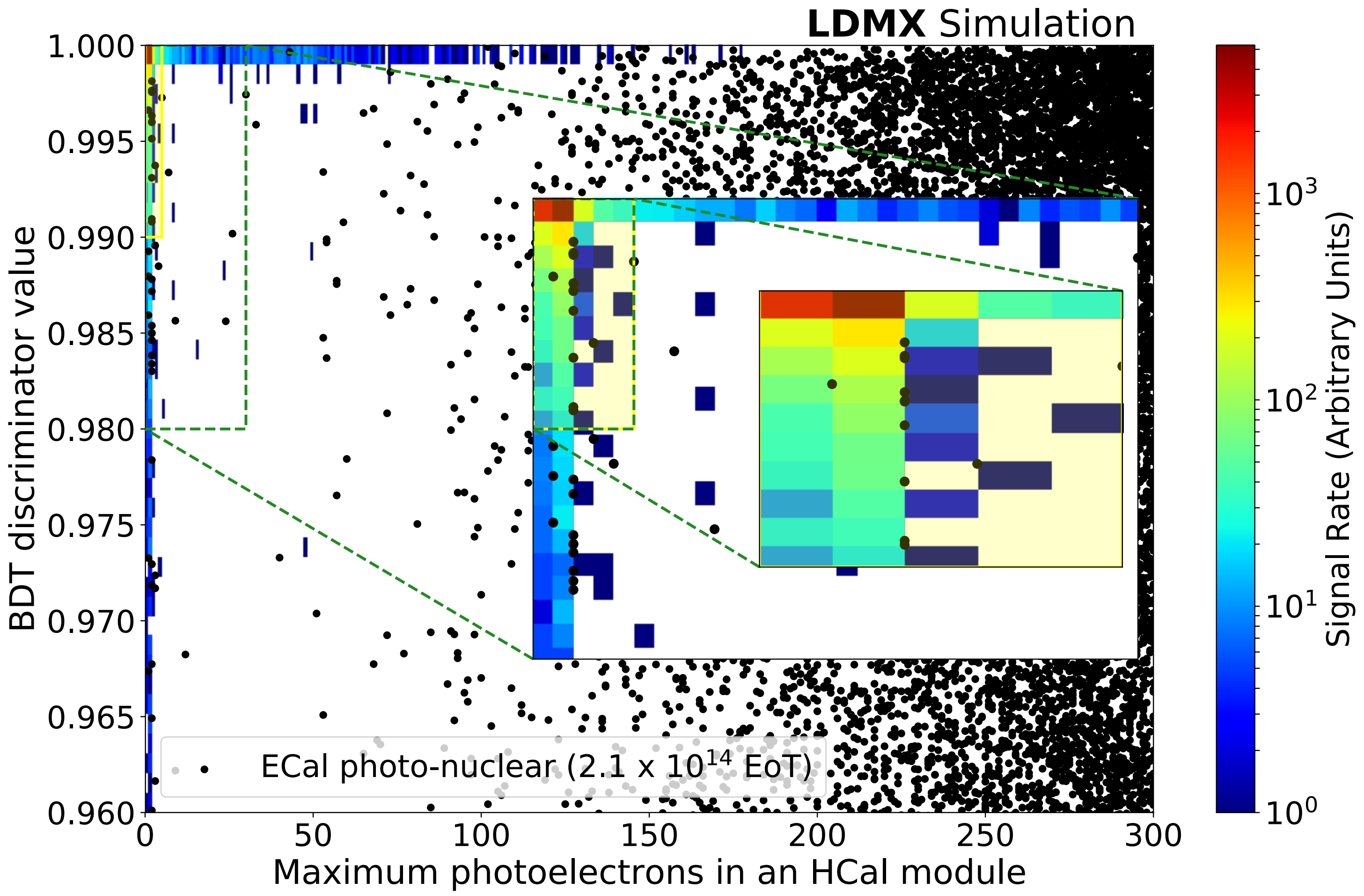
(and direct electro-nuclear analogues)

After ~2 years of operation with 4 GeV beam, LCLS-II upgrade to 8 GeV for Phase II

Phase III? A larger detector, operating at even higher energies (e.g. CERN eSPS at 16 GeV) would extend reach at high masses.

Possibility of operation with a muon beam at FNAL (M3) also being studied

Ultimate goal is exploration of entire thermal DM parameter space from MeV-GeV, where complementarity with Belle-II is important.



arXiv:1912.05535 [physics.ins-det]

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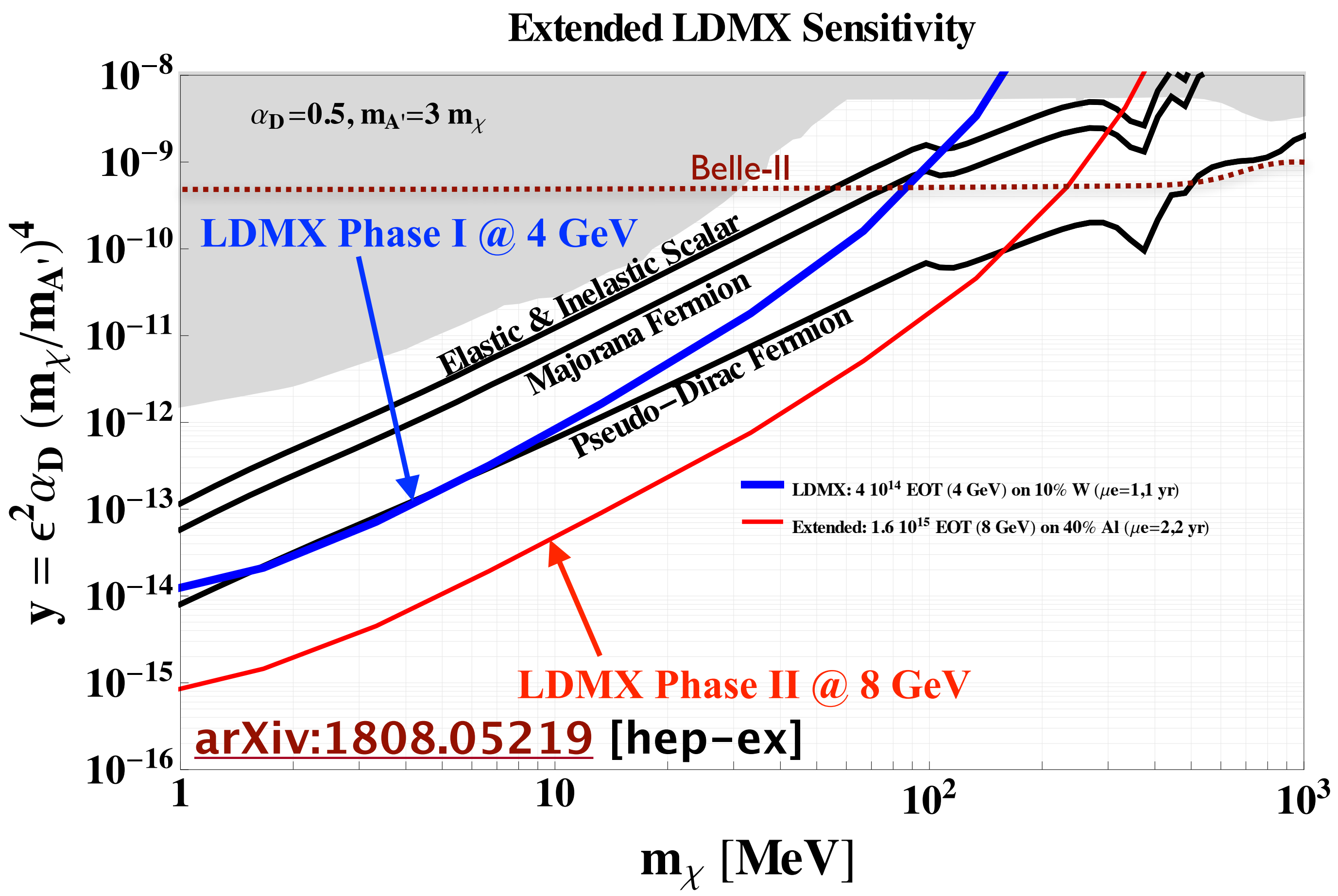

arXiv:1808.05219 [hep-ex]

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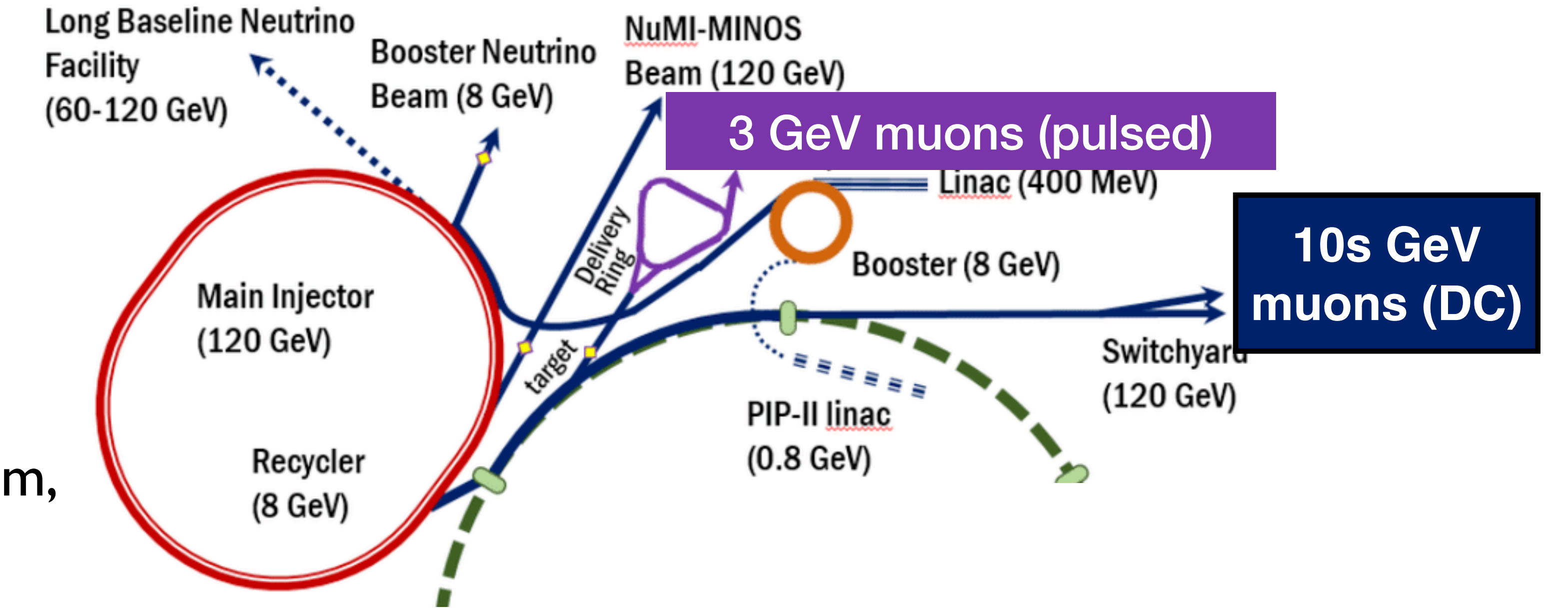

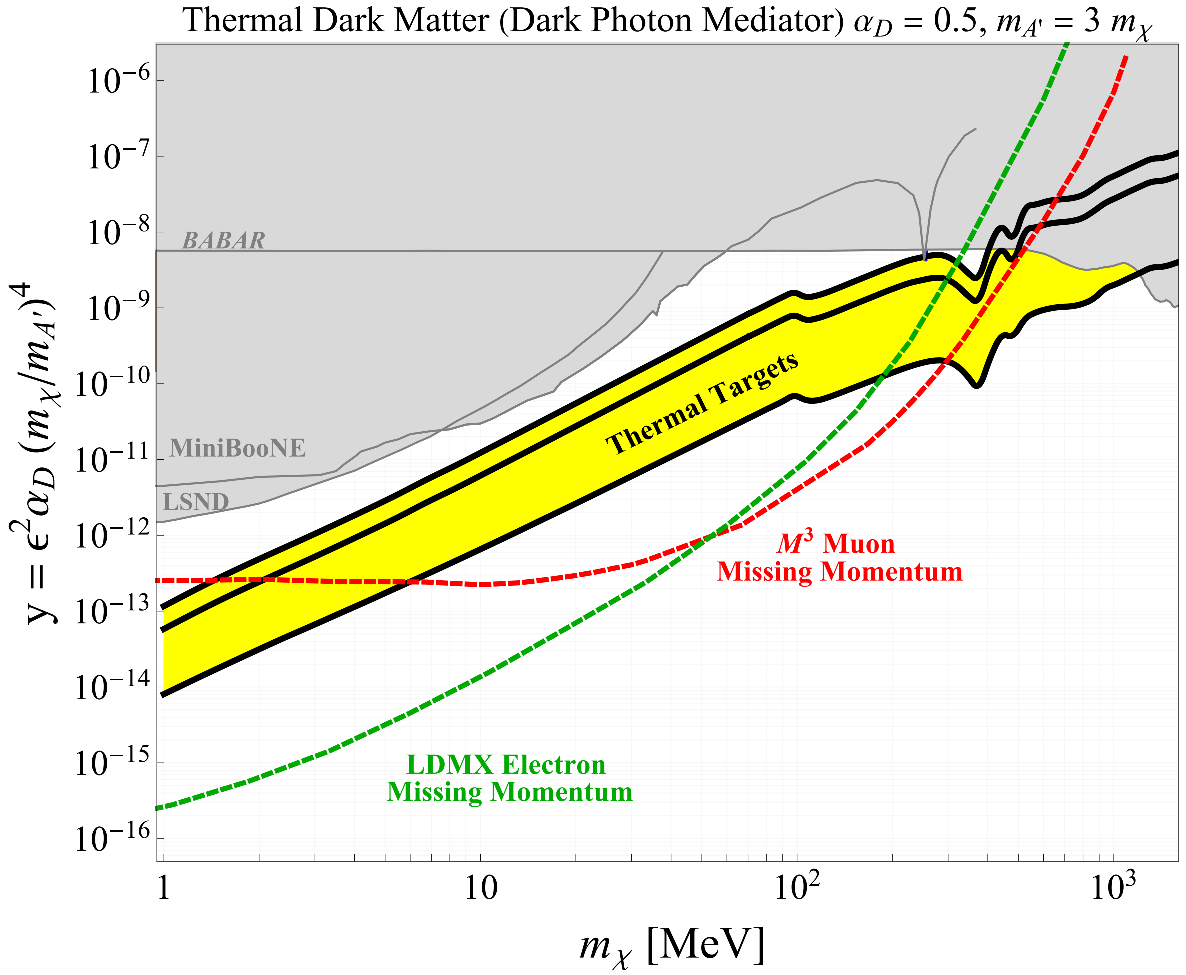

LDMX Beyond A'-mediated Freeze-out DM

Sensitive to a broader set of scenarios:

arXiv:1807.01730 [hep-ph]

- other mediators
- Strongly Interacting Massive Particles (SIMPs):
  a confining interaction in the dark sector
- millicharged particles:
  arise from ~massless dark photons and
  thrust into spotlight by EDGES anomaly
- Axion-like particles (ALPs):
  new pseudo-scalars can have either/both
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- inelastic Dark Matter (iDM):
  large mass-splittings in dark states, both visible
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- freeze-in DM, etc… *new ideas?*

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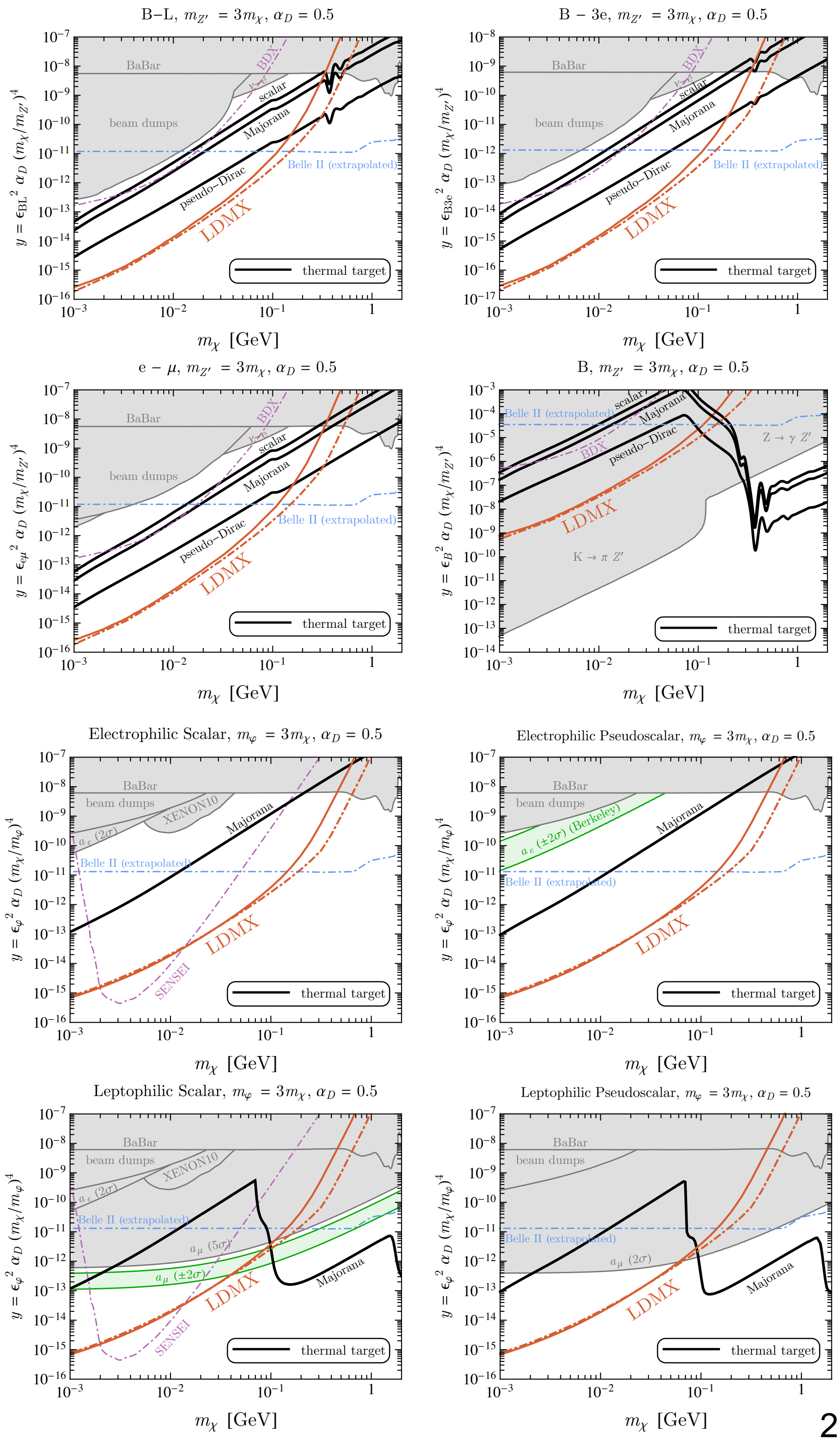

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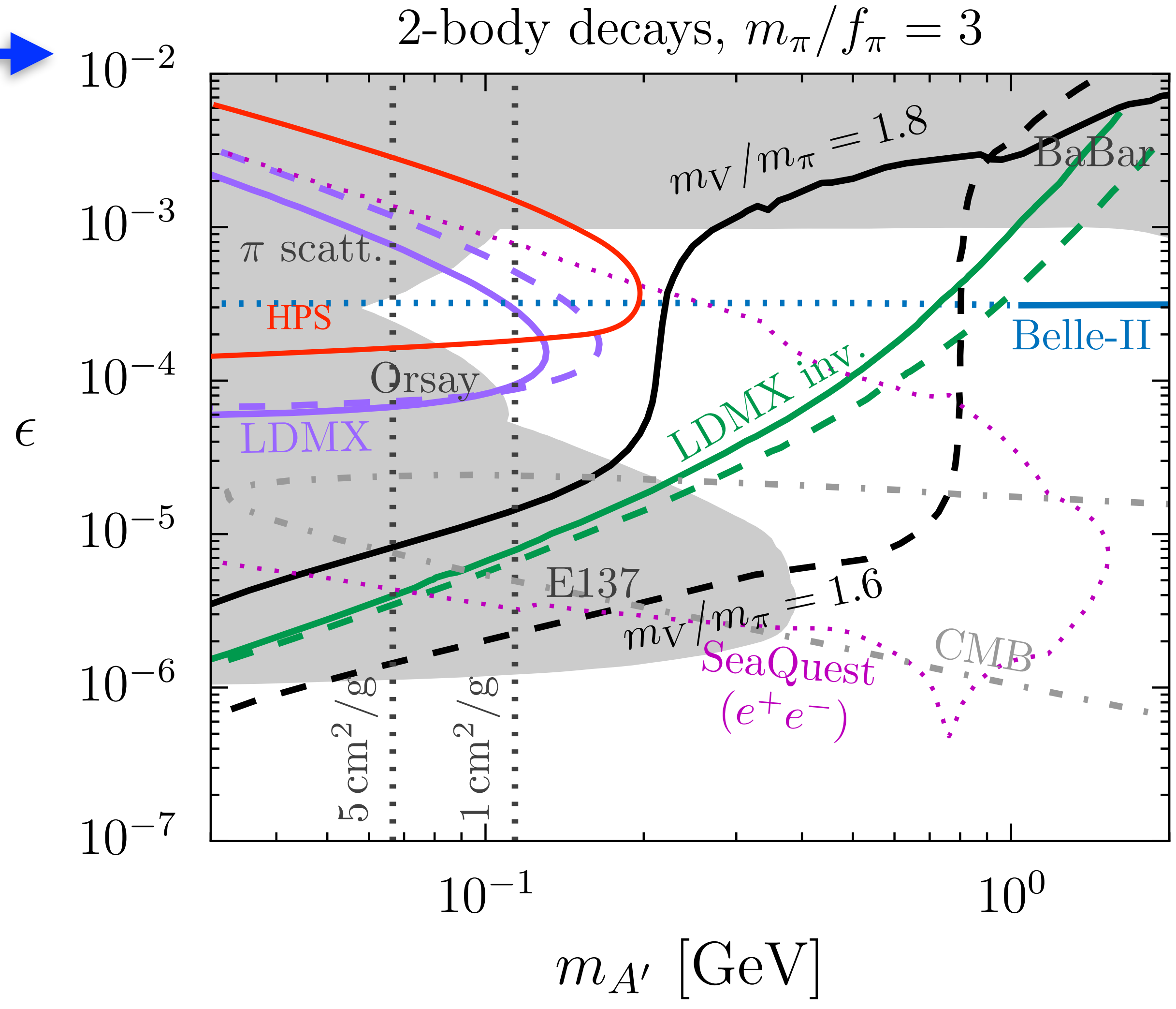

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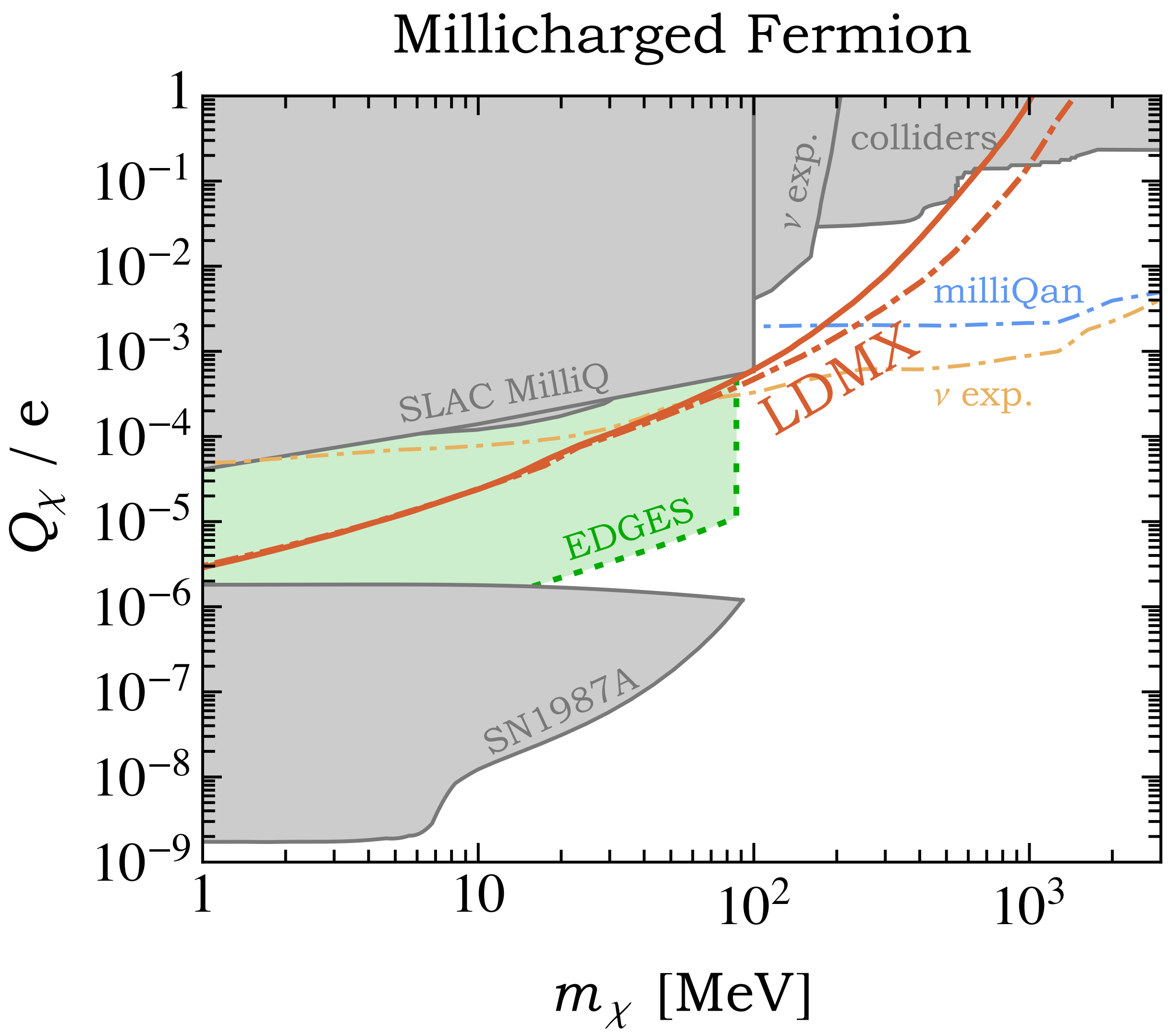

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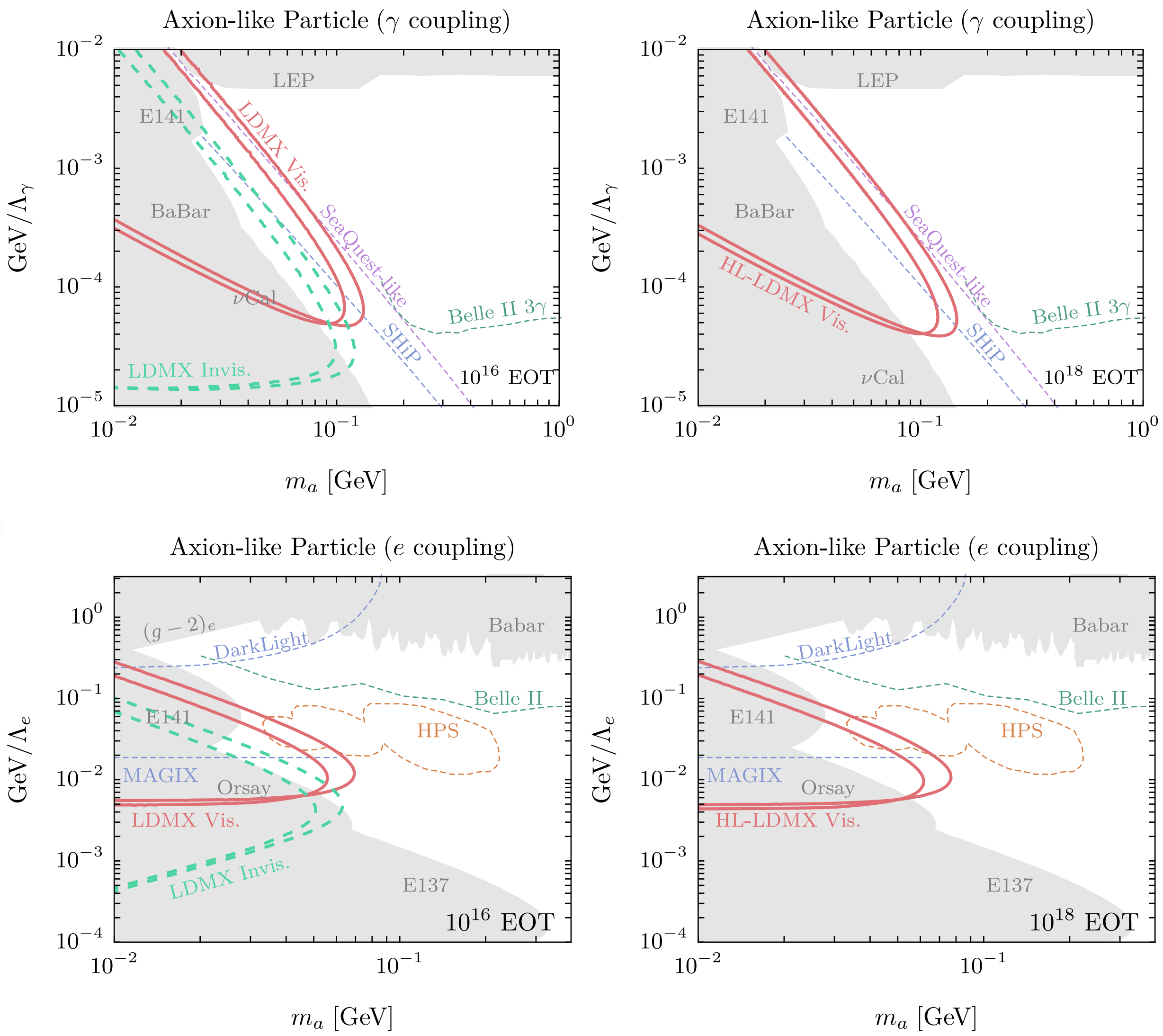

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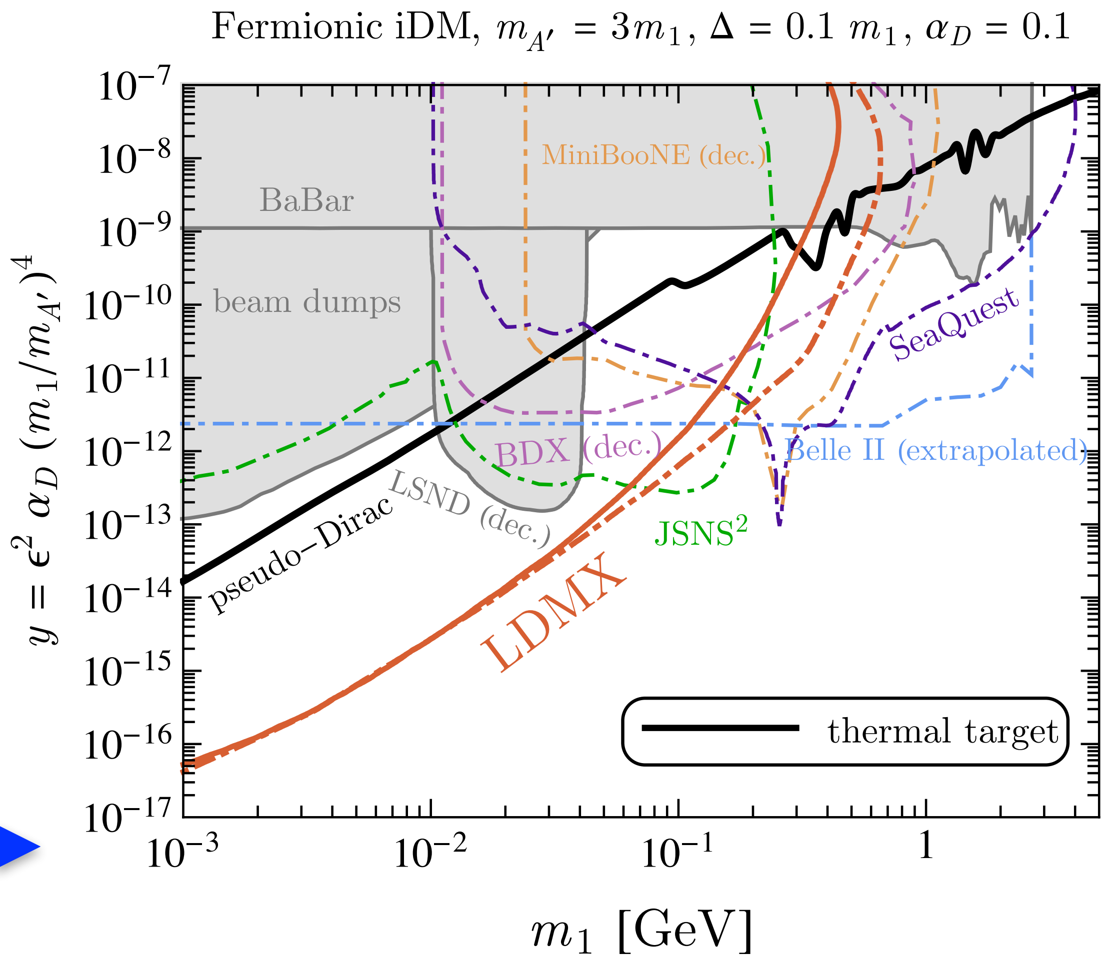

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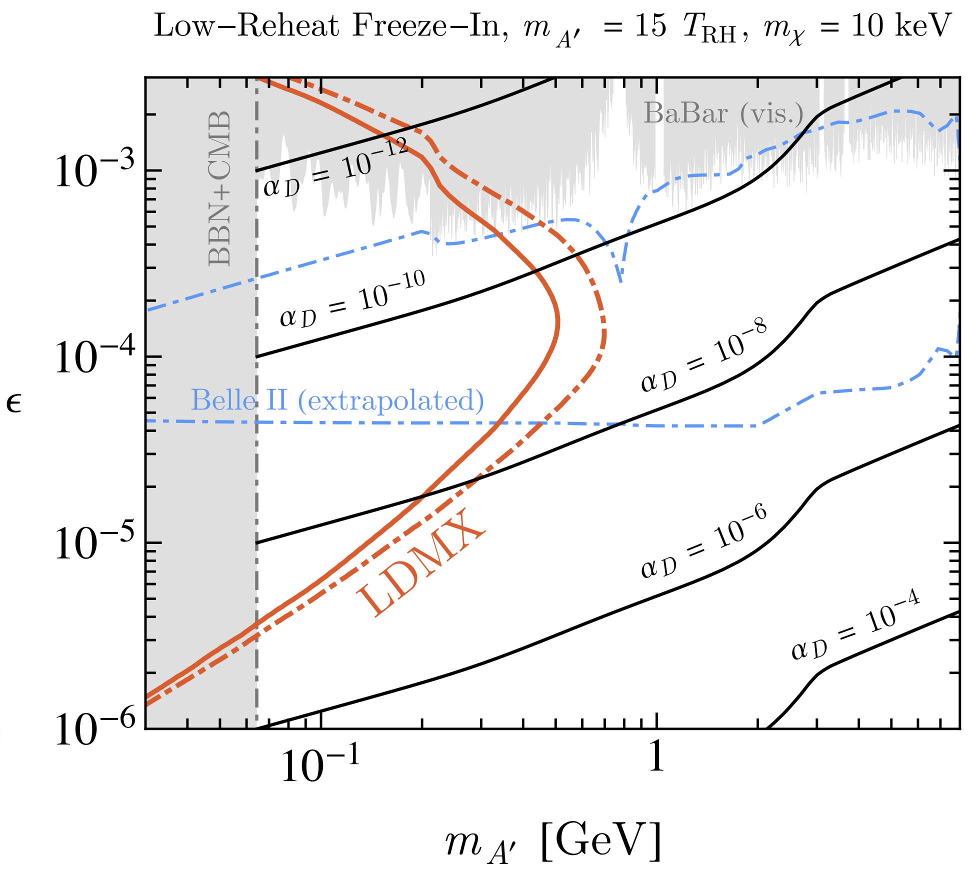


Low−Reheat Freeze−In, $m_{A'} = 15\ T_{\mathrm{RH}}$, $m_\chi = 10$ keV

Summary

Fixed target experiments continue to play an important role in searches for new vector mediators and dark matter in the MeV-GeV mass range.

An active US program in visible mediator searches begun almost a decade ago is being joined by many new proposals to search for MeV-GeV dark matter. A number of these efforts leveraging existing infrastructure are already underway, and new facilities are being developed to enable the next generation of searches.

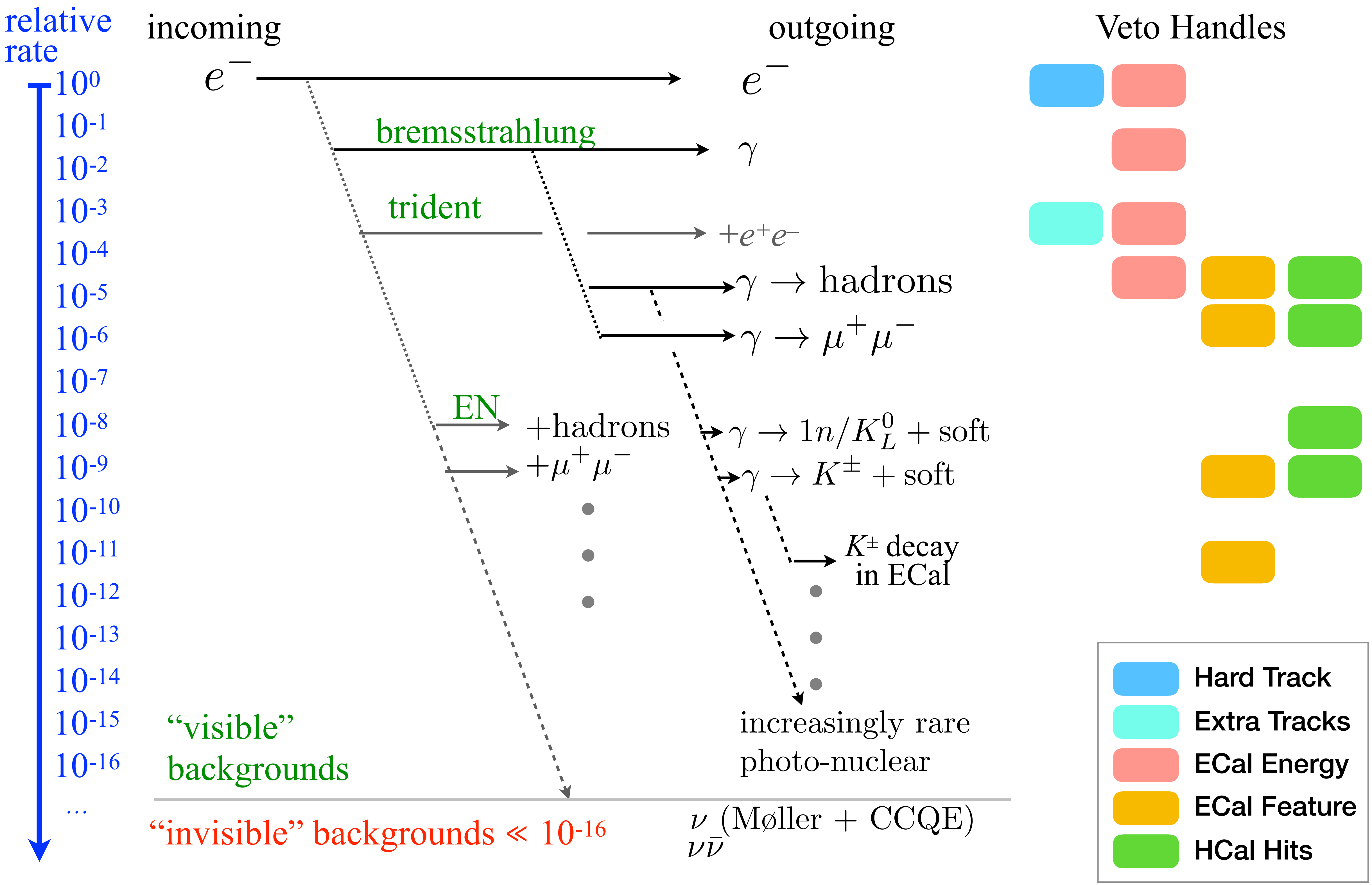
These experiments can explore the simplest thermal freeze-out DM scenarios in the MeV-GeV range over the next ten years in combination with e^+e^- colliders.

Completing the picture for secluded DM and other models with visible searches will be a longer, more piecemeal process, and new ideas are still needed.

The Snowmass process underway in the US should generate many new ideas and bring future plans into focus, much as the European Strategy update has in Europe.

Extra Slides

Missing Momentum Backgrounds



relative rate

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
…

incoming

outgoing

Veto Handles

e^- → e^-

bremsstrahlung → γ

trident → $+e^+e^-$

$\gamma \to$ hadrons

$\gamma \to \mu^+\mu^-$

EN → +hadrons

$+\mu^+\mu^-$

$\gamma \to 1n/K^0_L + \mathrm{soft}$

$\gamma \to K^\pm + \mathrm{soft}$

$K^\pm$ decay in ECal

increasingly rare photo-nuclear

"visible" backgrounds

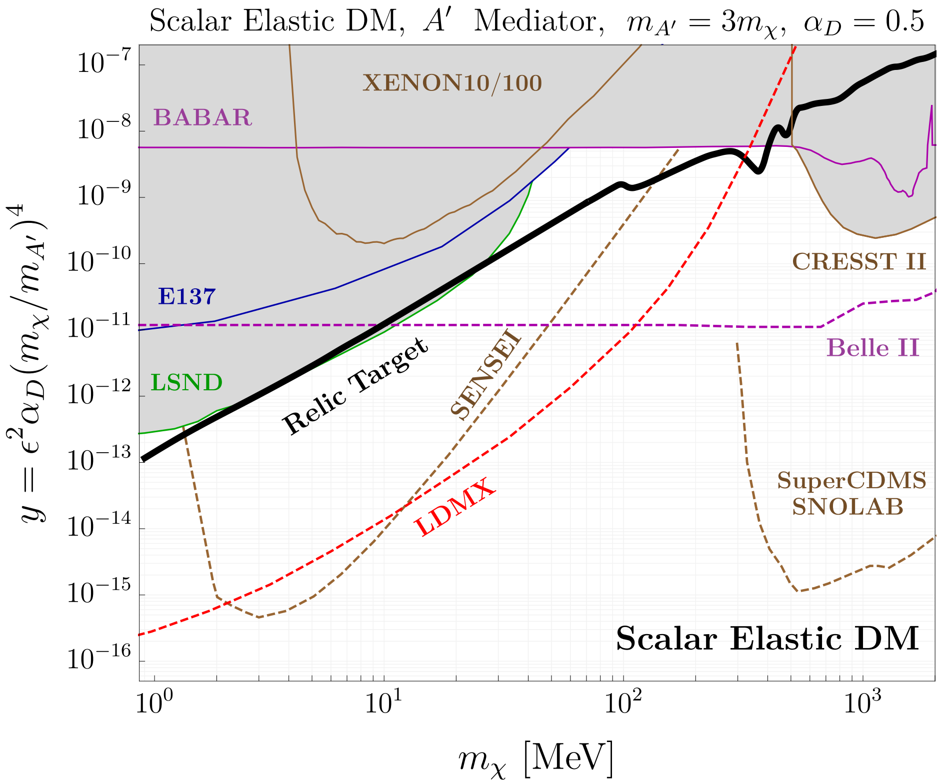
"invisible" backgrounds ≪ 10^{-16}

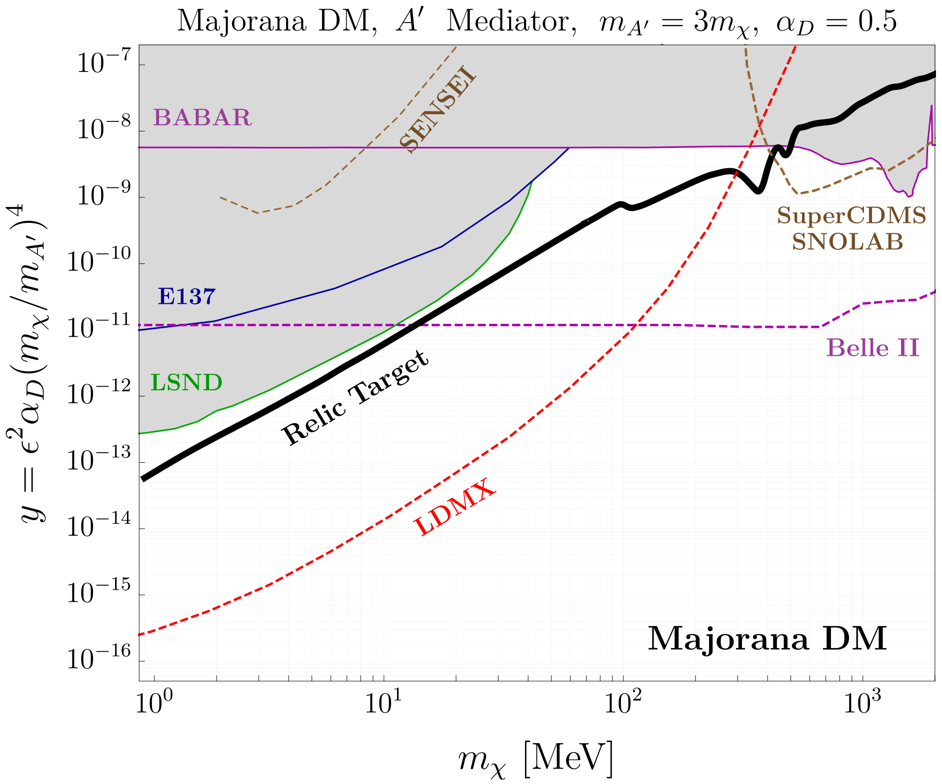
ν (Møller + CCQE)

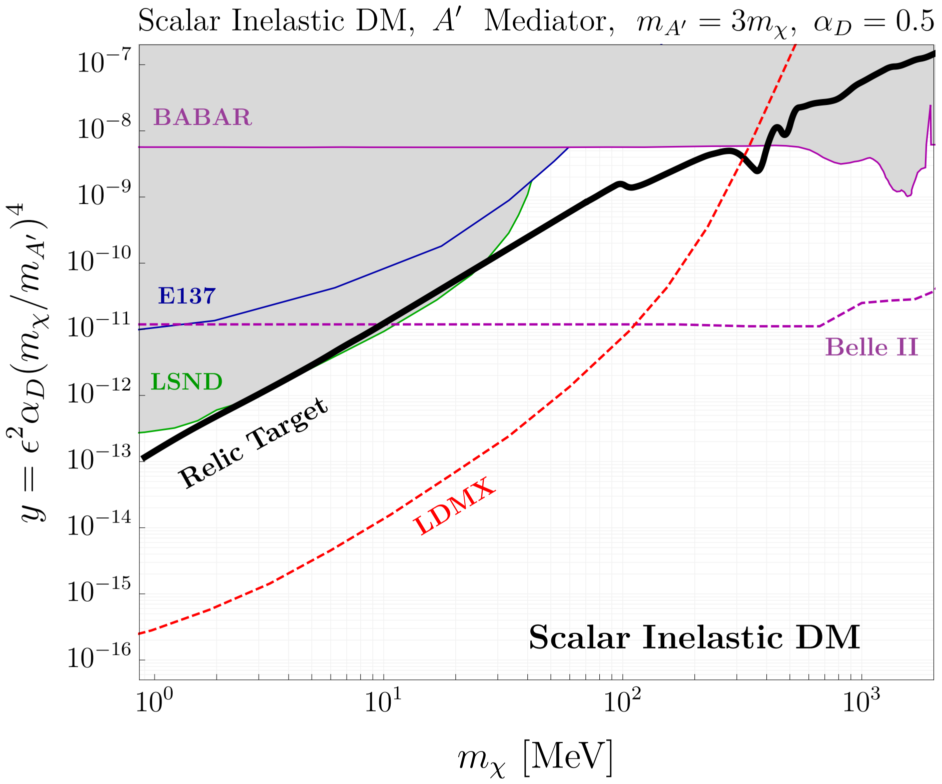
$\nu\bar{\nu}$

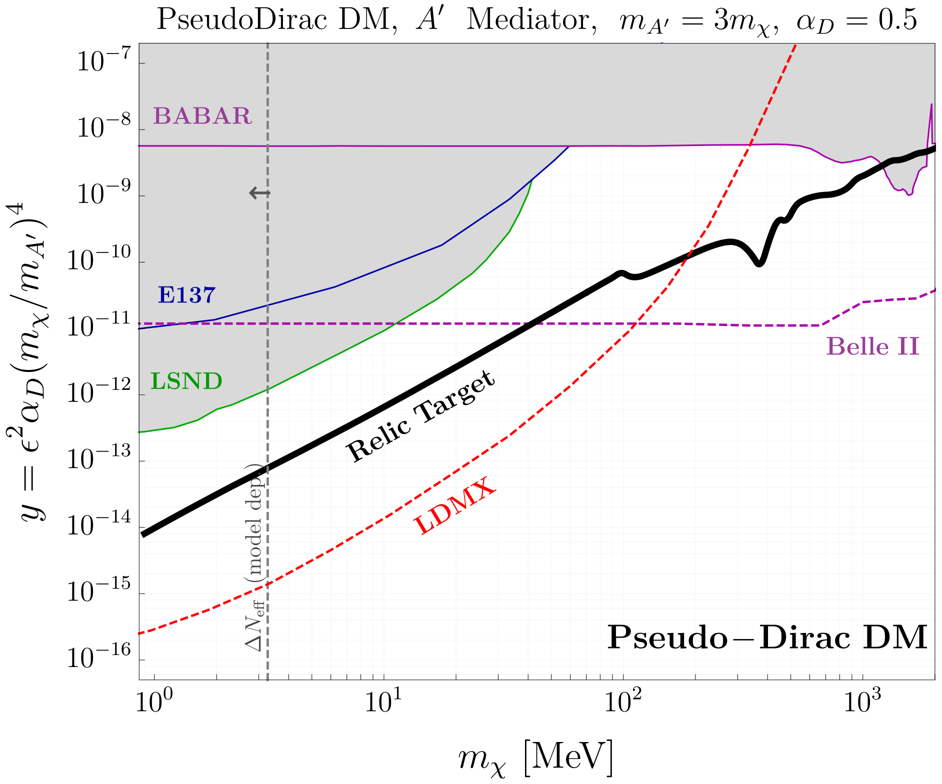
🟦 **Hard Track**
🟦 **Extra Tracks**
🟥 **ECal Energy**
🟧 **ECal Feature**
🟩 **HCal Hits**

Thermal Targets - Accelerators and Direct Detection

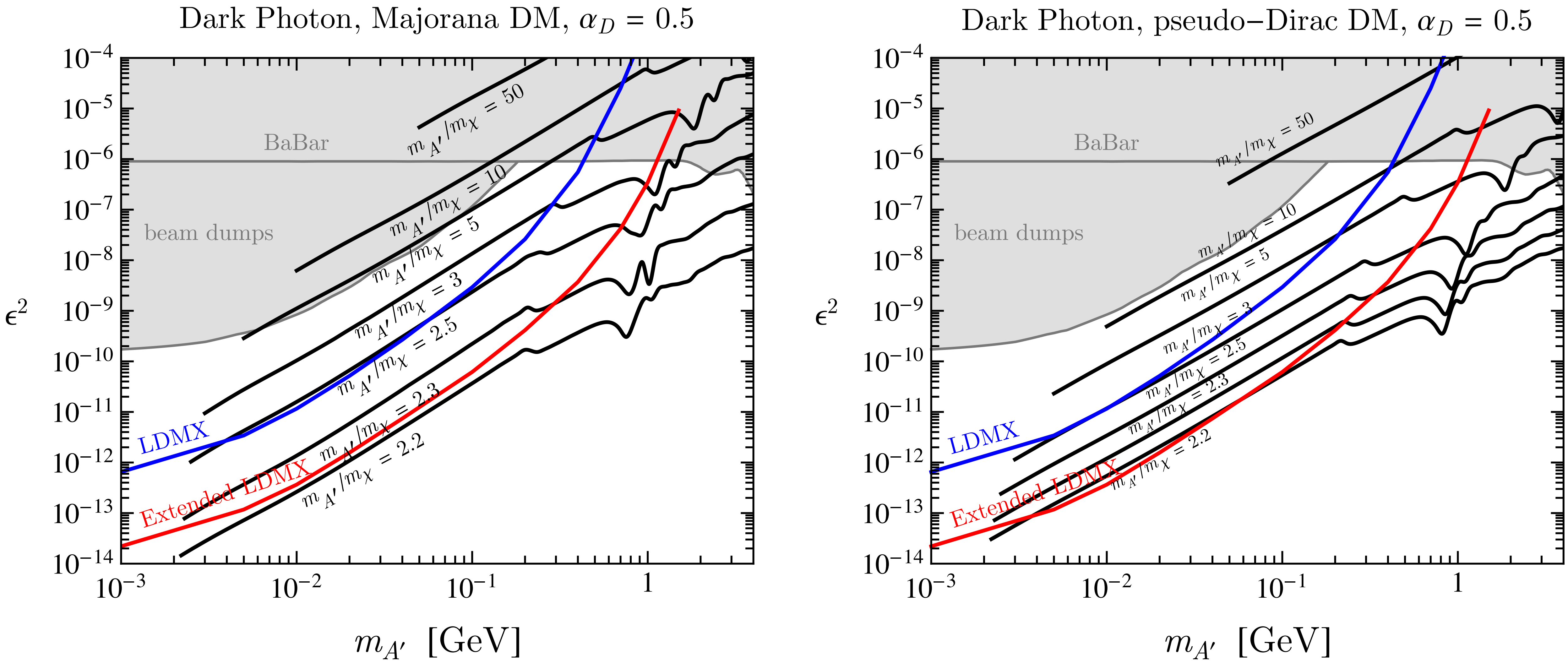






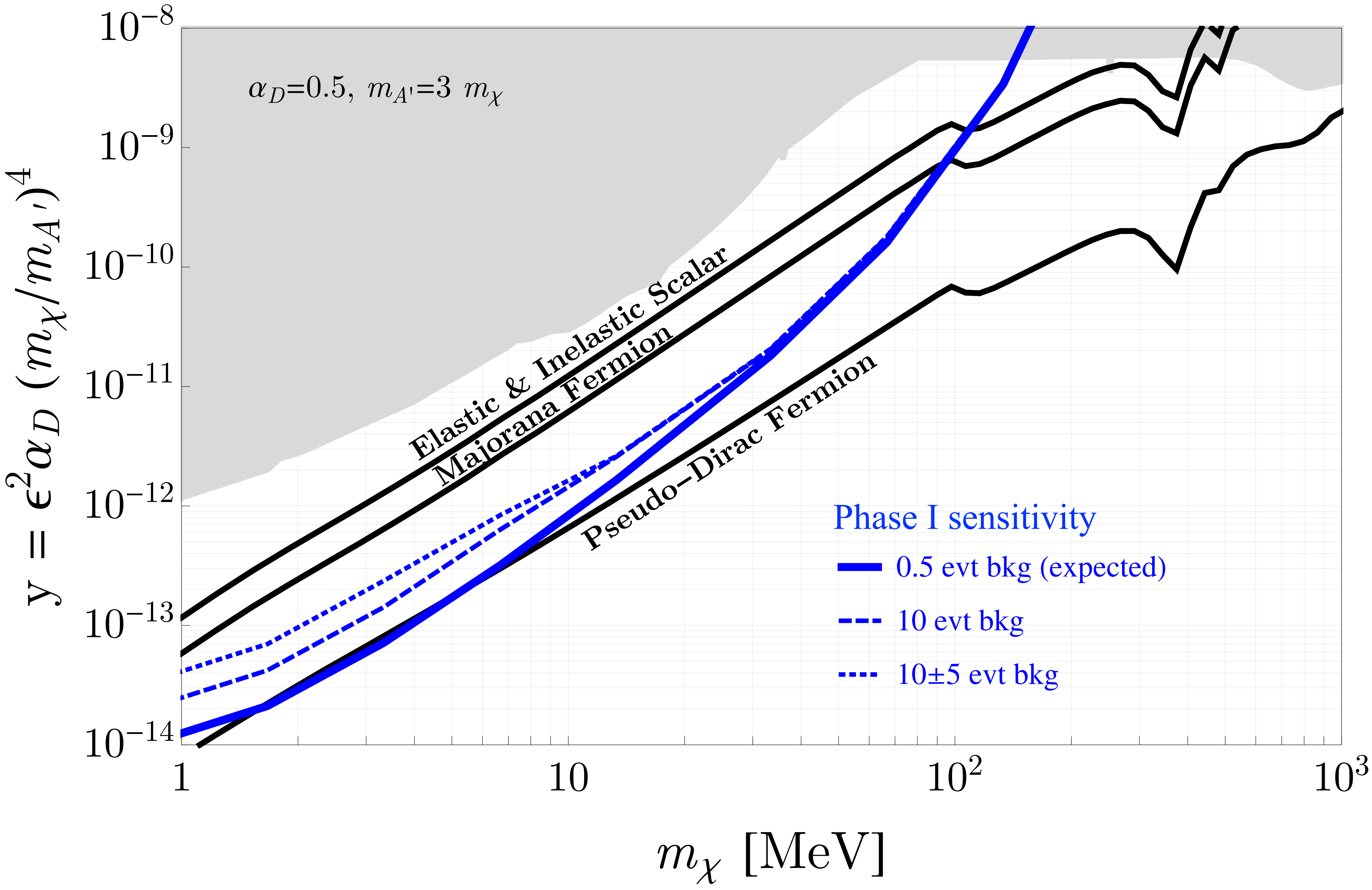


Resonance Effects

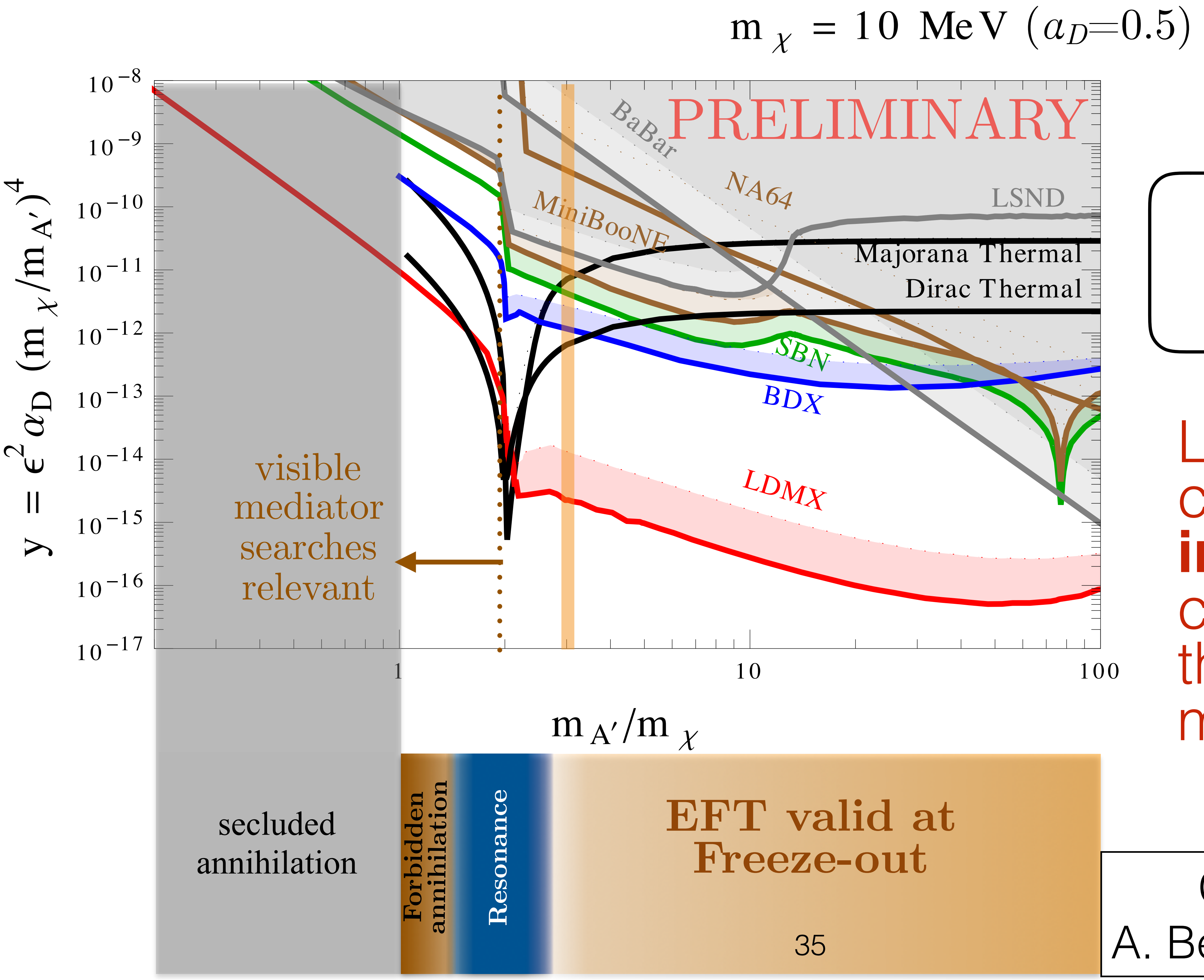


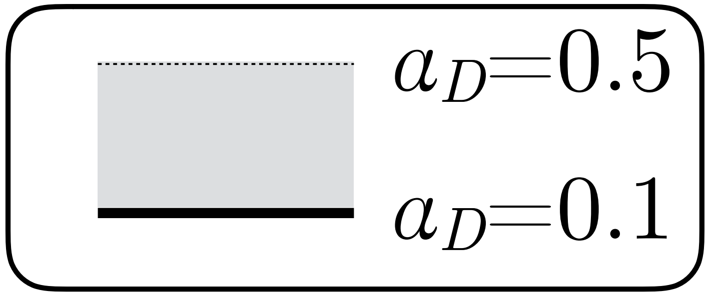
LDMX has good sensitivity even for finely tuned mass ratio.

LDMX: Using P_T to Eliminate Backgrounds



Robustness of Accelerator Reach





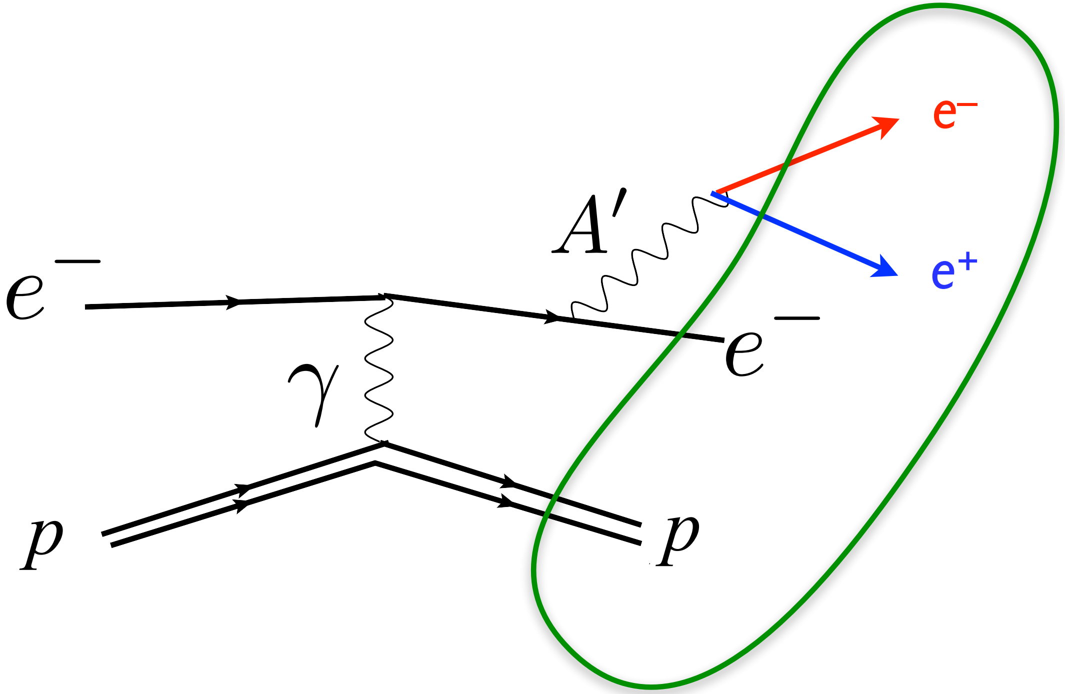
Lowering couplings only **improves** coverage of thermal milestones

Curves thanks to
A. Berlin & P. DeNiverville

e^- beam + spectrometer: Darklight at JLab (2022?)

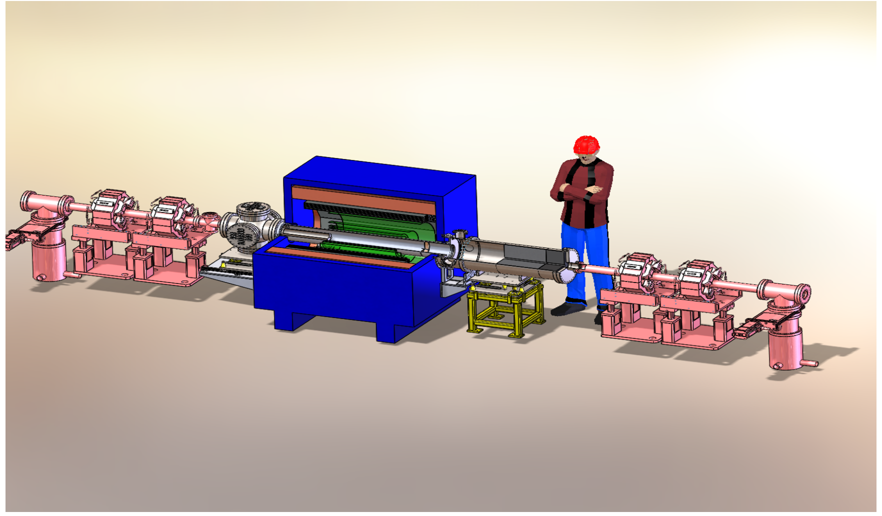
First proposed to run at JLab LERF:

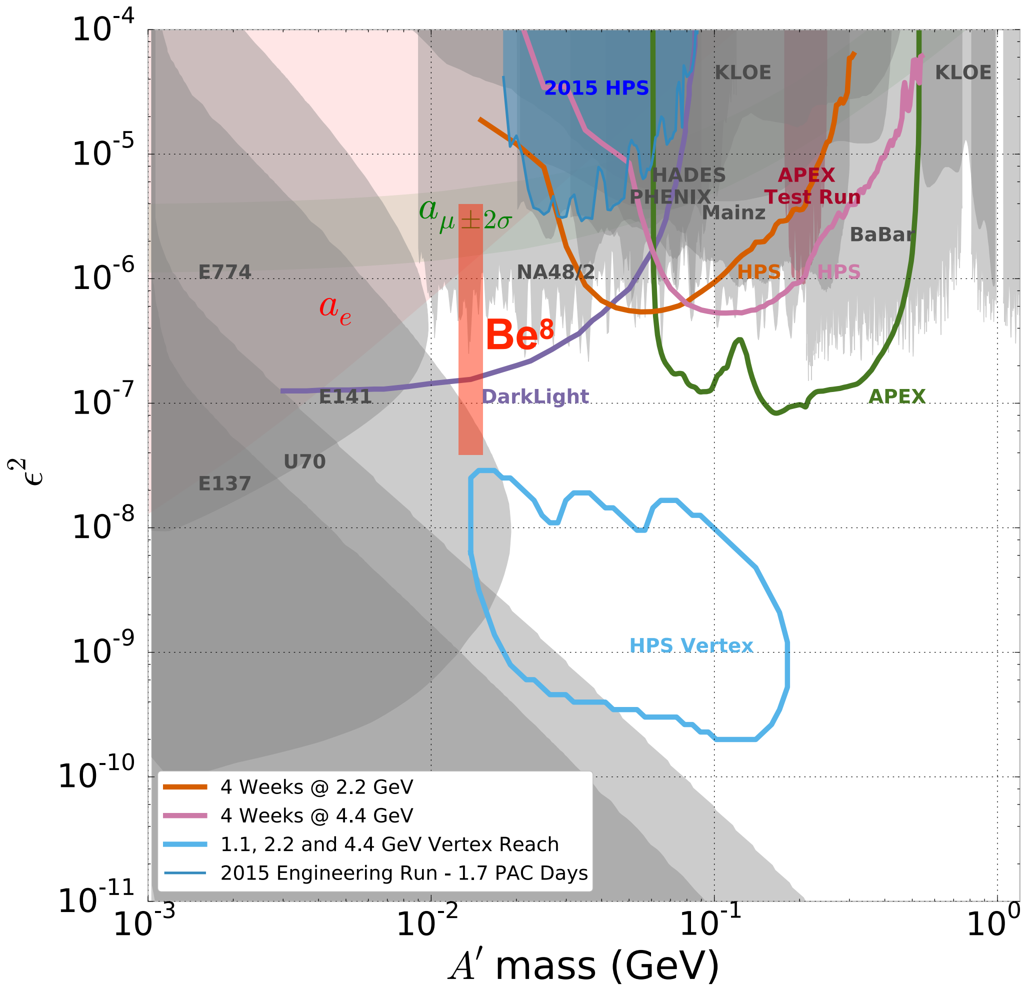
- 5 mA, 100 MeV e^-
- ~10^{19}/cm² H_2 gas target



complete reconstruction of final state allows sensitivity to invisible decays also

Darklight ca. 2017





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Motivated by various challenges and focus on 17 MeV observation a simpler proposal has emerged:
a low-energy two-arm spectrometer to operate using the CEBAF injector @ 45 MeV beam energy.

Proposed to JLab PAC this summer: decision deferred with questions regarding background estimates.

Darklight 2020