Dark sectors activities in North America

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Dark sector for this talk – a hypothetical sector consisting of relatively light (within kinematic reach) particles with interactions orders of magnitude smaller than electromagnetic interactions. It may (or may not) include particles that constitute dark matter.

Prime examples of dark sectors: Axions, axion-like particles, dark photons, sterile neutrinos, light Z’ and h’. And of course *light dark matter particles*.

Accelerator-based experiments: Fermilab, high-Luminosity e^+e^- machines, searches at Jlab, SLAC

An attempt for a comprehensive overview has been made in 2016 and 2017

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng

arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

… very long list of authors

Dark Sectors 2016 Workshop: Community Report

Jim Alexander (VDP Convener),[1] Marco Battaglieri (DMA Convener),[2] Bertrand Echenard (RDS Convener),[3] Rouven Essig (Organizer),[4,*] Matthew Graham (Organizer),[5,†] Eder Izaguirre (DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan

- Focus on light dark matter. *Not enough on light mediators*.
- However – the case of proton-initiated machines is not covered too well [in my opinion].

Contents

Outline of the talk

1. Introduction. Structure of dark sectors.

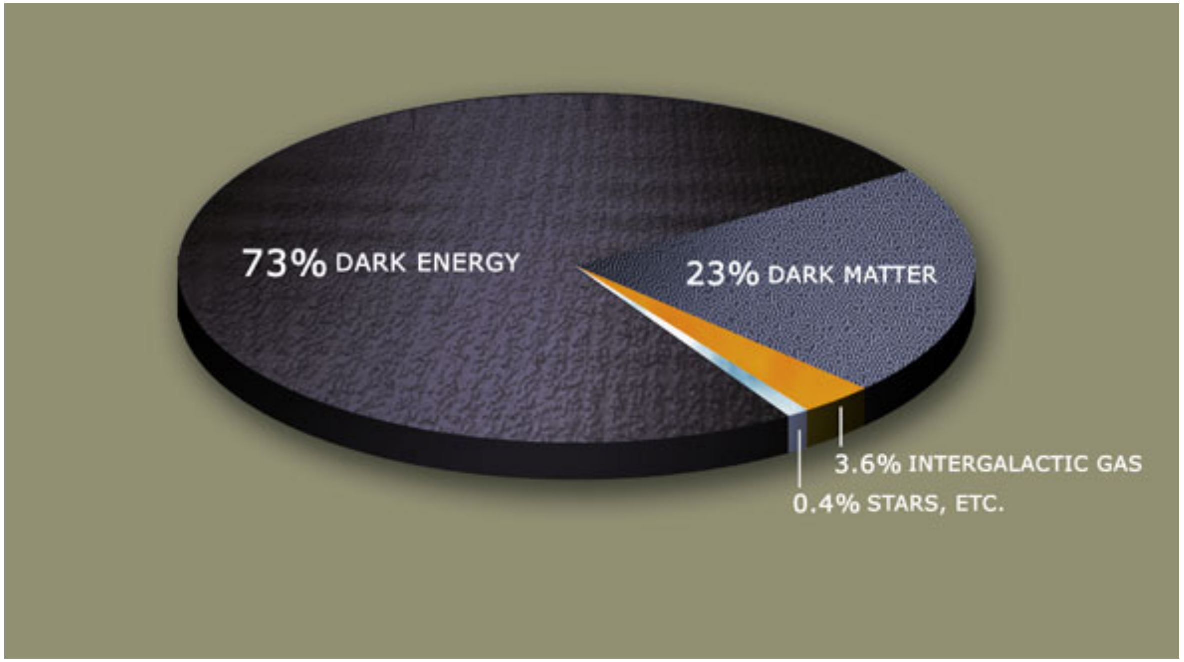
2. Electron-initiated searches. Analyses of existing data from BaBar. Projects at Jlab and SLAC (LDMX).

3. Fermilab + neutrino experiments and dark sectors

- Search for light dark matter in the beam dump mode.
- Possibility to search for visible decays of light particles with neutrino detectors.
- Additional possibilities with muons
- SeaQuest proposal

4. Conclusions

Big Questions in Physics



"Missing mass" – what is it? New particle, new force, …? *Both*? How to find out?

Challenges ?? Too many options for DM. In "direct detection" or collider experiments there is an extrapolations from ~ kpc scale (~ 10^{21} cm) down to 10^2 cm scale.

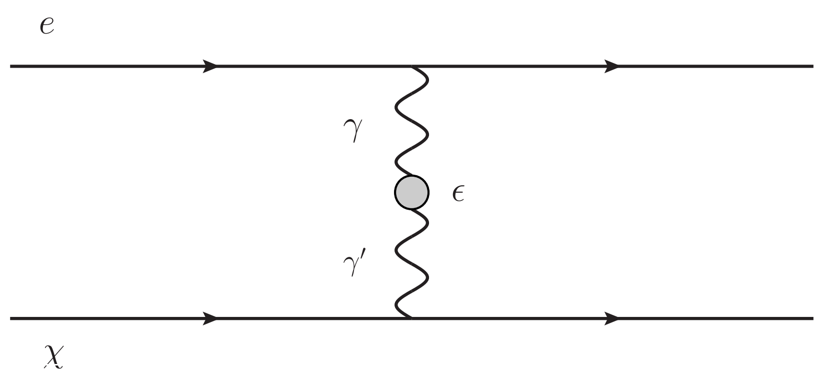
Given very "economical" outcome of the LHC experiments wrt New Physics, we can go back to simple possibilities for dark sectors

A simple model of dark sector

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m^2_{A'} (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F^2_{\mu\nu} + \bar{\psi}[\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi]\psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu (i\partial_\mu - g' A'_\mu) - m_\chi]\chi,$$



- "Effective" charge of the "dark sector" particle χ is Q = e × ε (if momentum scale q > m_V). At q < m_V one can say that particle χ has a non-vanishing *EM charge radius*, $r^2_\chi \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. Very light χ can be possible.

Example of dark sector couplings to the SM (also known as "portals")

Let us *classify* possible connections between Dark sector and SM

$H^{+}H\,(\lambda S^2 + A\,S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$LH\,N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^A\ \partial_\mu a\,/f$ axionic portal

……….

$$\mathcal{L}_{\text{mediation}} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\text{med}}^{(k)} \mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n},$$

Simplest models for light DM

some examples

- Scalar dark matter talking to the SM via a dark photon (variants: L_{mu}-L_{tau} etc gauge bosons). With $2m_{DM} < m_{mediator}$.

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 - \frac{\epsilon}{2} V_{\mu\nu} F_{\mu\nu}$$

- Fermionic dark matter talking to the SM via a "dark scalar" that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

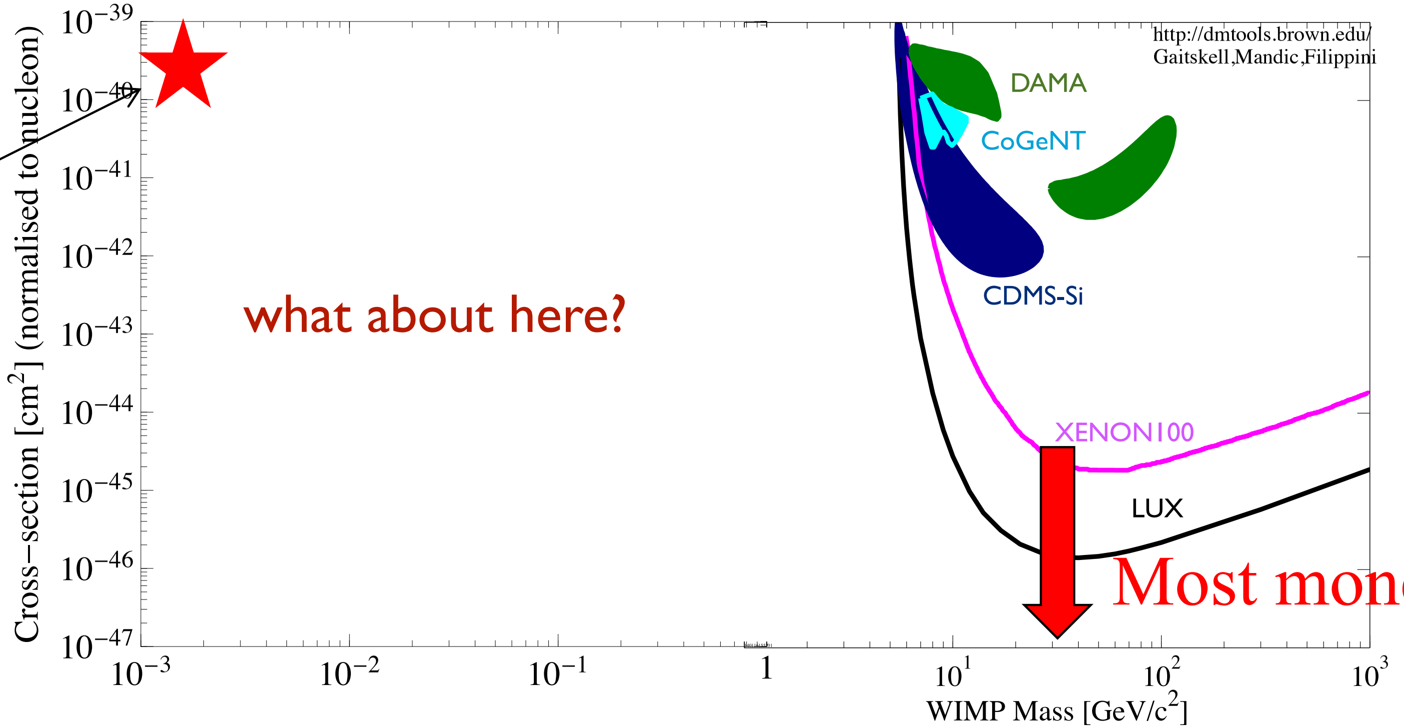
$$\mathcal{L} = \overline{\chi}(i\partial_\mu \gamma_\mu - m_\chi)\chi + \lambda \overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - AS(H^\dagger H)$$

After EW symmetry breaking S mixes with physical h, and can be light and weakly coupled provided that coupling A is small.

Sub-GeV particles from these sectors are within kinematic reach of Fermilab experiments

Light DM – difficult to detect via nuclear recoil

511 keV motivated



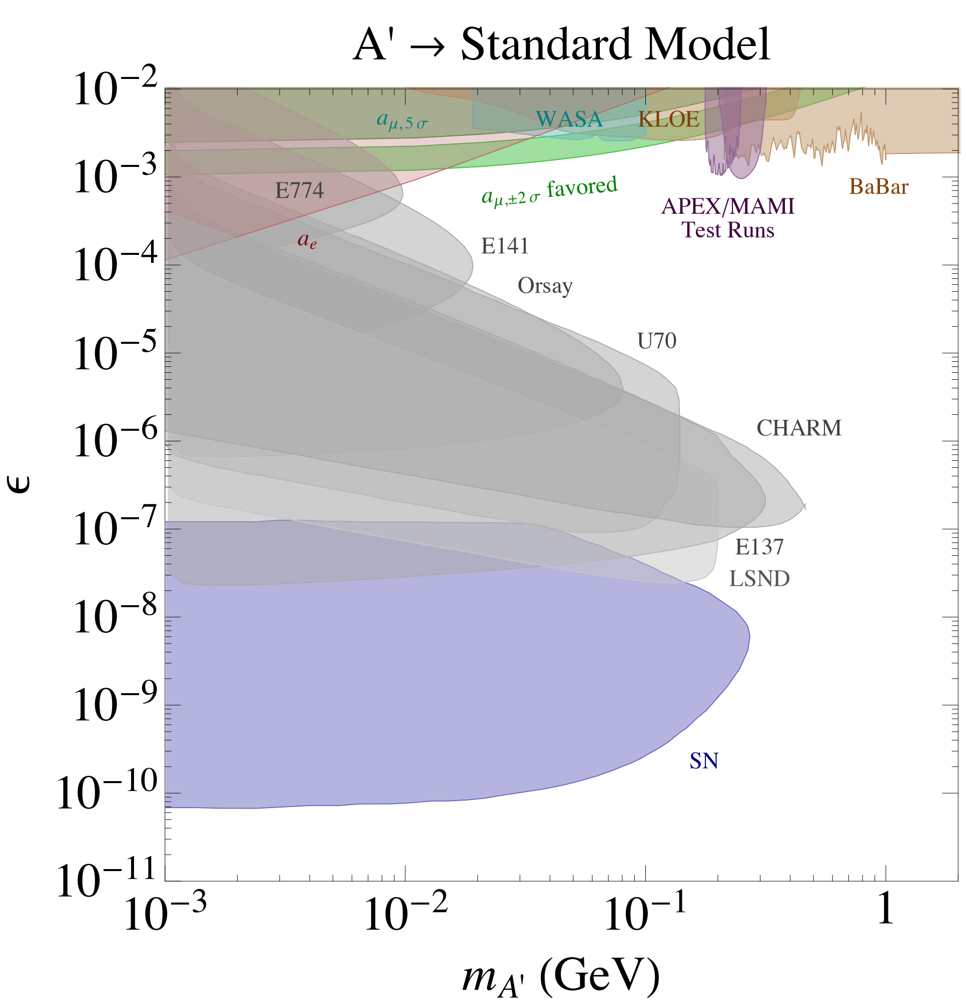
Most money spent

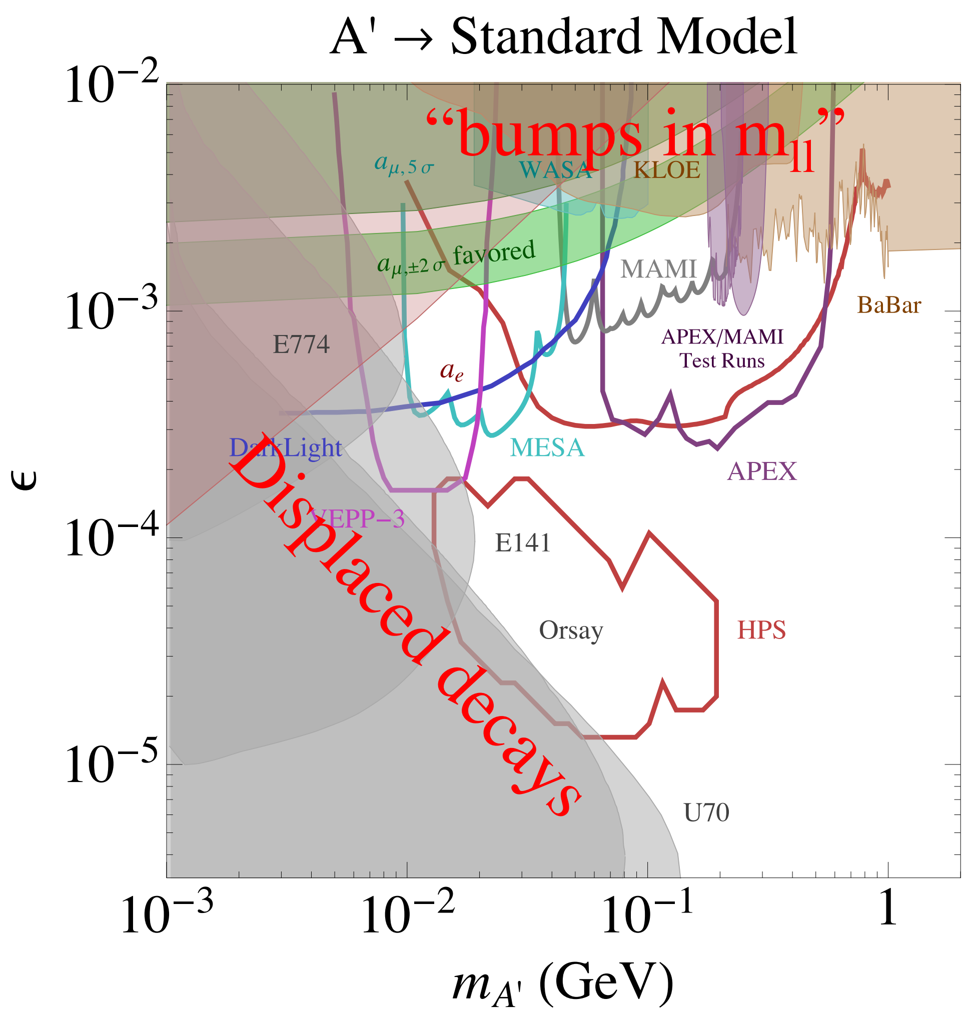
- There is a large, potentially interesting part of WIMP DM parameter space that escapes constraints from DM-nuclear scattering, but is potentially within reach of other probes
- Viable models imply *the dark sector*, or accompanying particles facilitating the DM → SM annihilation. Can create additional signatures worth exploring.

- Searching for light (e.g. MeV – 10 GeV) dark matter and mediators has become an important axis of activity at low and medium energies.

- It is important to probe both the dark matter and mediators.

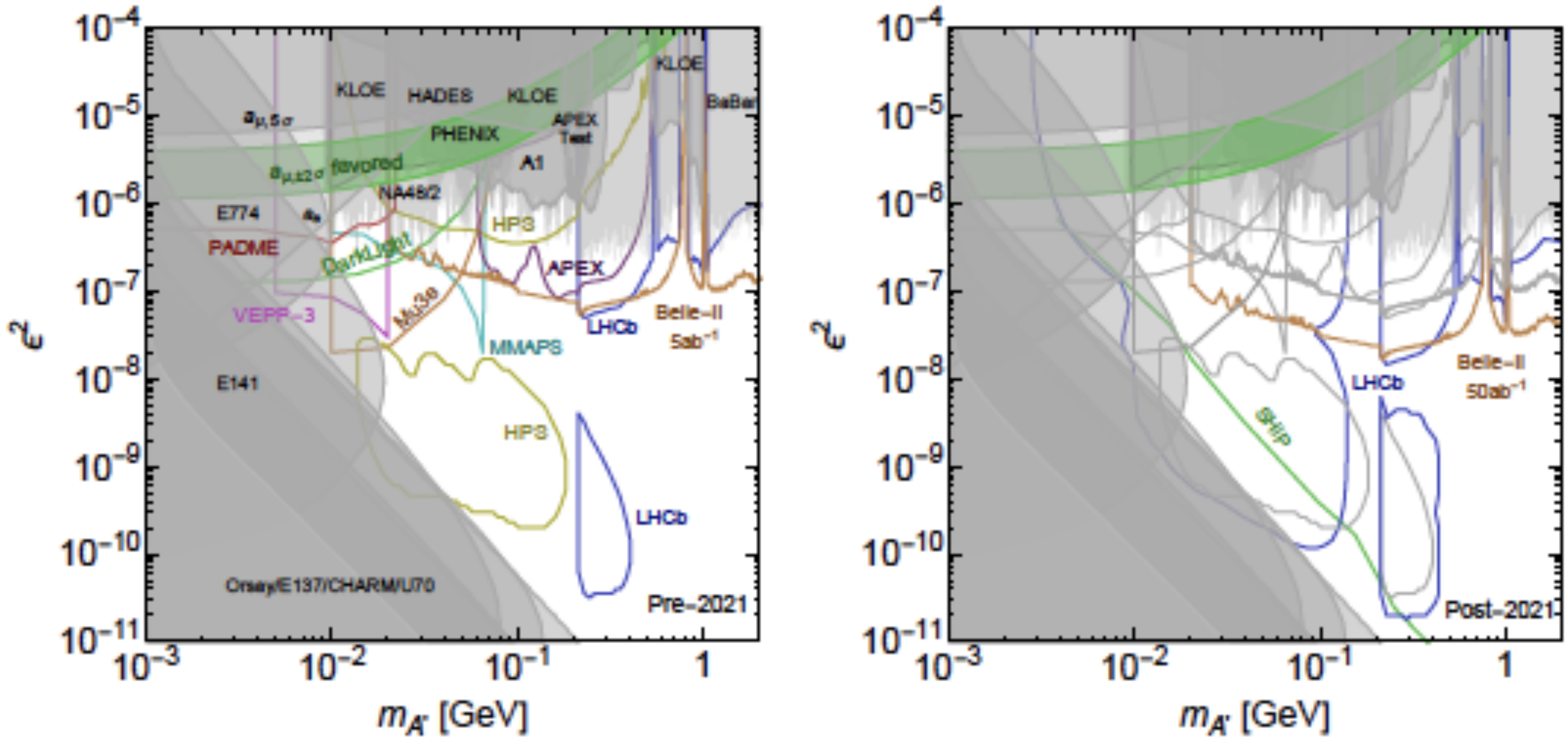
Search for dark photons, Snowmass study, 2013





Dark photon models with mass under 1 GeV, and mixing angles ~ 10^{-3} represent a "window of opportunity" for the high-intensity experiments, not least because of the tantalizing positive ~ $(\alpha/\pi)\varepsilon^2$ correction to the muon g - 2.

Update from 2016

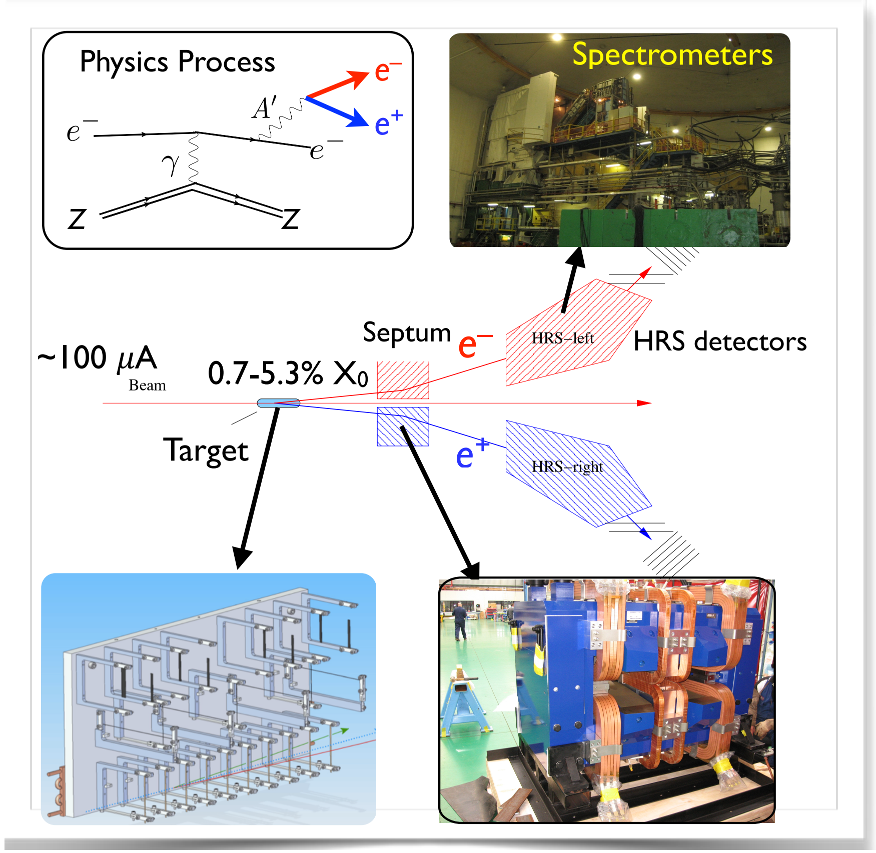


At Jlab, HPS, APEX and DarkLight experiments can further advance sensitivity to *light mediators coupled to electrons*, such as dark photons.

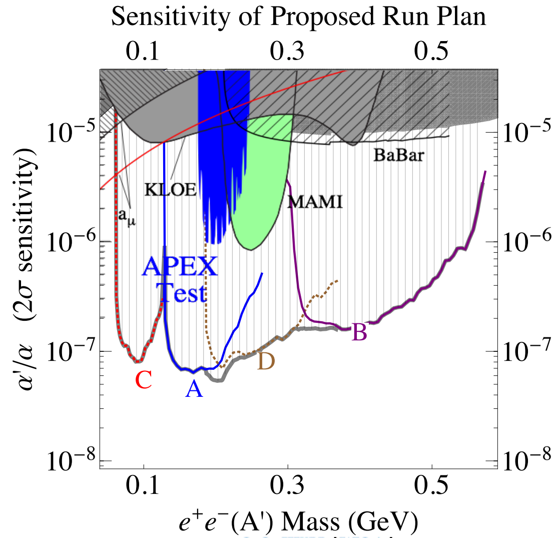
Jlab APEX, T. Nelson talk, 2017

APEX

A′ search using Hall A high-resolution spectrometers (HRS)



Test run (2010):
concept & technical demonstration; weekend run achieved; new sensitivity.



Full run:
PAC approved and prioritized, funded, projected to run ~2018. Optimized septa magnet constructed. Smaller beam line items funded and HRS detectors ready.

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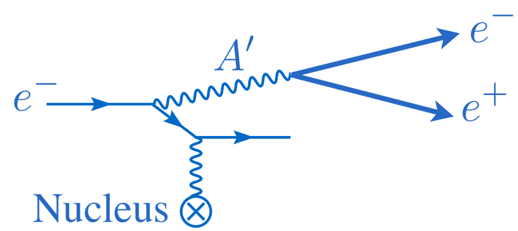
At Jlab, HPS, APEX and DarkLight experiments can further advance sensitivity to *light mediators coupled to electrons*, such as dark photons.

Jlab HPS, T. Nelson talk, 2017

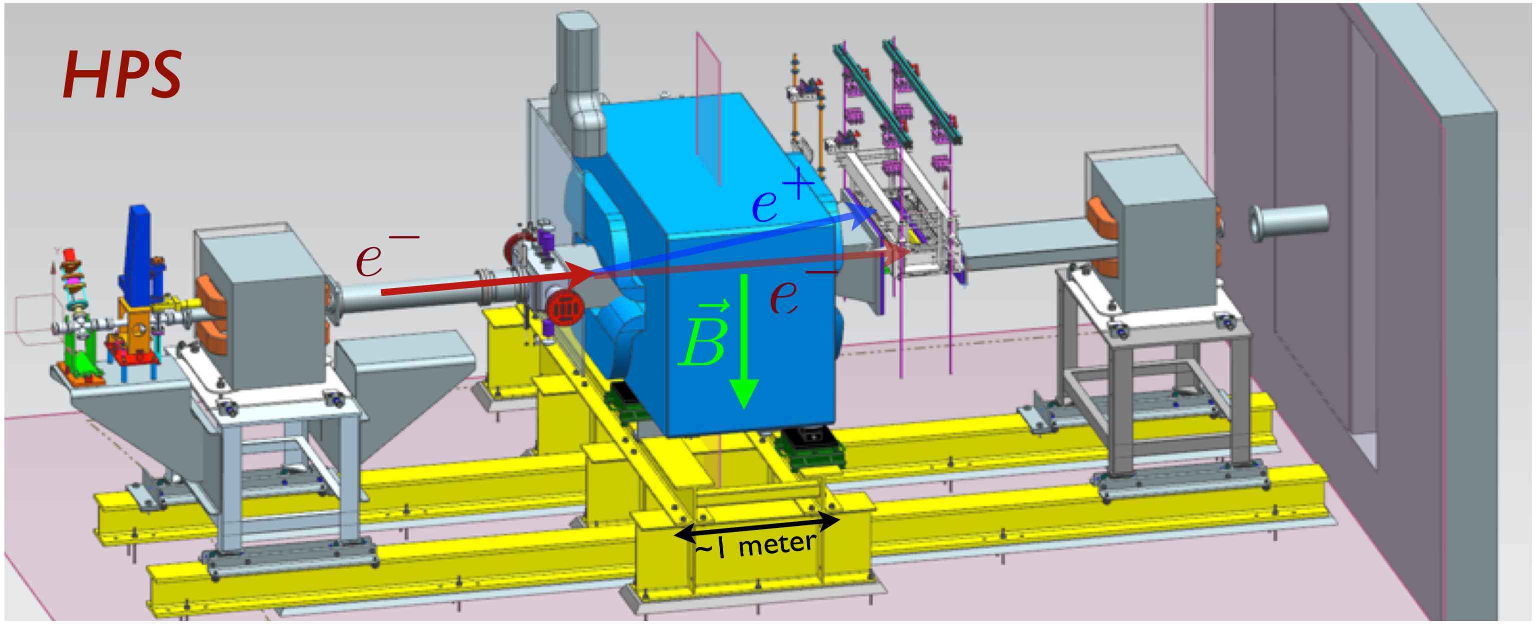
The Heavy Photon Search Experiment

HPS is a fixed-target search for visibly decaying hidden photons using ~10^{19} e^- of CEBAF (1.1–6.6 GeV) beam in Hall B at JLab.



dark bremsstrahlung in thin (0.125% - 0.25% X_0) tungsten foil

dipole magnet spreads out e^+e^- pairs, enables momentum measurement



At Jlab, HPS, APEX and DarkLight experiments can further advance sensitivity to *light mediators coupled to electrons*, such as dark photons.

Important activities in analyzing BaBar data

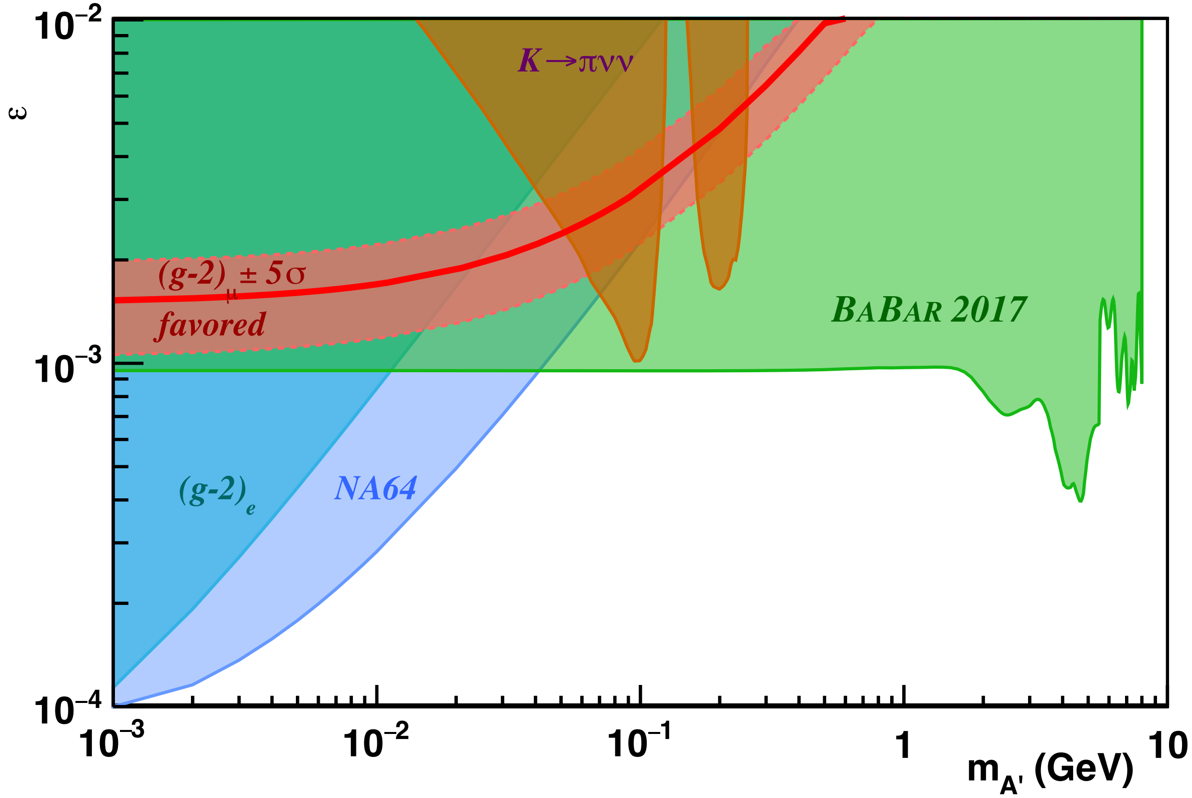
A lot of important activities happen in connection with dark sectors at BaBar (Analyses by B. Echenard ++)

- Search for light pseudoscalar Higgses (such as those in NMSSM)
- Direct search for a visibly decaying dark photon up to 10 GeV
- Direct search for an invisibly decaying dark photon (e.g. to a pair of light dark matter particles)
- Searches for multi-particle final states (Higgs-prime-strahlung, resulting in 3 charged pairs, search for bound states of light dark matter)
- Search for light exotic particles coupled predominantly to muons and tau leptons.

All of these searches can be improved at Belle II.

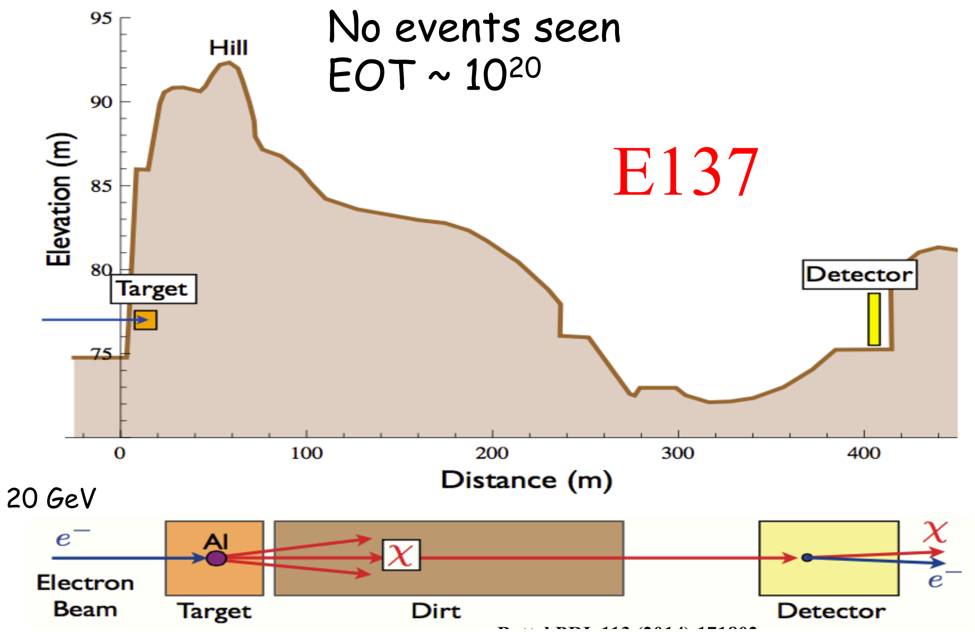
BaBar result on invisibly decaying A'

BaBar collaboration has published new results two weeks ago, 1702.03327. Search of $e^+e^- \rightarrow \gamma + V \rightarrow \gamma + \chi\chi$

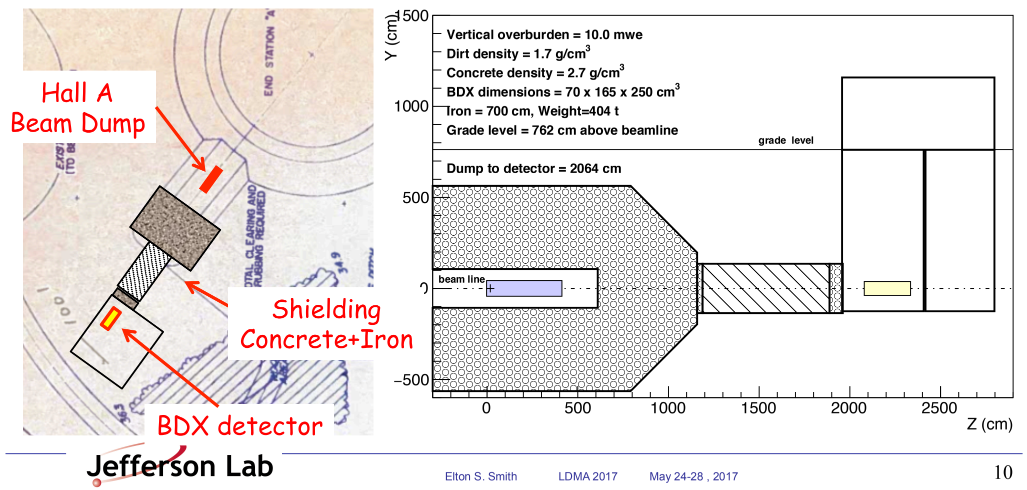


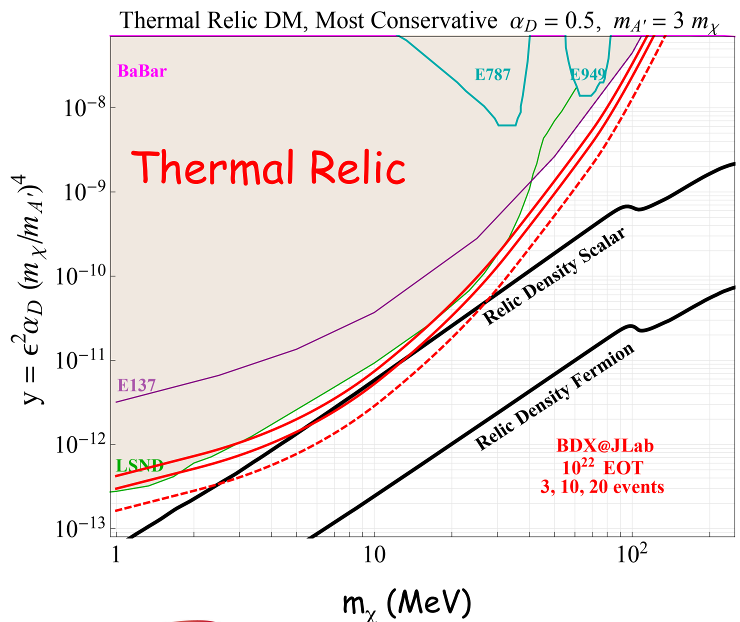
- Complementary to NA64
- Covers all of the dark photon parameter space, decaying invisibly, consistent with alleviating the muon g-2 discrepancy

New ideas for a beam dump searches at JLab and SLAC, E. Smith talk 2017



- Highest beam current ~ 65 μA
- Integrated charge ~ 10^{22} EOT (41 weeks)
- E_{beam} up to 11 GeV
- New underground facility ~$1.5M

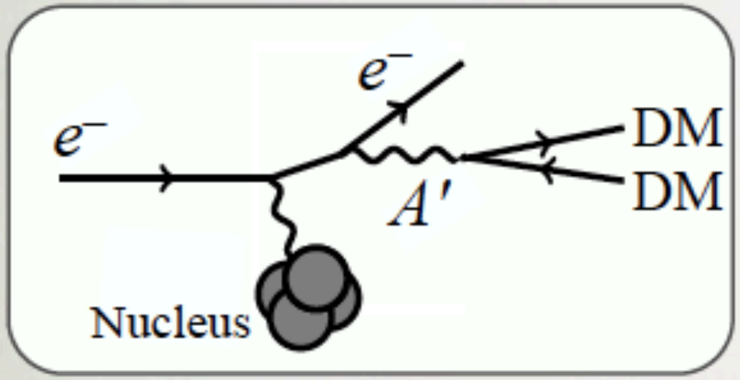




BDX proposal is to look for production and scattering of light DM. [Jlab beam is not pulsed – might be a challenge. Still could improve over LSND and E137]

New project LDMX.

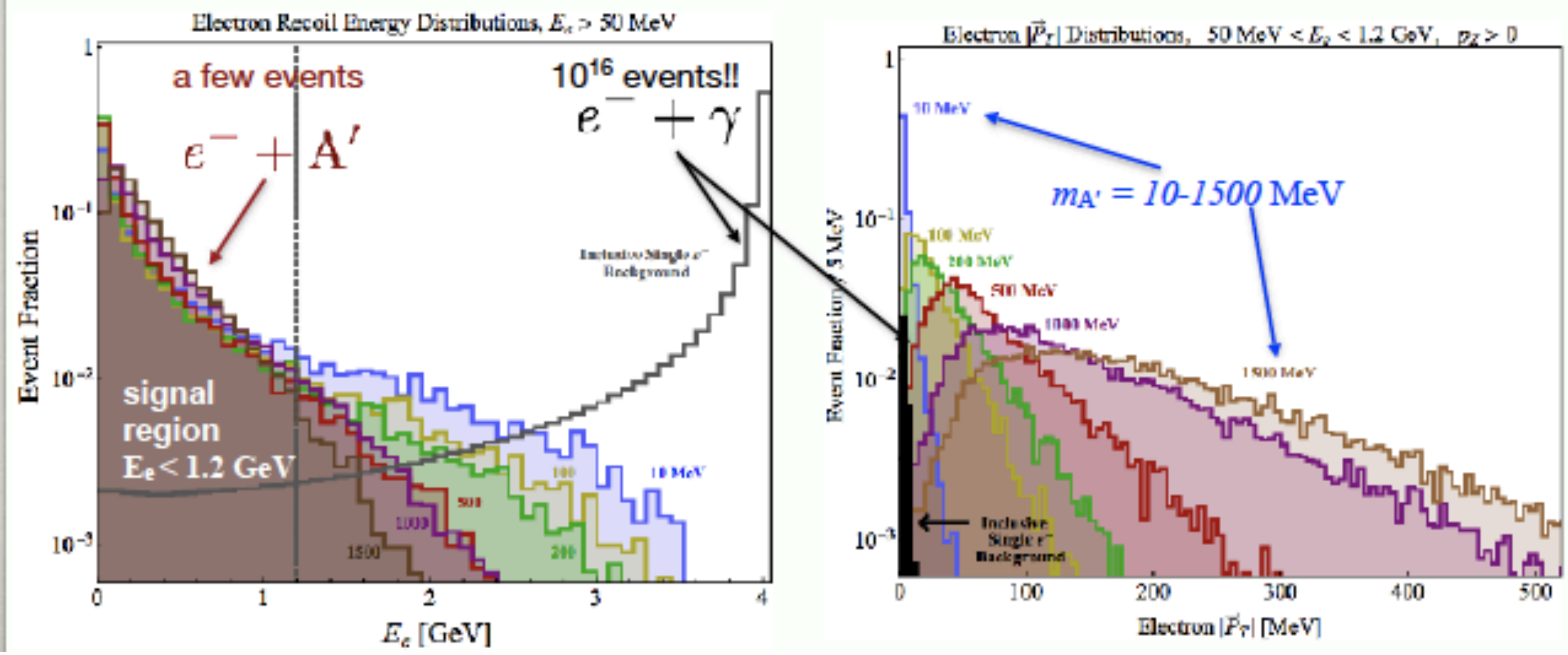
Similar in idea to NA64, but with more particles on target and improved detection



$E(A') \approx E_{beam}$ $E(e) \ll E_{beam}$

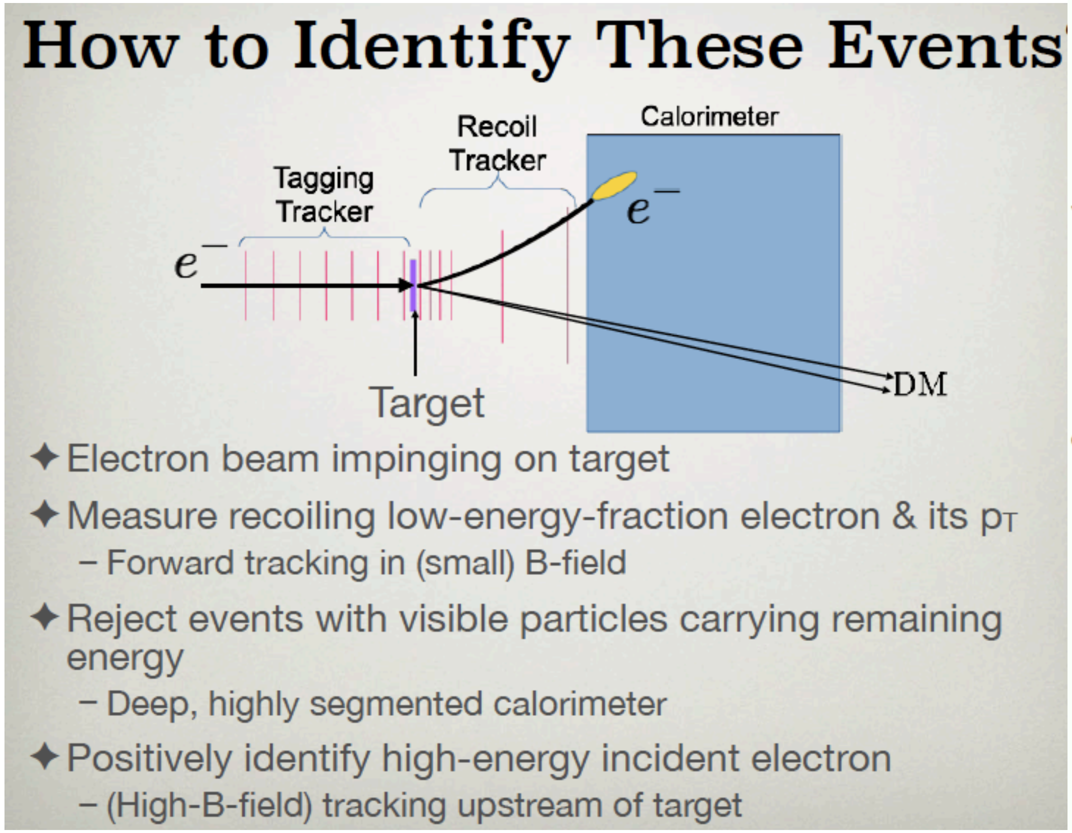
$p_T(A') \sim p_T(e) \sim m_{A'}$

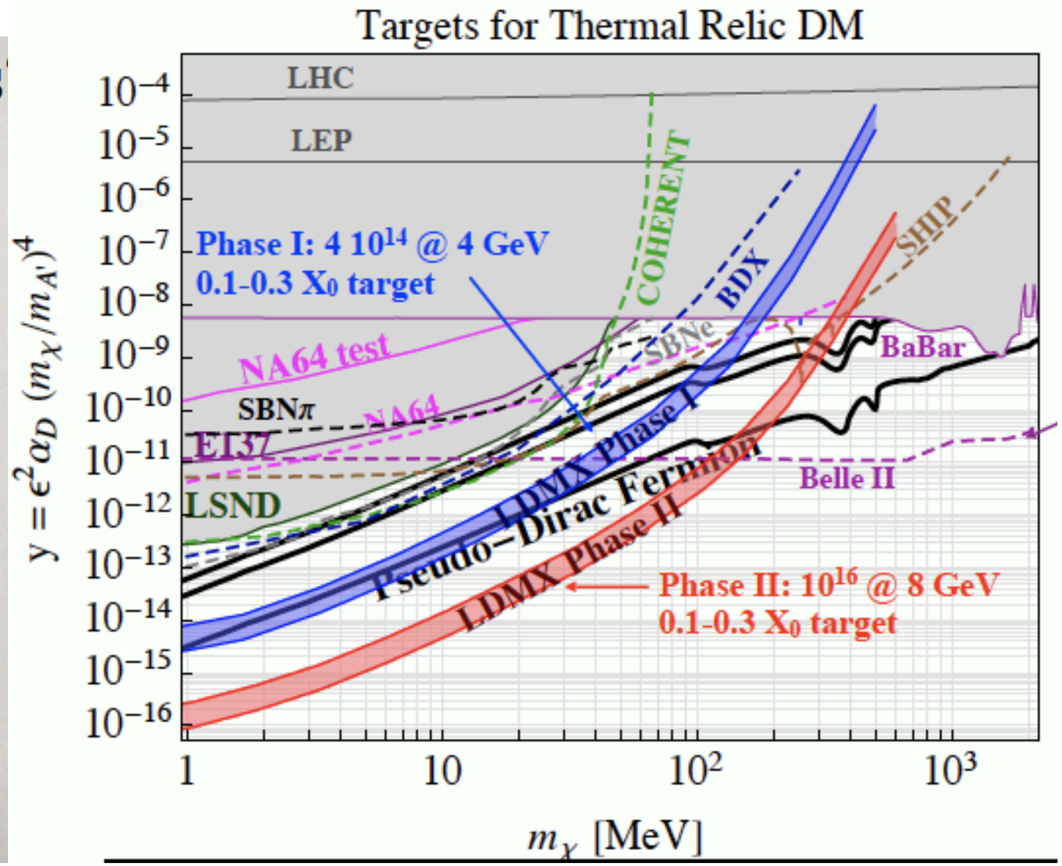
recoil distributions, 4 GeV e^- on 10% X_0 target – NOT TO SCALE



Slides from P. Schuster

New project LDMX.





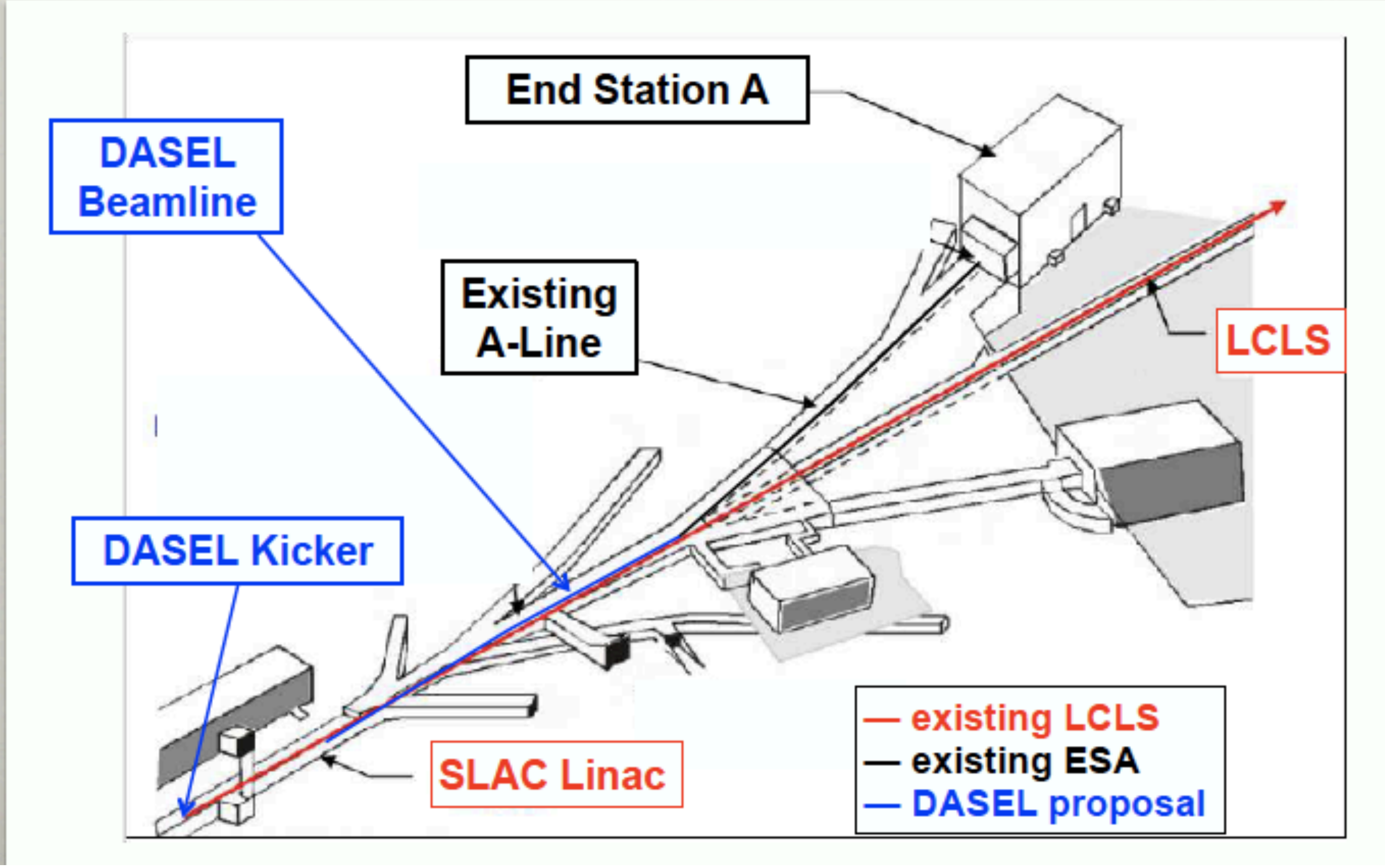
The challenges are great (e.g. what else can create missing energy/momentum and escape detection at 1 ppb level?) but the potential pay-off is quite significant!

ε^2 scaling (rather than ε^4) allows a “faster” increase of sensitivity(POT)

Do we see a revival of in-house particle physics at SLAC?

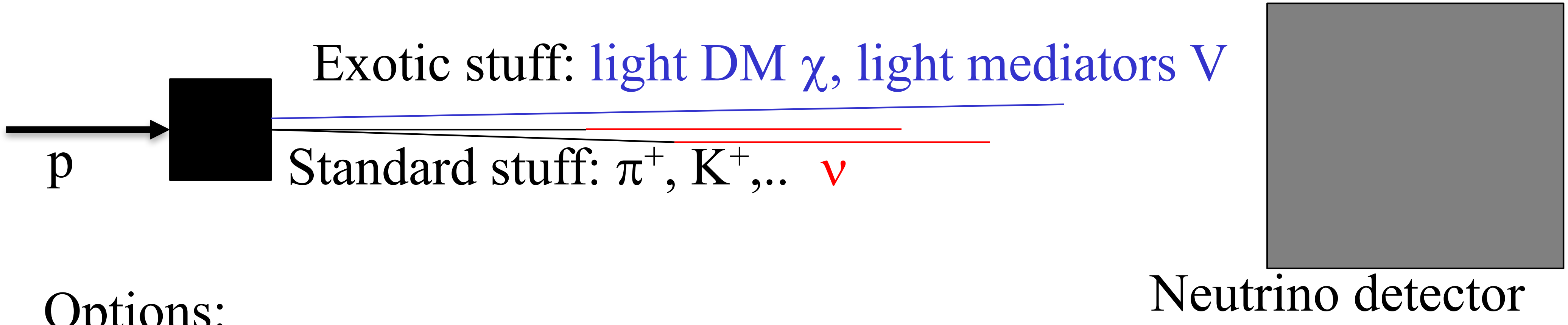
DASEL Beamline @ SLAC

Low-current but “continuous” multi-GeV beam needed for LDMX can be delivered parasitically!



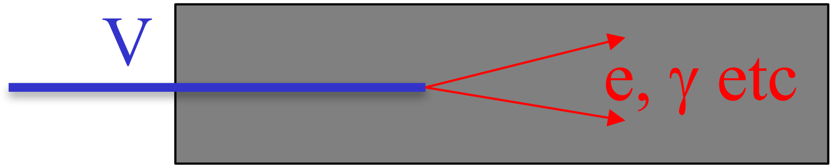
- Fermilab is the main Lab in the US solely devoted to particle physics.
- And among all particles, its focus is on neutrinos and muons
- Lots of still unexplored sensitivity to dark sectors.
- In particular, light scalars mixed with the Higgs can be most efficiently studied at hadron machines (produced via K or B decays).
- *It has not been enough theoretical interest yet in studying Fermilab experimental sensitivity to dark sectors.*

How to look for dark sectors in neutrino experiments ?

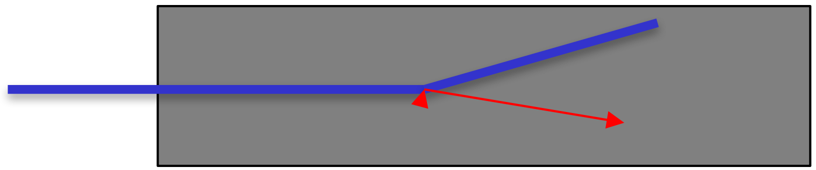


Options:

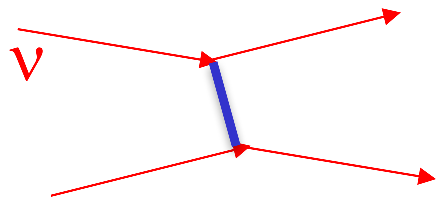
1. Exotic stuff is “metastable”, decays to SM inside the detector



2. Exotic stuff is ”stable”, but can scatter on SM particles



3. Exotic particles can modify neutrino scattering itself.



Types of new physics

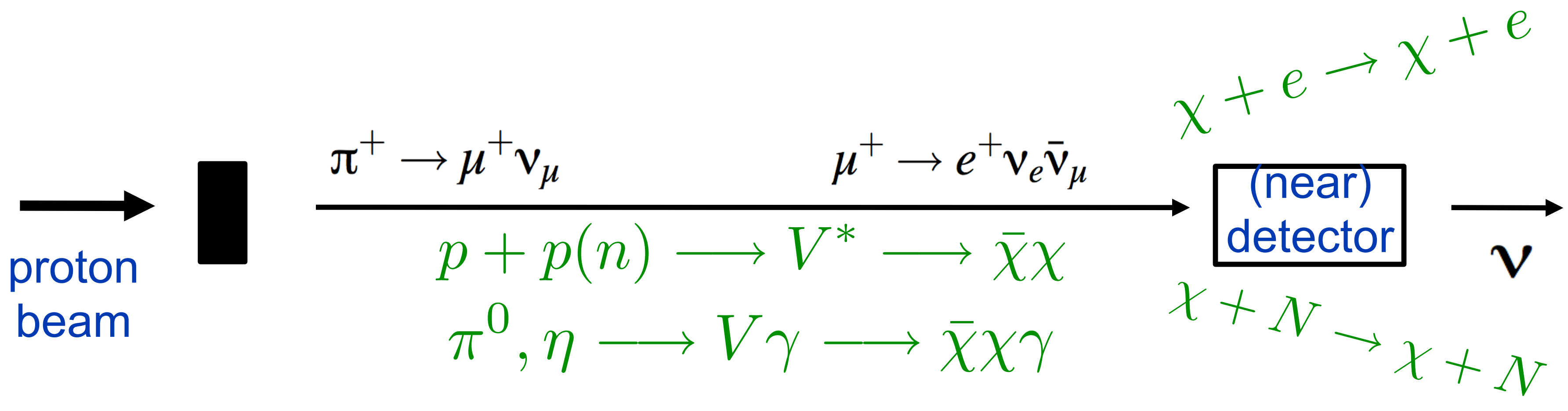
4. There is of course also a possibility of active-sterile oscillation

5. Combination of all of the above: e.g. Sterile neutrinos can have ”secret interactions”, and also scatter off SM particles.

(In light of recent cosmological constraints, ~1eV mass LSND/Miniboone-style sterile neutrinos *imply* a dark sector!)

Fixed target probes - Neutrino Beams

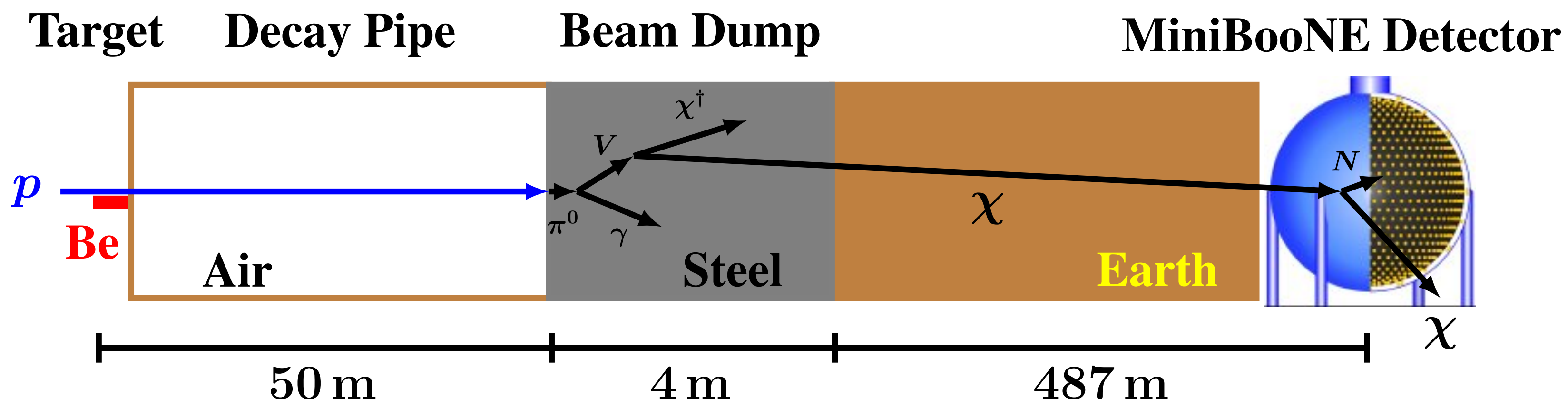
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM



We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

T2K	MINOS	MiniBooNE
30 GeV protons	120 GeV protons	8.9 GeV protons
(➠ ~5x10^{21} POT)	10^{21} POT	10^{21} POT
280m to on- and off-axis detectors	1km to (~27ton) segmented detector	540m to (~650ton) mineral oil detector

MiniBooNE search for light DM



MiniBoone has completed a long run in the beam dump mode, as suggested in [arXiv:1211.2258]

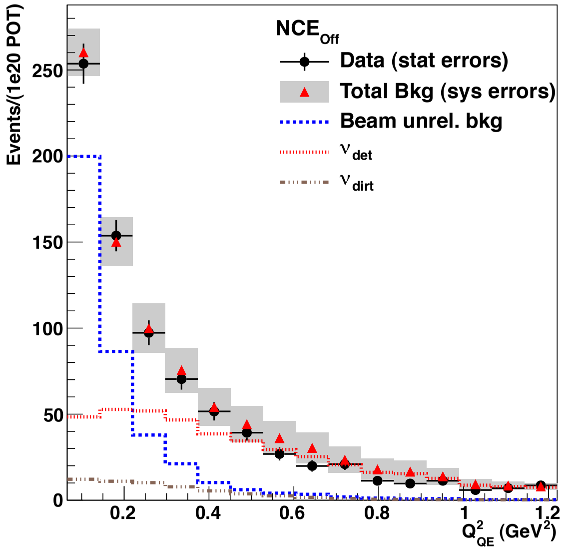
By-passing Be target is crucial for reducing the neutrino background Currently, suppression of ν flux ~50.

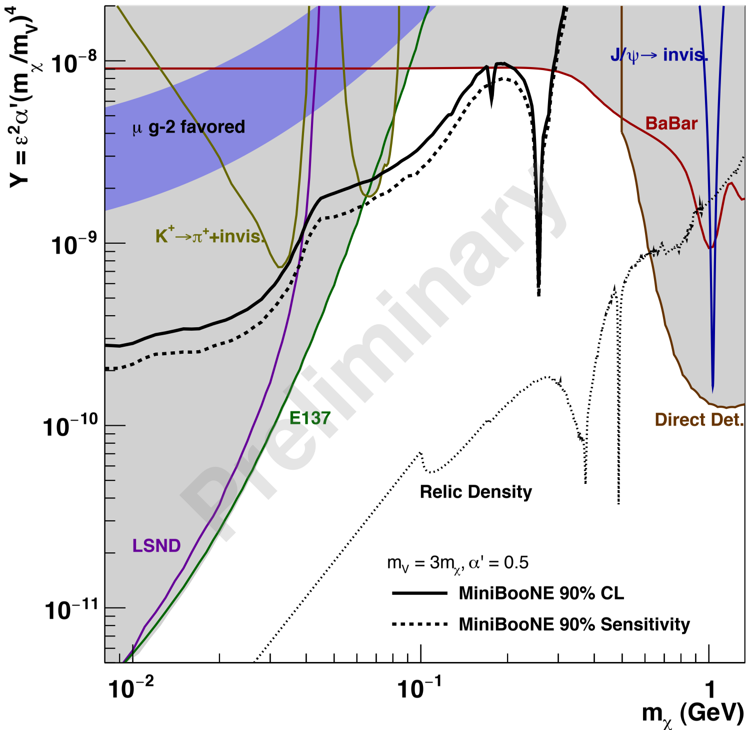
Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds. First results – 2016, 2017

Important contribution from P deNiverville, B Batell.

Results of the MiniBoone search

From 1702.02688 (PRL)



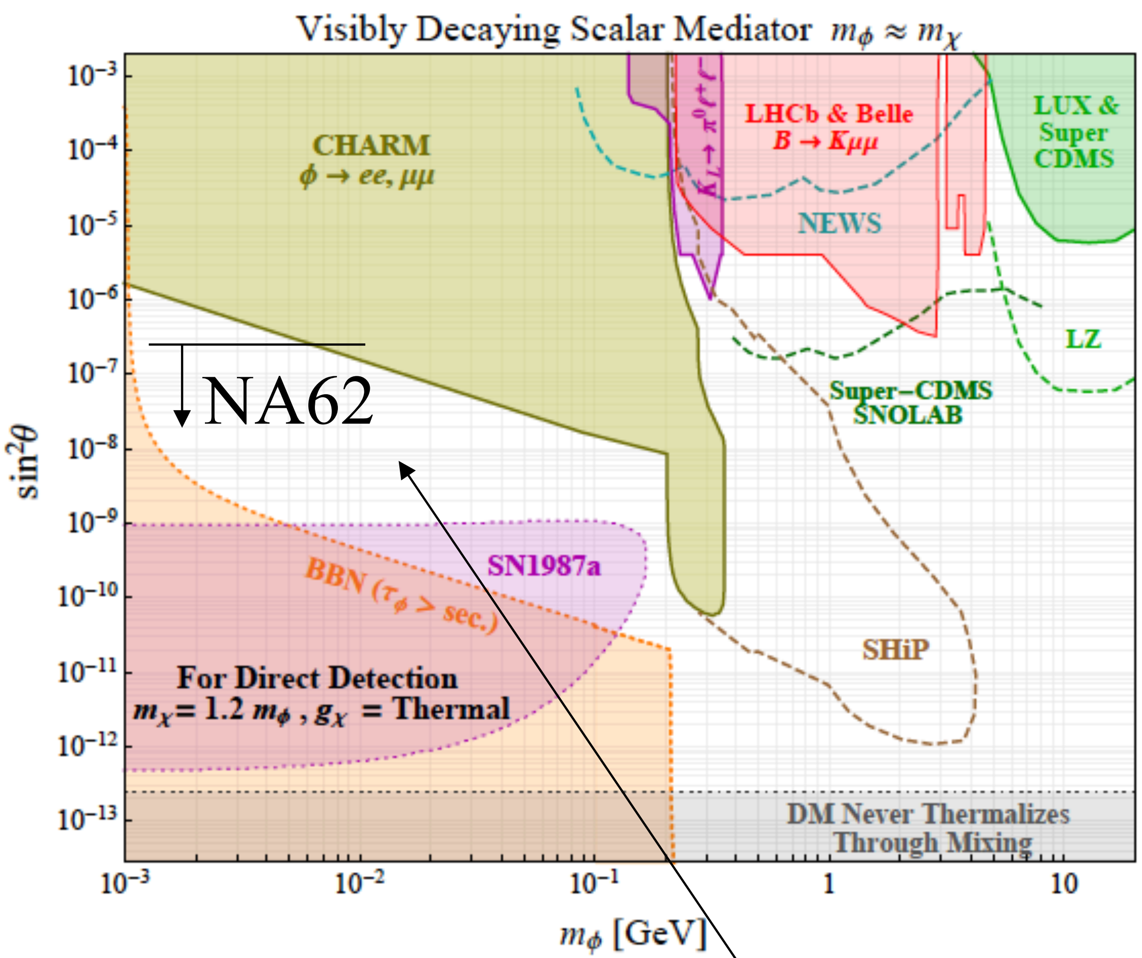


	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)

The off-target run of MiniBoone is a success (despite the absence of DM signal!):

- Neutrino background from the beam is brought down to be comparable from cosmics
- Data are well described by MC
- More sensitivity in future exp

Constraints on Higgs-like mediators



From Krnjaic 2015 (certain curves need to be revised)

Question: Is there a further sensitivity to S from K→π S followed by S decay in the near detector at SNB (LAr1ND)?

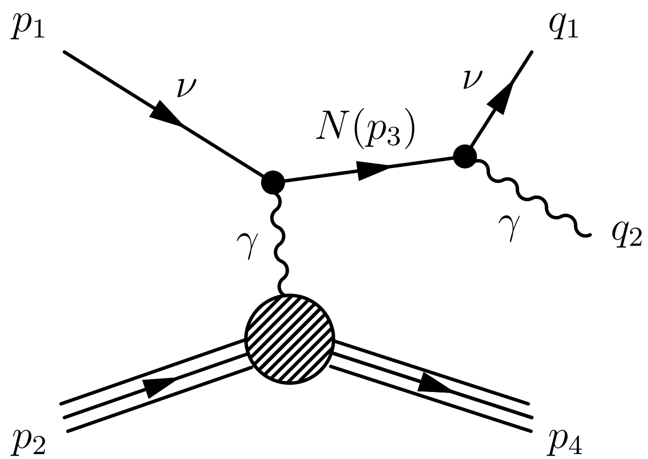
Models with HNL and a dipole coupling

- Magill, Plestid, MP, Tsai, to be submitted. Consider a heavy neutral lepton with dim=5 couplings to photons and neutrinos:

$$\mathcal{L}_d = i\bar{N}_D \partial\!\!\!/ N_D + (d_\gamma \bar{\nu}_L \sigma_{\mu\nu} F^{\mu\nu} P_R N_D + h.c.) - m\bar{N}_D N_D$$

- This model has two free parameters, m_D and d_γ, and the dipole coupling gamma has a dimension of inverse mass.

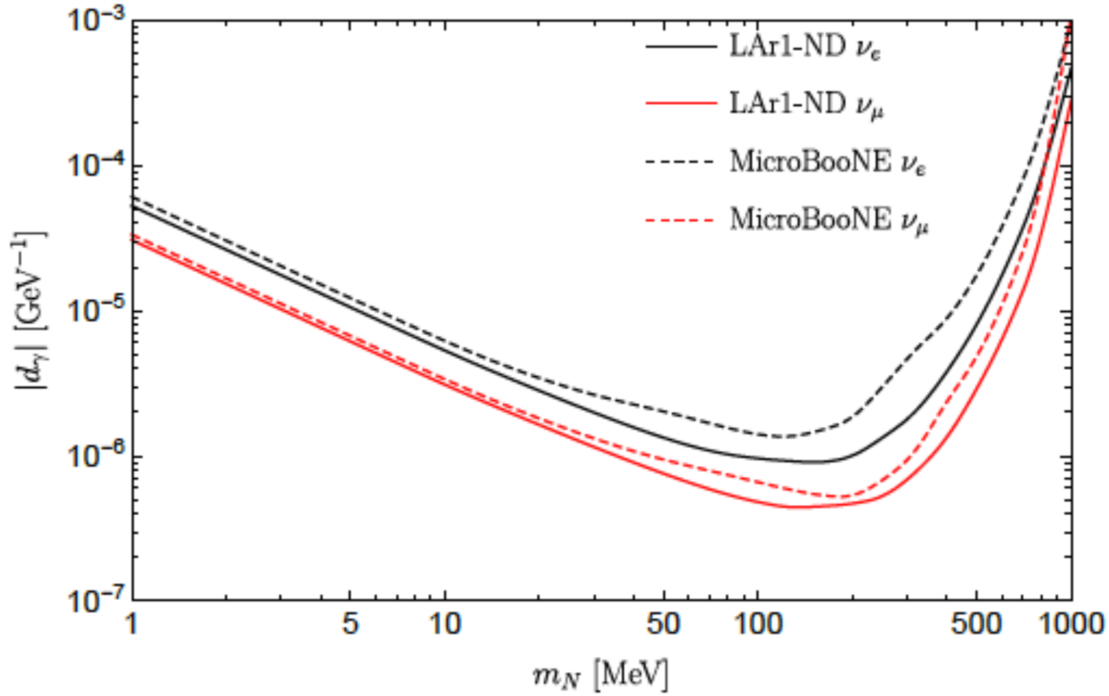
- The signature of this model is an upscattering of normal neutrino into N_D, and subsequent [discplaced] decay of N with a gamma in the final state:

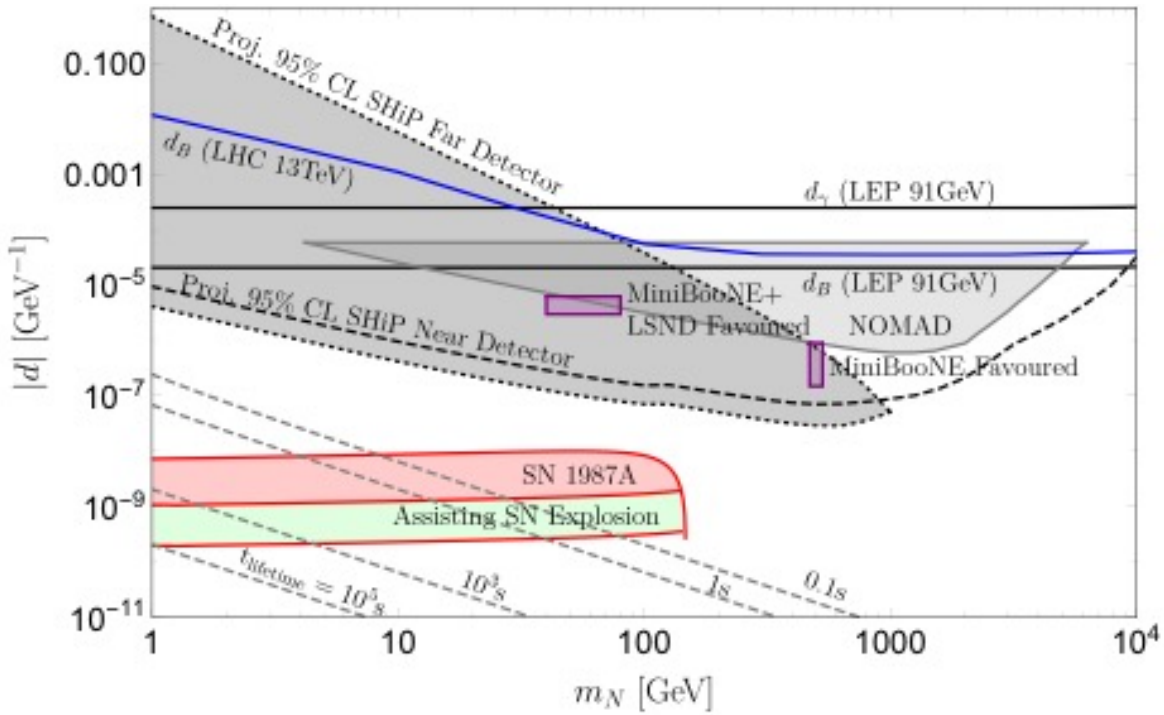


$$L_{\rm dec} = c\tau\beta\gamma = 100m \left(\frac{500\ {\rm MeV}}{m_N}\right)^4 \left(\frac{10^{-7}\ {\rm GeV}^{-1}}{d}\right)^2.$$

- In the past, this model has been suggested as a candidate for explaining extra ν_e like events at Miniboone, Gninenko, 2011.

Sensitivity to dipole coupling

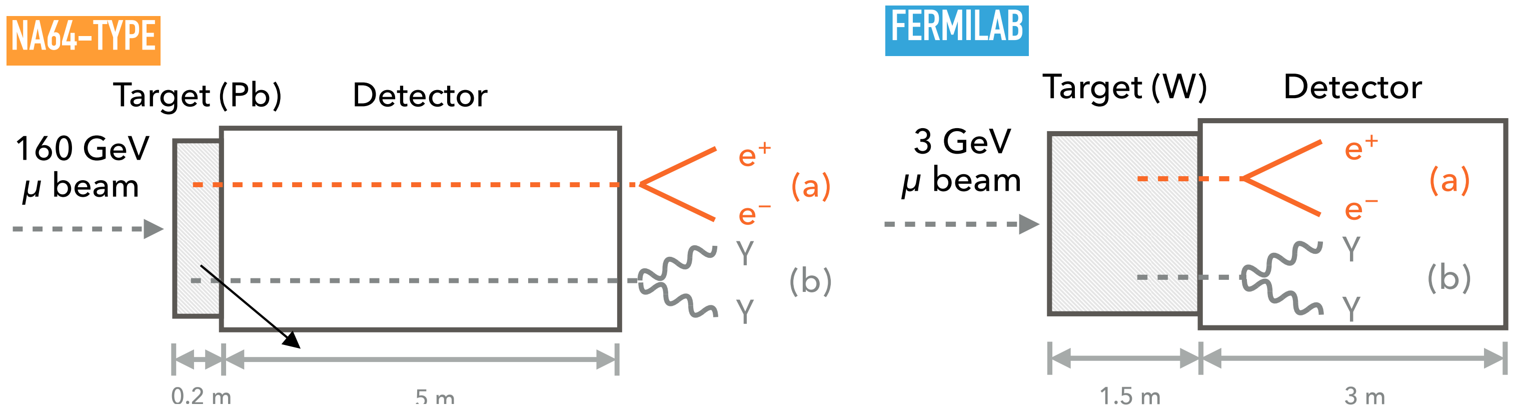


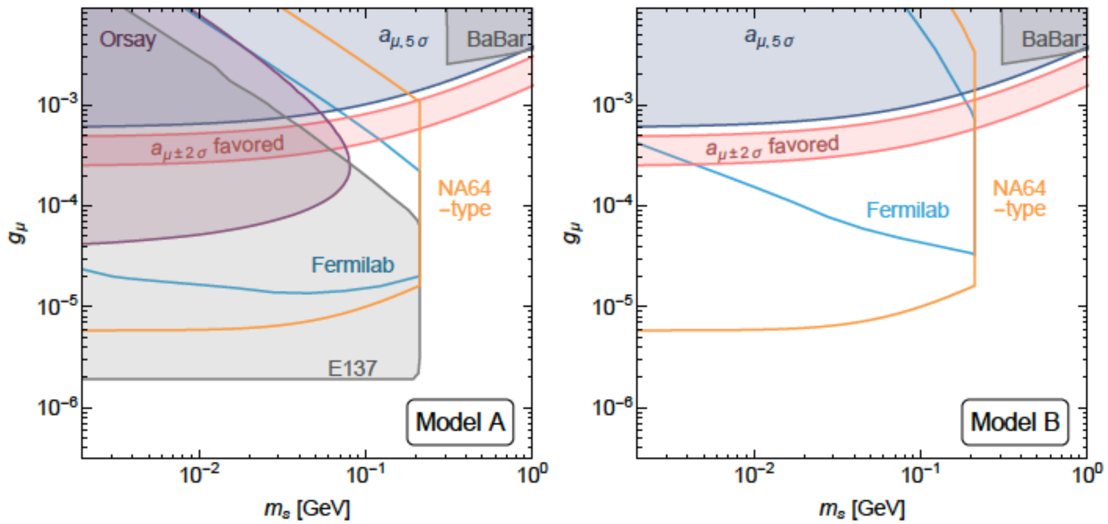


- MiniBoone and future LAr1-ND have sensitivity to $d^{-1} \sim 1000$ TeV scale!
- We need help in understanding backgrounds at MiniBoone and LAr1-ND
- CERN experiment SHiP will also have a strong sensitivity (but only in ~10 time scale).
- **One need to have a closer look at the sensitivity of various ν experiments in many models, as it is quite significant!**

New experimental opportunities with muon beams

- *An accumulation of anomalies in the muon sector?* (discrepancy in g-2, muonic atom Lamb shift, new anomalies in semileptonic B-decays….)
- Muon beam dump (to look for displaced vertices)
- PNC experiment, where the muon helicity is switched using the g-2.

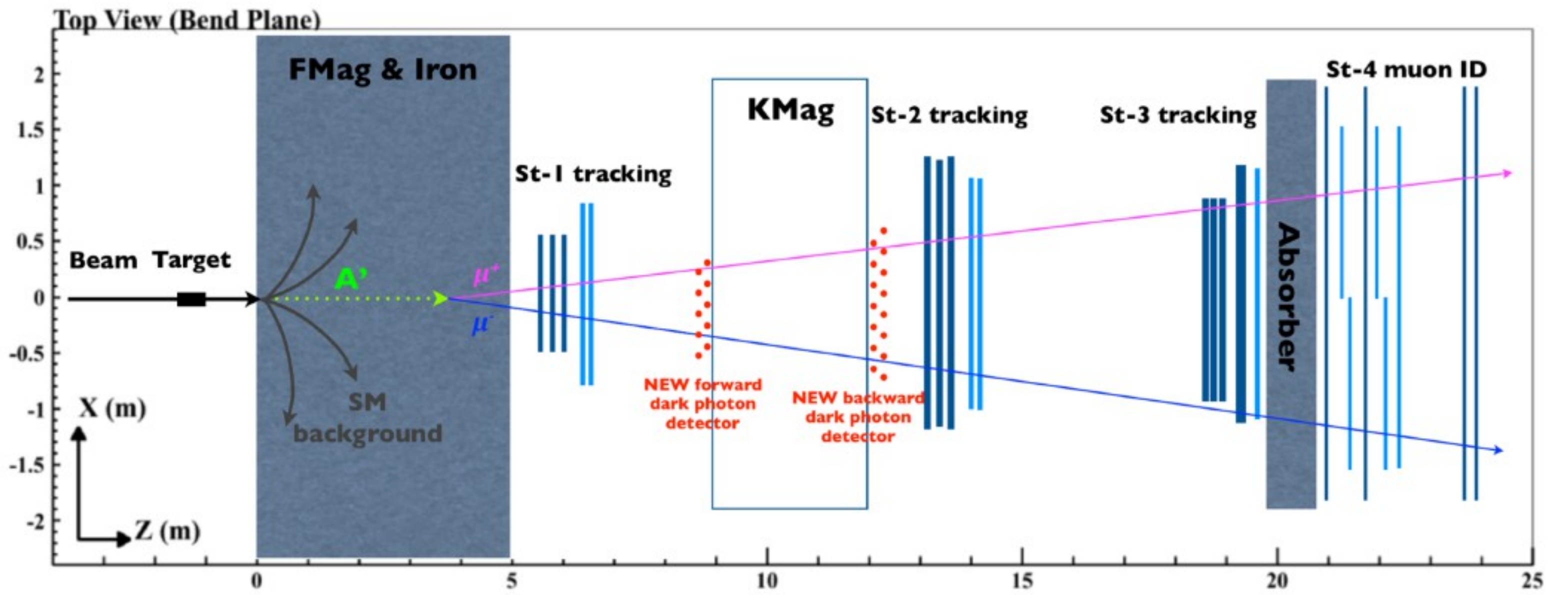




Sensitivity to lepto-phylic scalars in the muon beam dump can be comparable or complementary to NA64. (Chen, MP, Zhong, 2017)

Possible re-purposing of SeaQuest experiment into a dark sector search, S. Gori talk

5% main injector beam



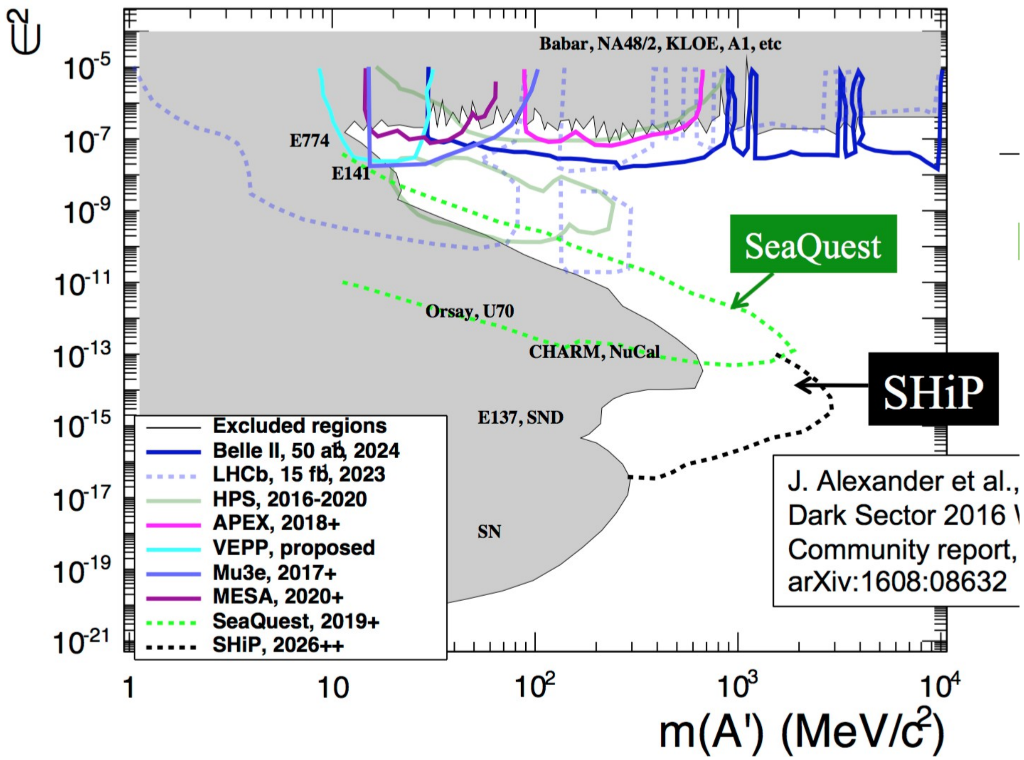
Program for searches for New Physics?

- Proton beam of 120 GeV, $\sqrt{s} \simeq 15$ GeV
- Recent installation of a displaced trigger
- Phase I parassitic run: 1.44 × 10^{18} POT in 200 days
- Possible Phase II: upgrade of the detector + larger luminosity (~ 10^{20} POT?)

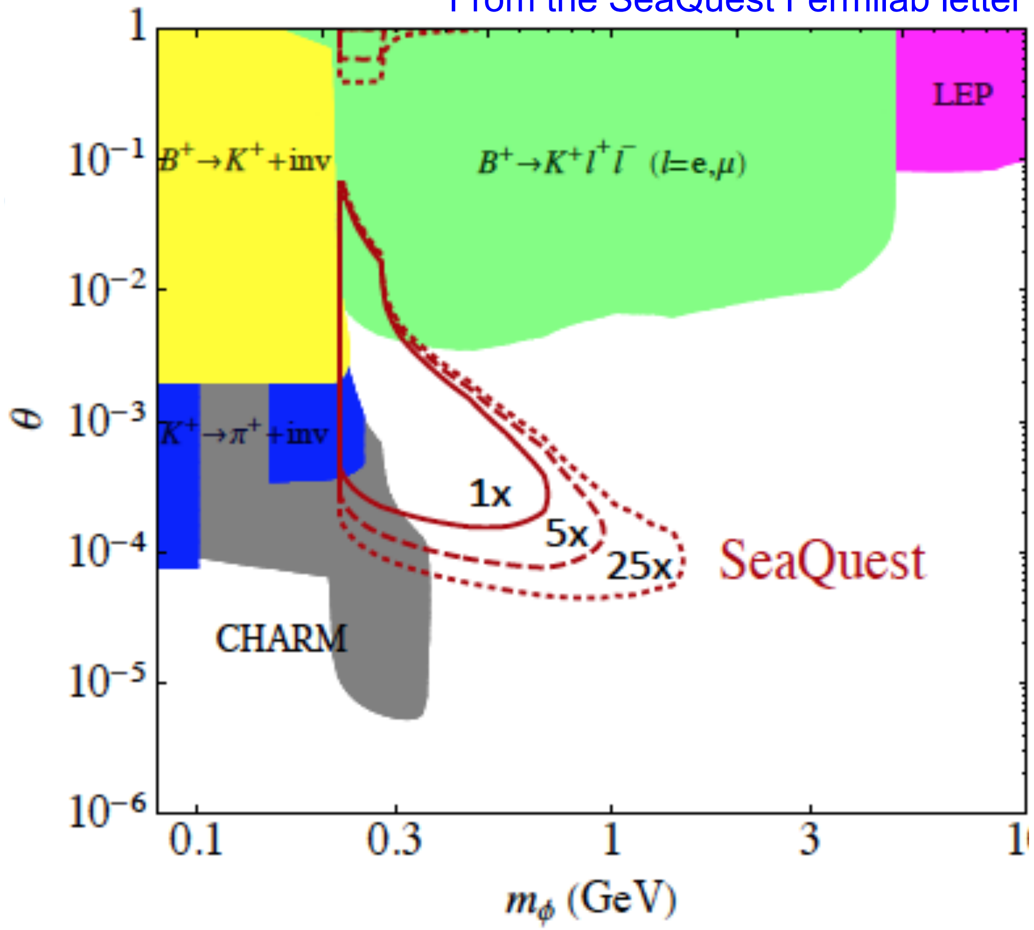
Main features:

- Higher beam energy (if compared to LSND, MiniBooNE, …)
- Smaller detector-target distance (if compared to CHARM, NOMAD, ...)

SeaQuest possible reach



From the SeaQuest Fermilab letter



Some advance in sensitivity is possible (and the advantage is a moderate cost)

Conclusions

- There is a lot of interest to search for light weakly coupled states [dark sectors] in North America.
- *I gave a brief overview of some accelerator-based experiments, progress and hopes.*
- Electron-initiated searches were a main focus of the US community for a while, yet there are many opportunities at FermiLab.
- May be it is a good time for Fermilab to take a closer look at sensitivity of upcoming programs (SNB experiments, DUNE, SeaQuest, muon experiments, possibly REDTOP) to the leading dark sector candidates/models. And may be even co-ordinate with CERN.