DARK INTERACTIONS WORKSHOP SERIES AT BNL

Dr. Kétévi A. Assamagan
BNL

Outline

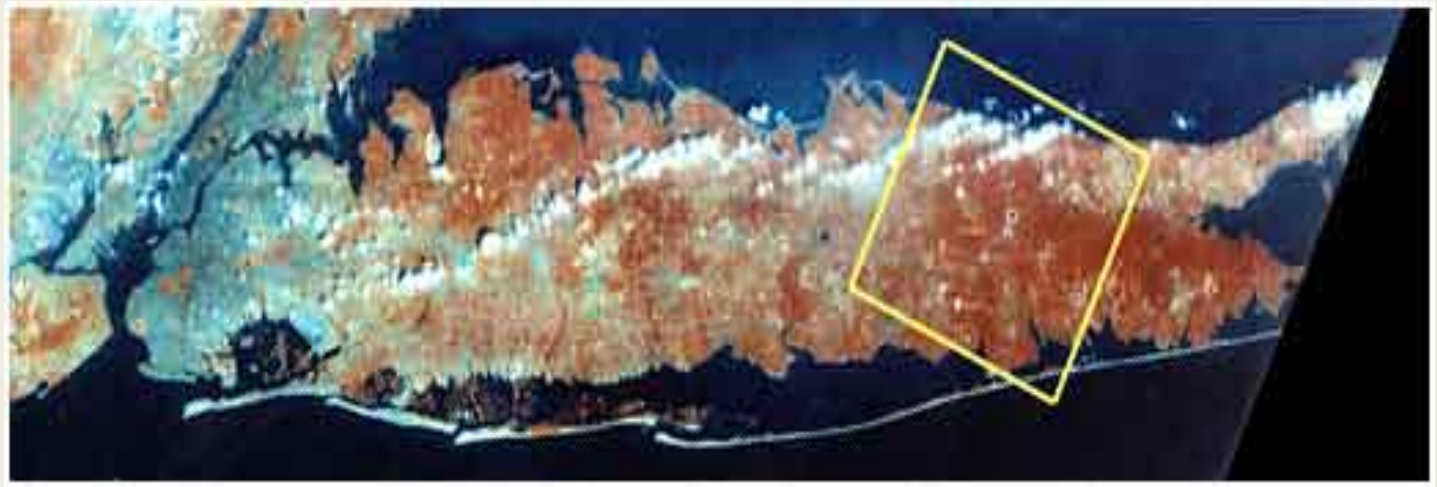
- Dark interactions workshop series at BNL
  - *Purpose*
  - *Format*
  - *Contents*
  - *outlook*

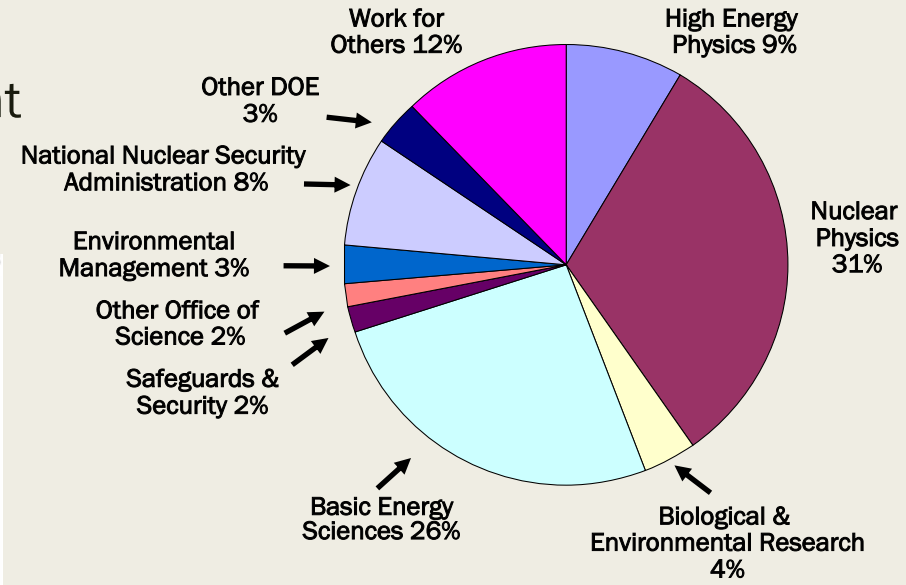
Dark Interactions: perspective from theory and experiment

To review and discuss the theoretical context as well as the status and future of the searches for dark sector particles, such as dark vector bosons, and the implications for dark matter.

Location & Venue

- Brookhaven National Laboratory (BNL) , Physics Department
- Long Island, New York and BNL





- ~2950 employees;
- Budget – about $750M
- >4000 scientific facility users annually
- Seven Nobel Prizes garnered
  - *12 Scientists honored (users & staff)*
  - *First in 1957, latest in 2009*

Ideal Lab for this type of workshop series on Dark Interactions

Major Research Facilities

RHIC
NY Center for Computational Science
Long Island Solar Farm
National Synchrotron Light Source
National Synchrotron Light Source II
Center for Functional Nanomaterials
BNL HEP
ATLAS, LBNE, LSST, DUNE

Future: eRHIC

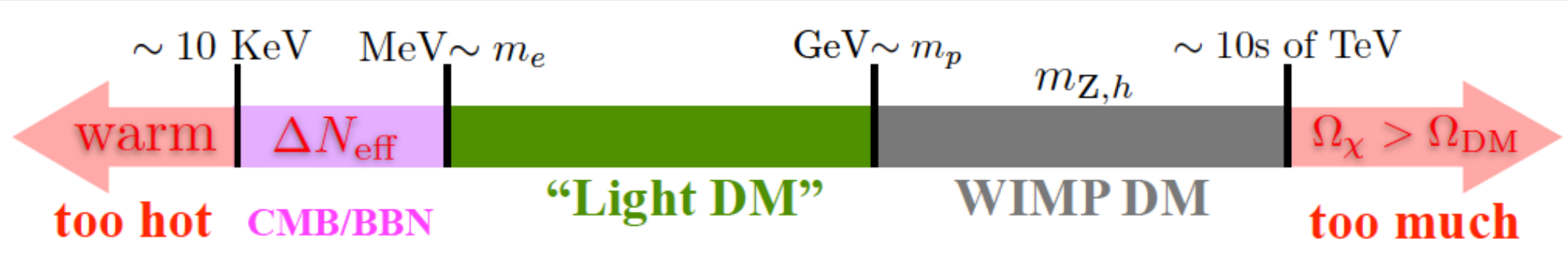
Organizing Committee

- Kétévi A. Assamagan (Chair, BNL)
- Oliver Keith Baker (Yale U.)
- Michael Begel (BNL)
- Mary Bishai (BNL)
- John Paul Chou (Rutgers U.)
- Hooman Davoudiasl (BNL)
- Rouven Essig (SBU)
- Tobias Golling (Université de Genève)
- Christopher S Hill (Ohio State U.)
- William Marciano (BNL)
- Gopolang Mohlabeng (BNL)
- Neelima Sehgal (SBU)
- Anze Slosar (BNL)
- Stéphane Willocq (U. of Mass.)
- Christian Weber (BNL)

Scope

- Theoretical Motivation for Dark Sectors
- Constraints from Collider or non-Collider Experiments
- Cosmological and astrophysical Constraints
- Prospects for LHC and future Intensity Frontier Experiments
- Brookhaven Science Associates (BSA) Distinguished Lectures
  - *Neil Weiner (NYU), Hitoshi Murayama (Berkeley), …*

Topics



- Theory—overviews of (light) dark sector
- Direct Detections
  - + *Low mass dark matter. Detection strategies for low-energy particle recoils*
- Indirect detections
- Cosmological & astrophysical probes
- Neutrinos and the dark sector
- Collider searches
- Fixed targets
- Beam dump experiments
- Future experiments
- Many contributed talks
- Read My Paper (RMP) sessions

Duration & Form

- **Duration**
  - *2.5 to 3.5-day workshop*
- **Format**
  - *Invited talks*
  - *Contributed talks*
  - *“Read My Paper” sessions*
  - *Discussions*
- **All plenary sessions**

“Read My Paper” sessions:

7-min (or less) talks to explain why anybody should read your latest paper

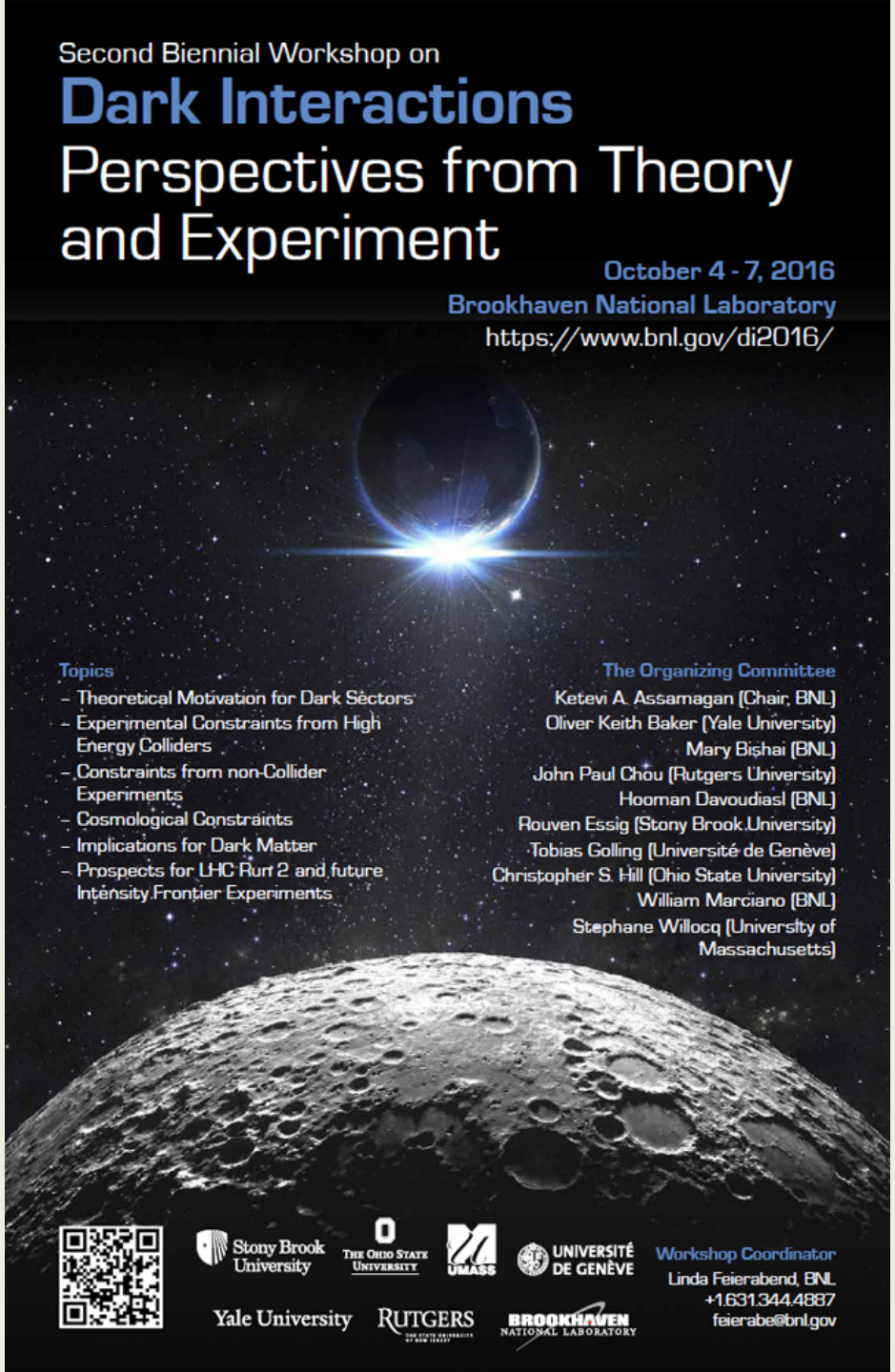
Agenda of past workshops

- https://www.bnl.gov/di2014/
- https://www.bnl.gov/di2016/
- https://www.bnl.gov/di2018/

Photos (2014)

Photos (2018)

Poster (2016)


Second Biennial Workshop on
Dark Interactions
Perspectives from Theory and Experiment
October 4 - 7, 2016
Brookhaven National Laboratory
https://www.bnl.gov/di2016/
Topics
- Theoretical Motivation for Dark Sectors
- Experimental Constraints from High Energy Colliders
- Constraints from non-Collider Experiments
- Cosmological Constraints
- Implications for Dark Matter
- Prospects for LHC Run 2 and future Intensity Frontier Experiments
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Stony Brook University
The Ohio State University
UMASS
Université de Genève
Yale University
Rutgers
Brookhaven National Laboratory
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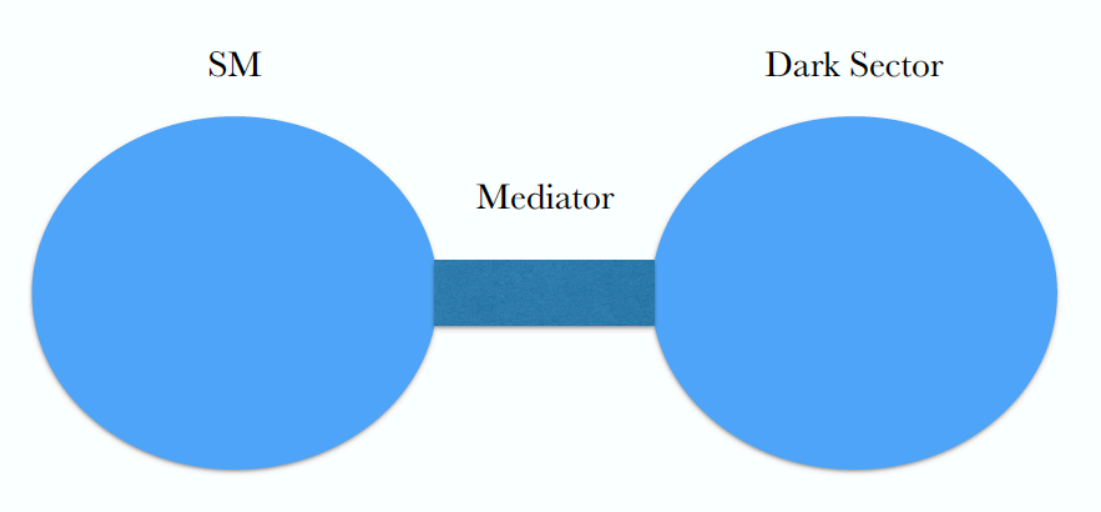
Dark Sector

- Dark Sector as ”New Physics” beyond the SM



Need new force / interaction
to connect SM to Dark Sector

Dark Matter could just be one example of Dark Sector State

- A hidden or dark sector can be introduced with an additional U(1)d dark gauge symmetry
  - *The dark sector could couple to the SM through kinetic mixing with the hypercharge gauge boson*
- Exotic Higgs boson decays have been proposed as a way to search for evidence of new physics
  - *In the decay of the discovered Higgs boson*
  - *To measure the coupling strengths between the SM and the dark sector*
- Such decays predicted in many extensions to the SM to explain
  - *Muon g-2 discrepancy*
  - *Astrophysical observation of positron excess*

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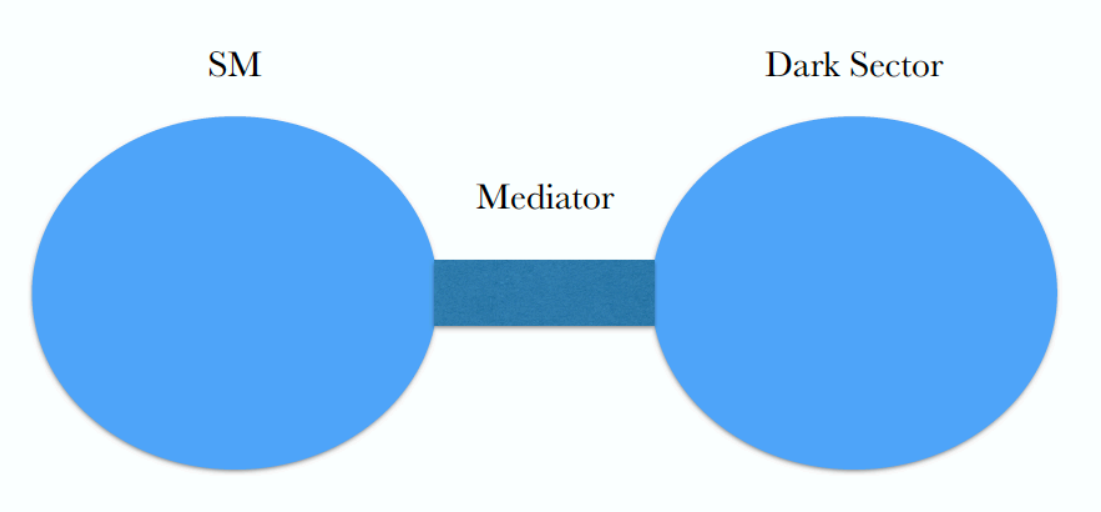

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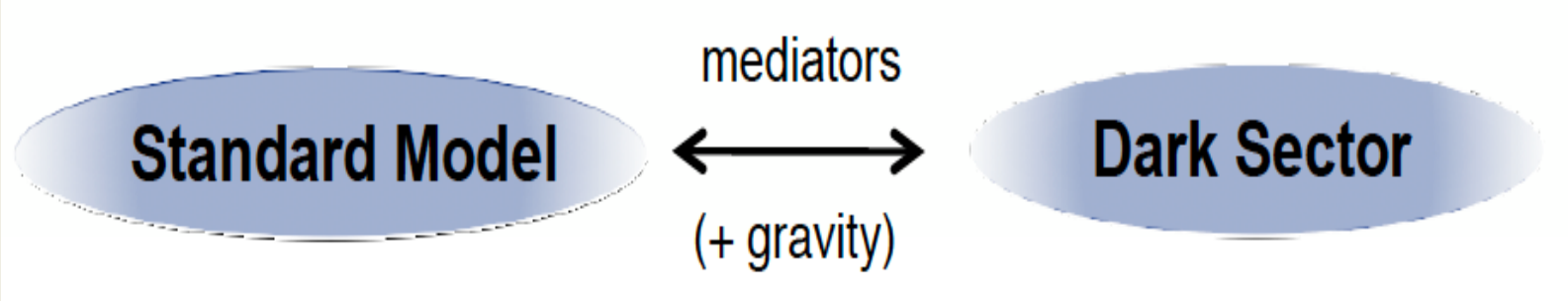
Minimal Interactions

- Symmetries of the SM restrict interactions with Dark Sector States



$$\mathcal{L} \supset -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j$$

Vector portal [Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal [Patt & Wilczek]

Neutrino portal

$$+\frac{1}{f_a}\left(\mathrm{tr}(G\tilde{G}) + c_F F\tilde{F}\right) a + \mathcal{O}(\dim \geq 5)$$

Axion portal [Weinberg, Wilczek, KSVZ, DFSZ]

Vector Portal:

Min. Lagrangian =

SM Lagrangian

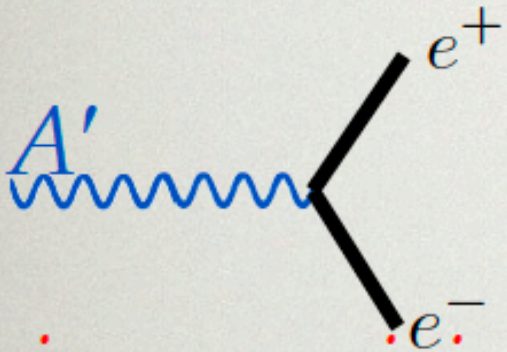
+ Dark QED

+ "Kinetic Mixing (ε)"

Dark Photon Decays

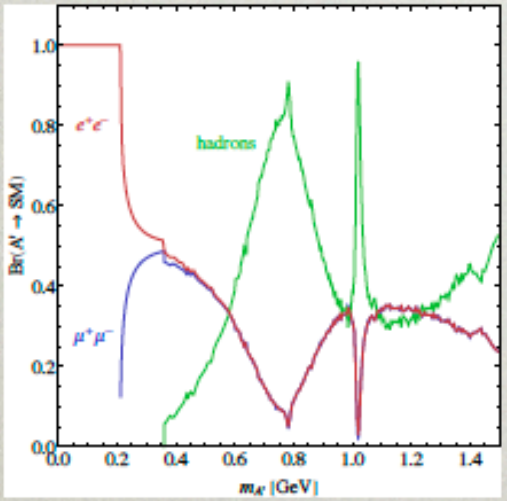
- **Kinetic mixing gives matter of electric charge qe an A' coupling $\propto q\varepsilon e$**

"Minimal" Decay:

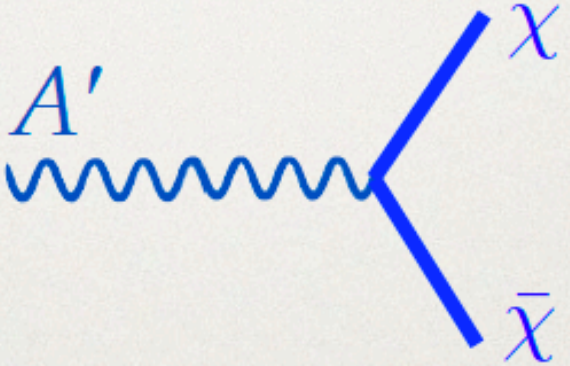


via same mixing operator as production
⇒ tiny width

$$\Gamma \sim \epsilon^2 \alpha m_{A'}$$



"Generic" Decay:



(not ε-supressed!)

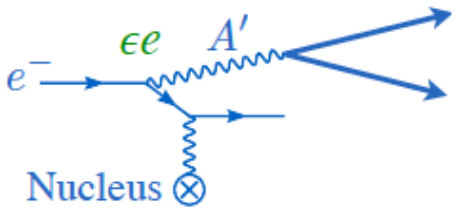
*If **any** dark-sector matter χ has $m_\chi < 2m_{A'}$, this decay dominates*

Two cases:
- χ stable & invisible
- χ decays into SM particles, A′→ >2 charged particles

searches at BaBar and KLOE

Dark Photon Production

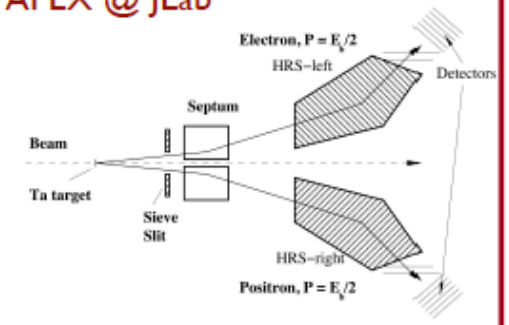
e fixed target



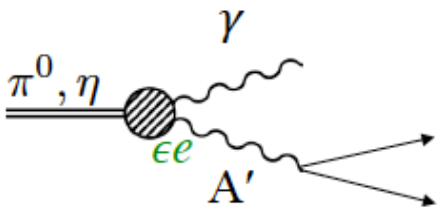
$N \propto \epsilon^2$

- dark bremsstrahlung
- $e+e- \rightarrow A'\gamma$

APEX @ JLab

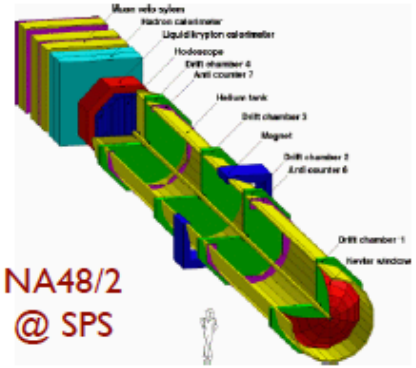


p fixed target



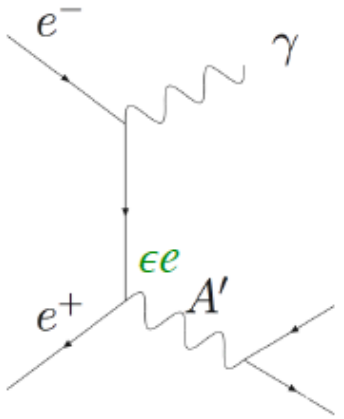
$N \propto \epsilon^2$

- meson decays
- dark bremsstrahlung



NA48/2 @ SPS

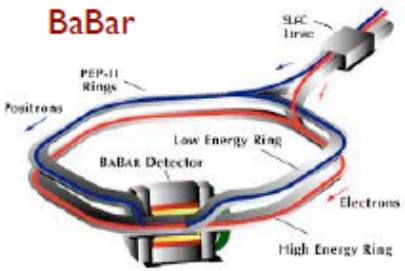
e^+e^- colliders



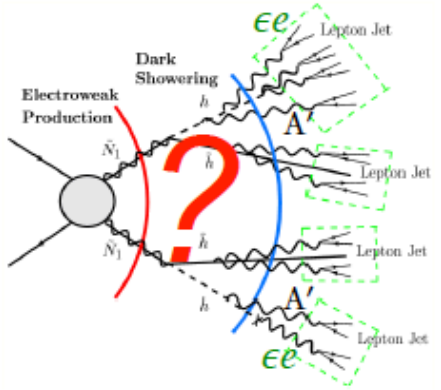
$N \propto \epsilon^2$

- $e+e- \rightarrow A'\gamma$
- meson decays

BaBar

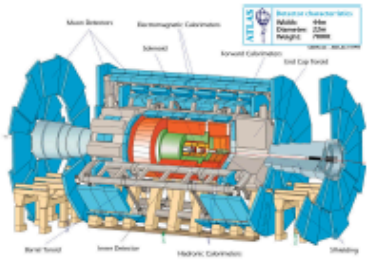


pp collider



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

ATLAS
CMS
LHCb



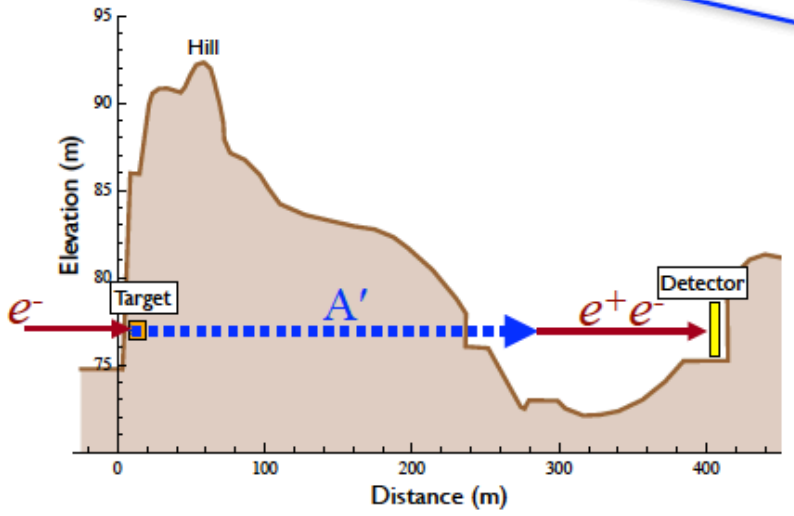
Mediator Decays to SM

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

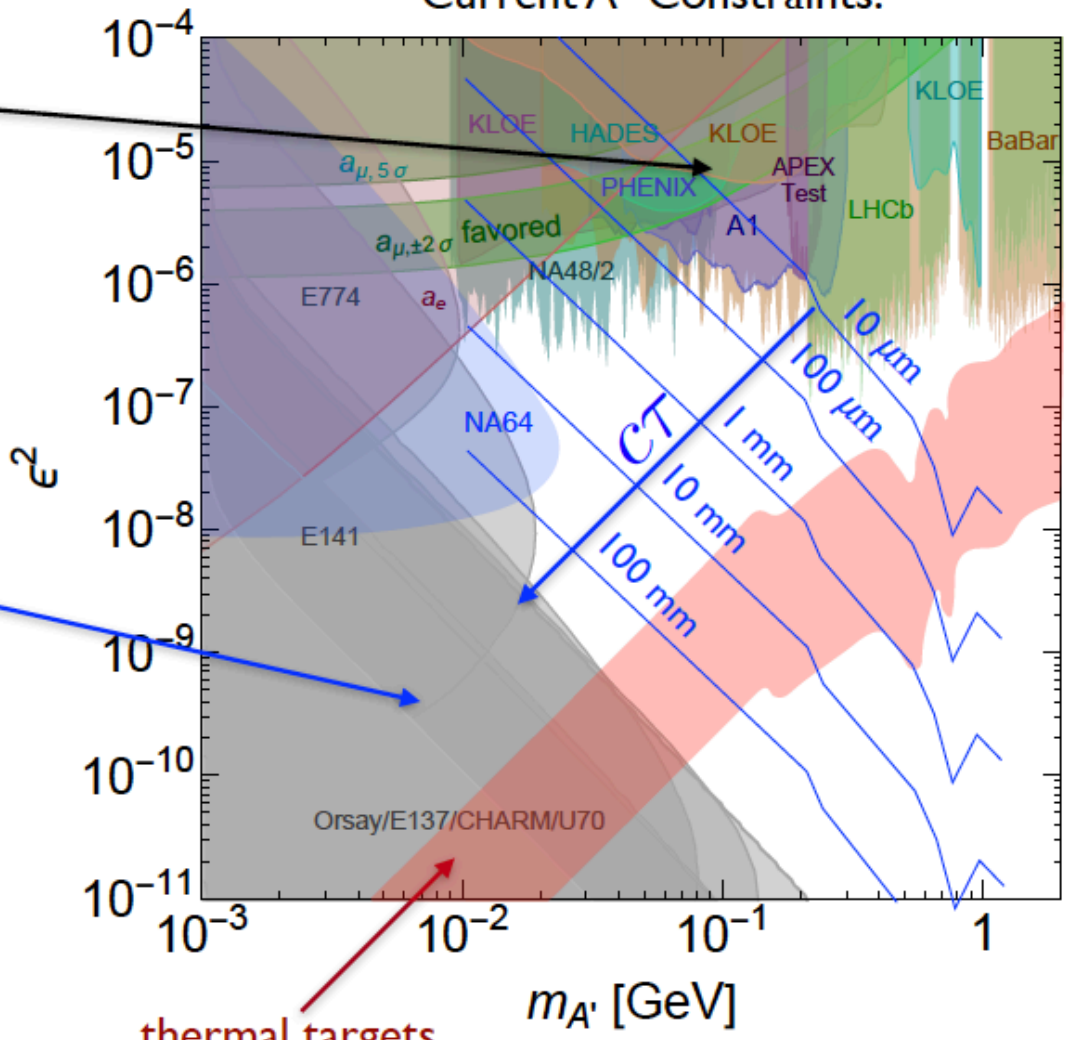
A′ becomes long lived at small couplings.

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

Leads to constraints from "beam dump experiments"



Current A′ Constraints:



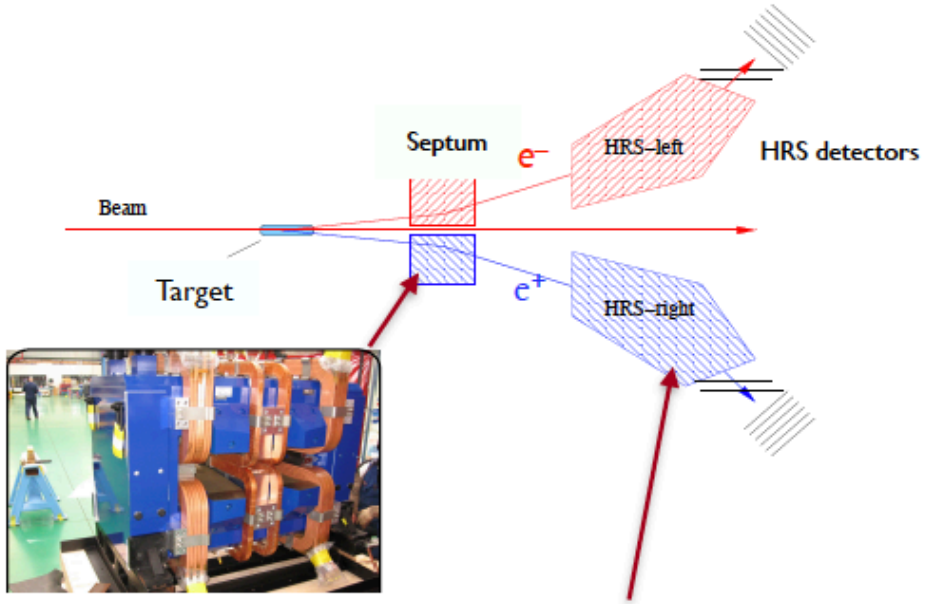
thermal targets

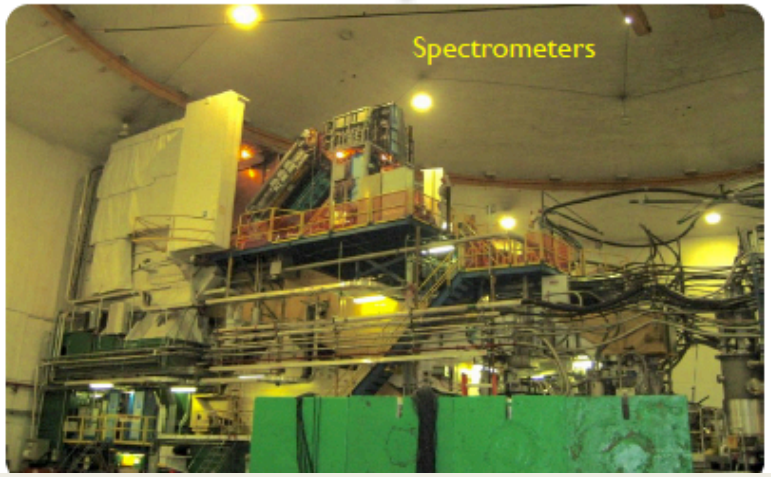
$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

6

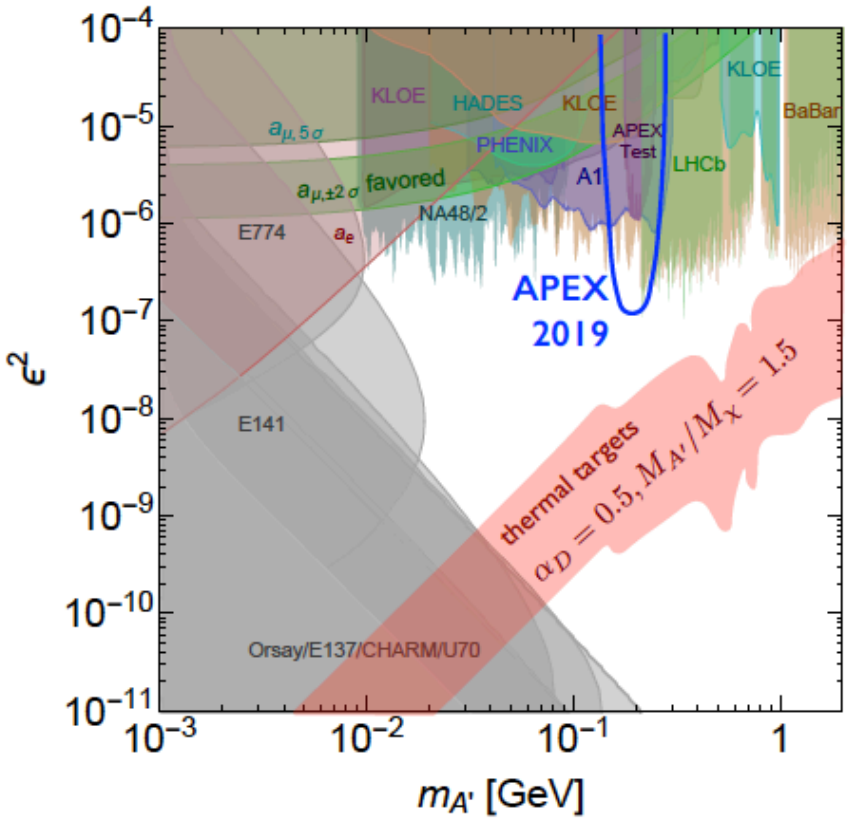
Electron fixed target—APEX at JLAB CEBAF

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





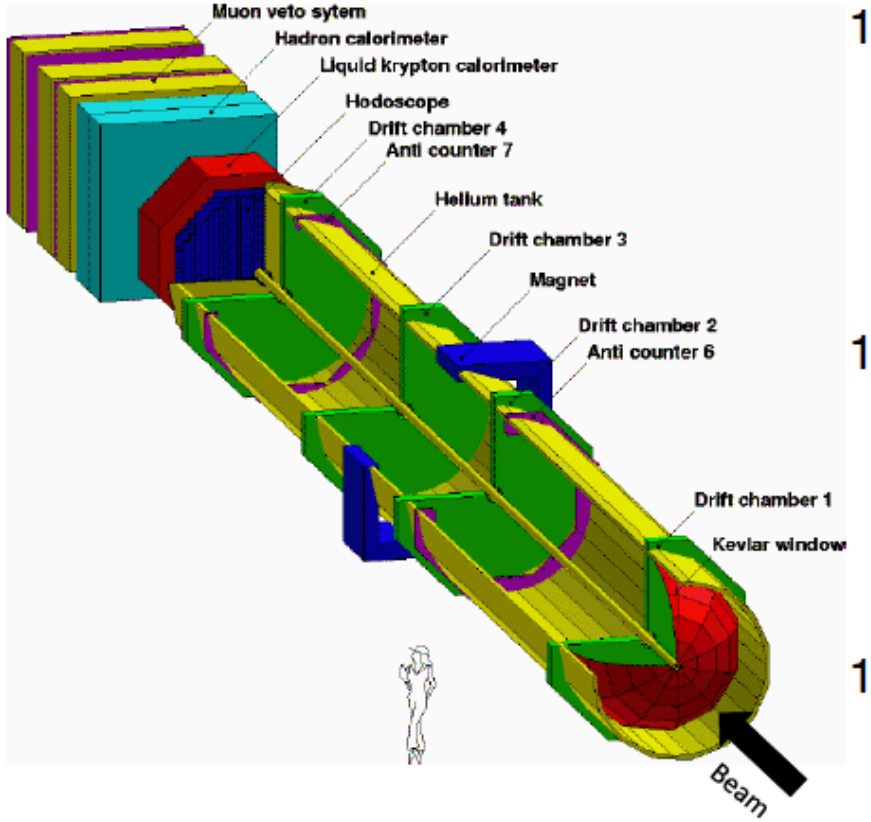
2019 Physics Run *(2/1 - 3/10 2019)*
15 days at E_{beam} = 2.2 GeV

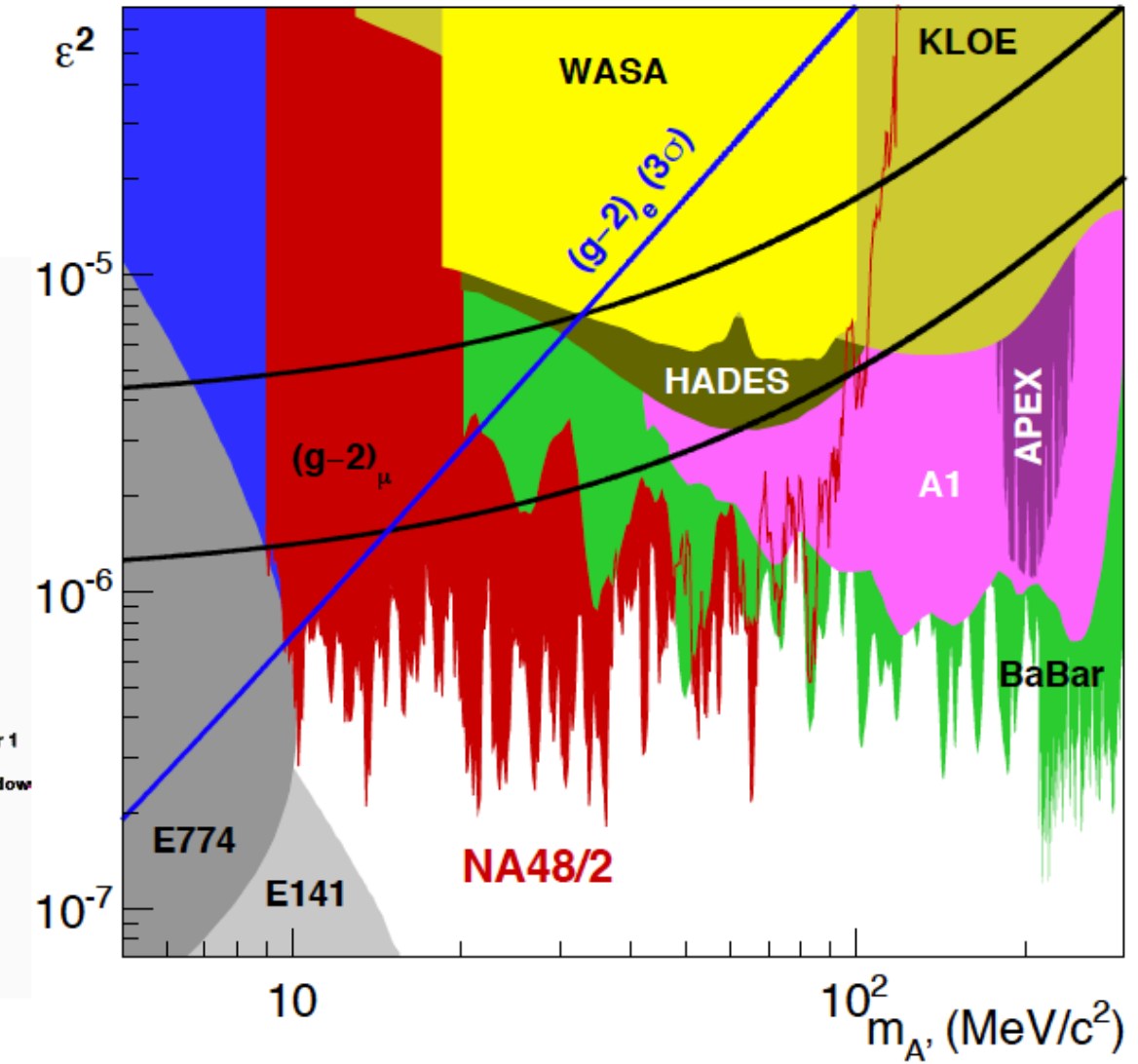


Proton fixed target—NA48/2 at CERN SPS (2015)

CERN SPS Kaon CP-violation/rare decay experiment collected a large sample of π^0

$$\pi^0 \to \gamma A' \to \gamma e^+ e^-$$



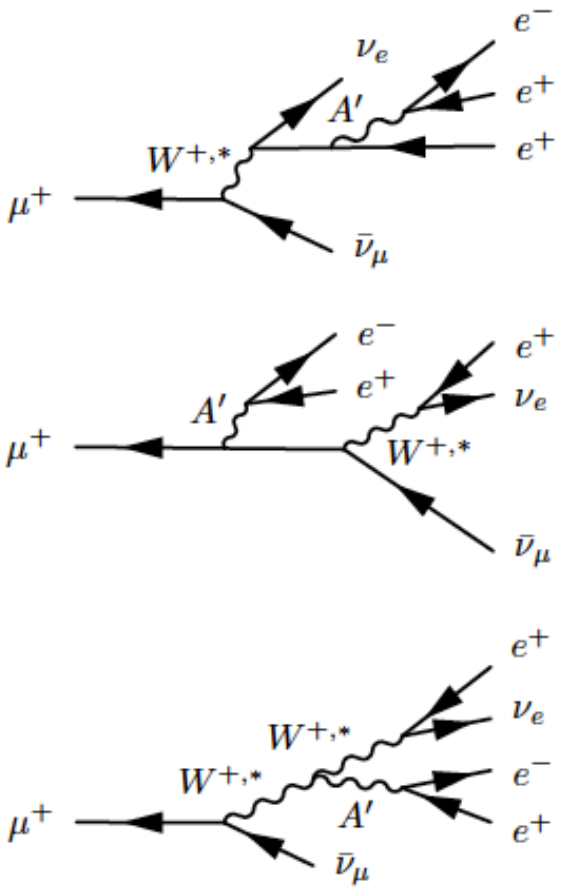


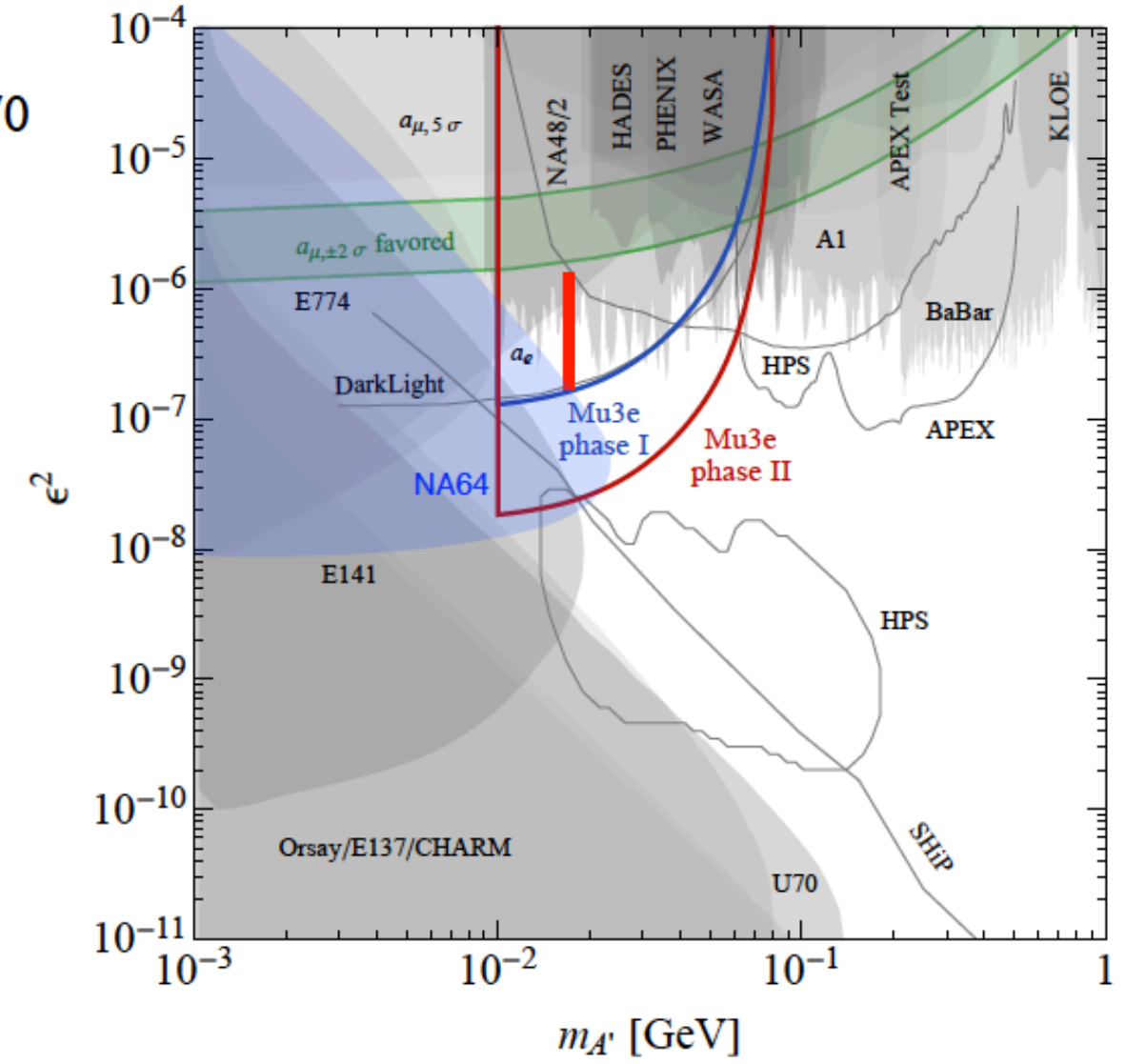
The NA48/2 Collaboration, Phys. Lett. B 746 (2015) 178

10

μ^+ beam: ISR/FSR (mu3e)

Experiment at PSI using secondary muon beam to search for $\mu^+ \to e^+e^-e^+$ with up to 5×10^{16} μ arXiv: 1411.1770

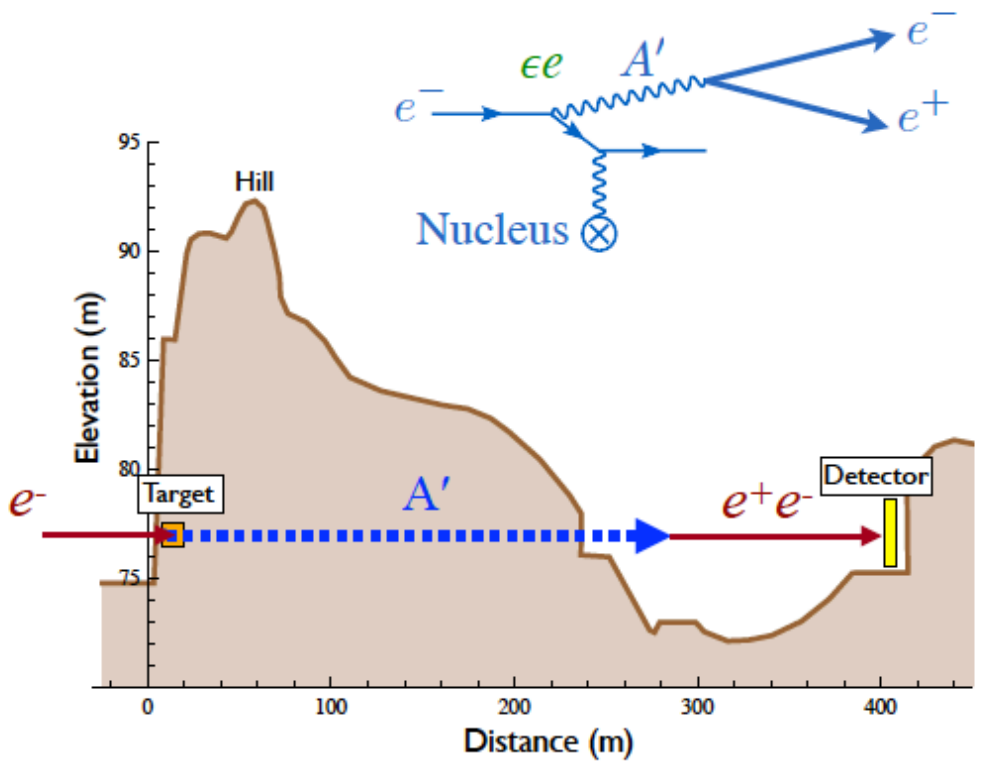


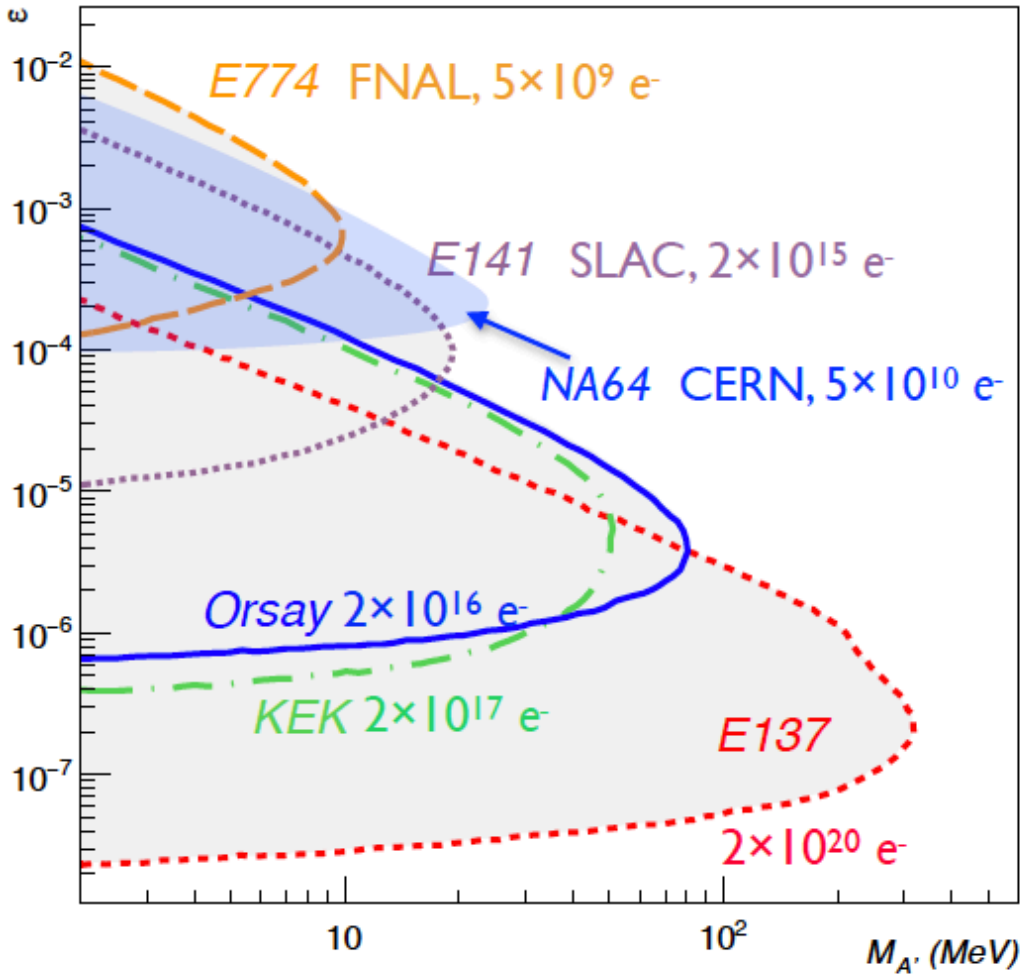


e^- beam dump—SLAC E137 (1980-1991+2018)

SLAC E137: search for metastable particles run during 1980-1982(!)

- 2×10^{20} e^- (30 C) @ 20 GeV
- 179 meter shield





Still the best limits in parts of parameter space for many dark sector models!

e.g. arXiv: 1209.6083, 1406.2698, 1802.03794

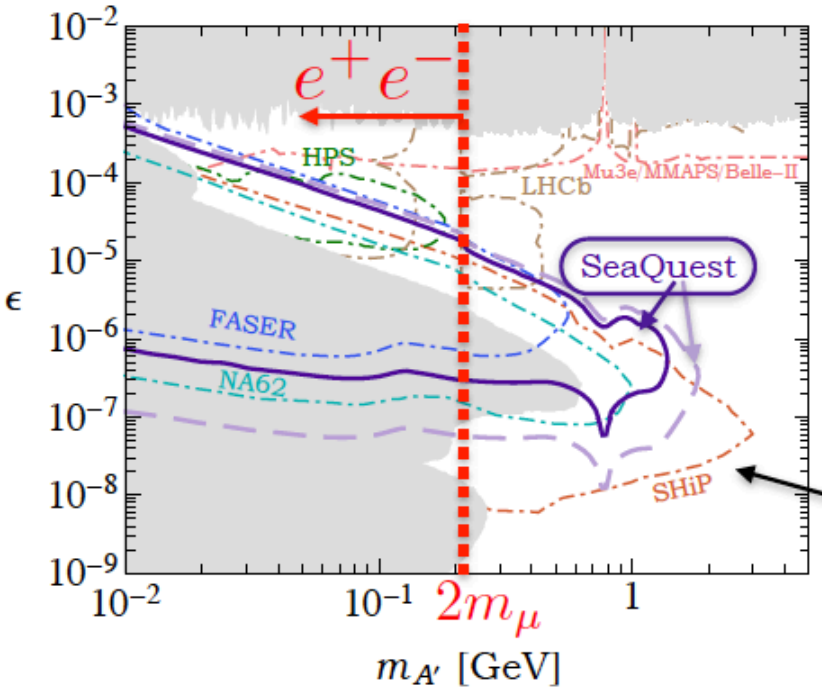
13

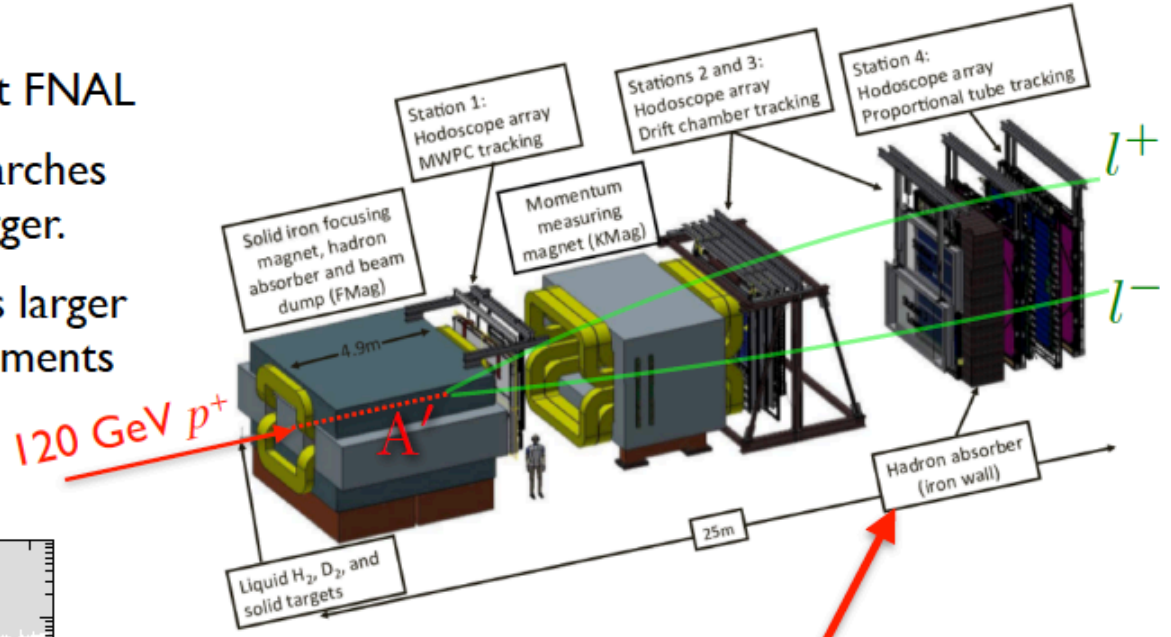
p+ beam dump—SeaQuest at FNAL ($\mu^+\mu^-$ 2019, 2021? e^+e^-)

Fixed target muon spectrometer for Drell-Yan sea quark measurements at FNAL

Parasitic program of dark photon searches with addition of displaced vertex trigger.

Shallow dump + large boost accesses larger couplings than previous dump experiments

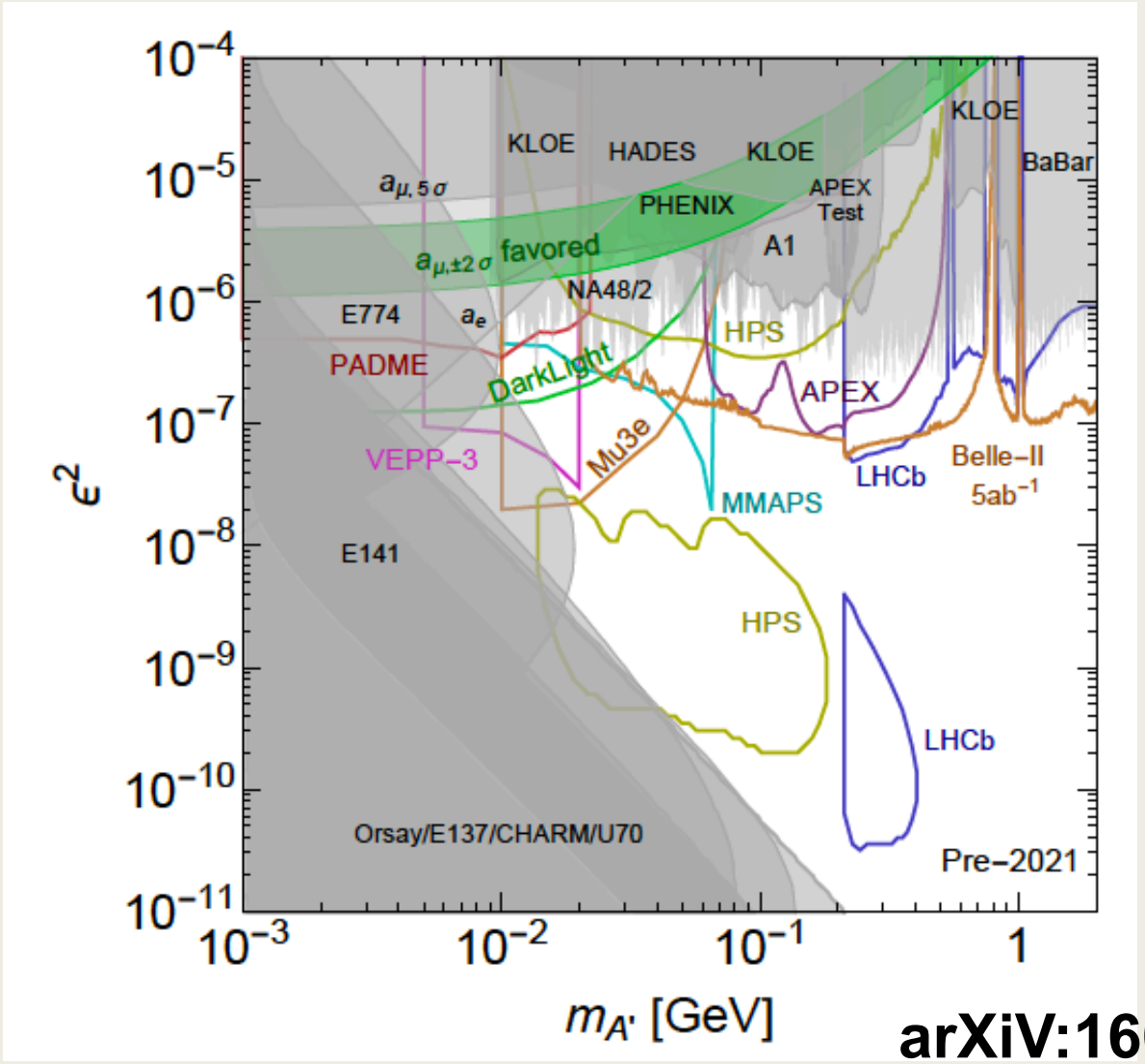


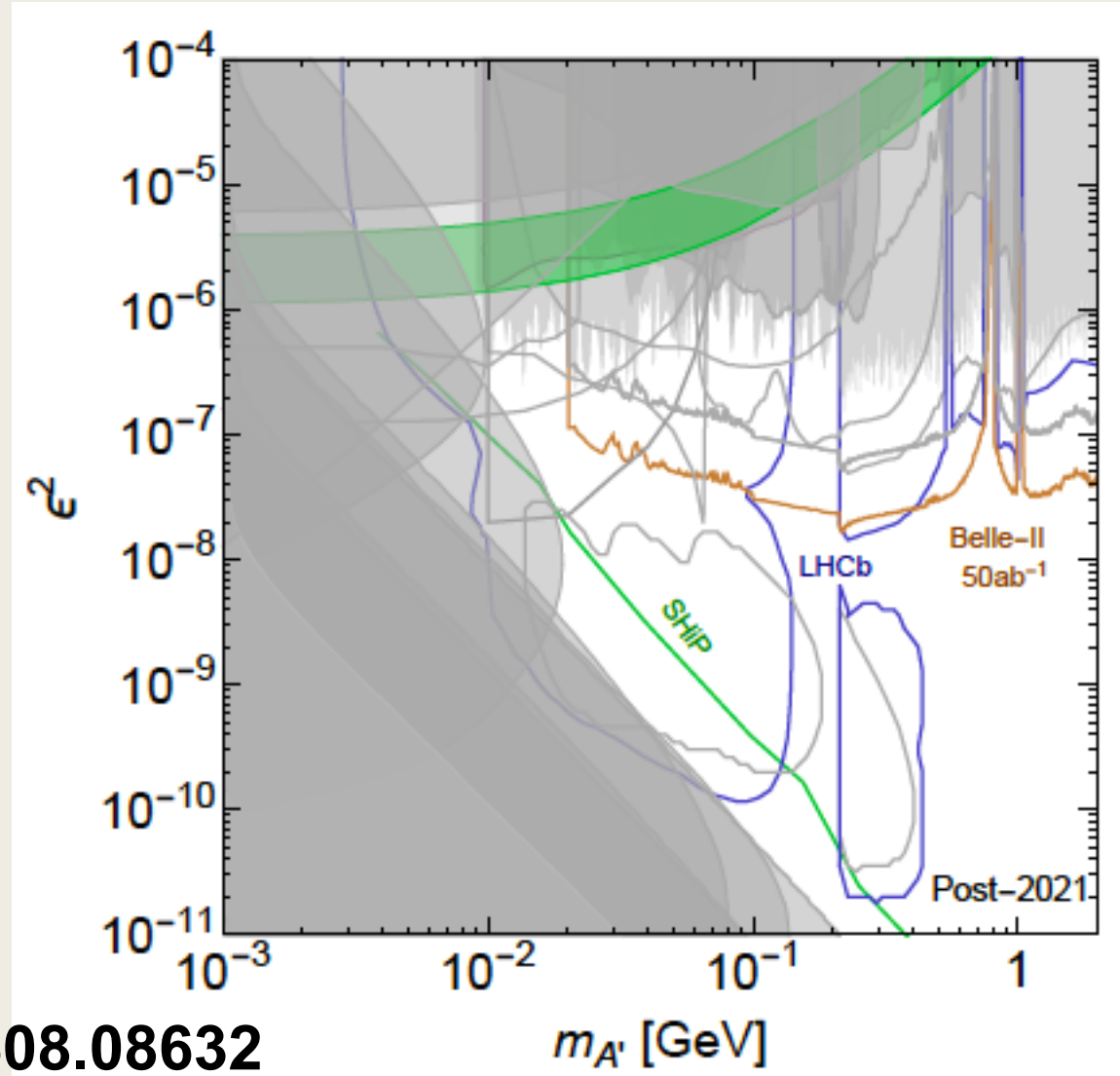


Potential future upgrade to replace Hadron absorber with EMCal to enable reach below $2m_\mu$

Very similar: NA62, SHiP

Kinetic Mixing – for experiments seeking $A' \rightarrow ll$





arXiV:1608.08632

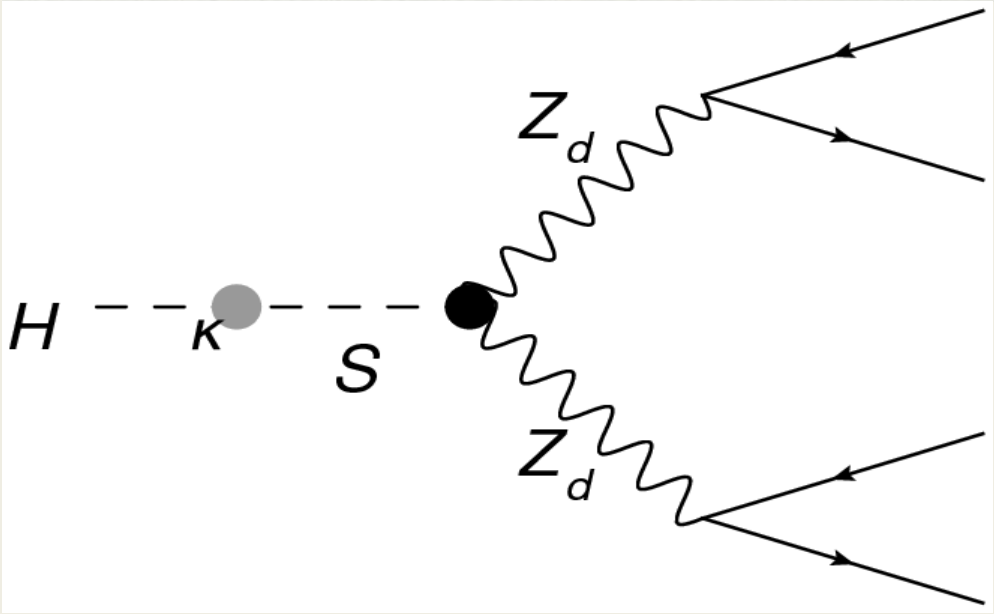
Previous constraints

Projections

The Higgs Portal

Phys. Rev. D 90, 075004 (2014)

$\epsilon_h |h|^2 |\phi|^2$ exotic rare Higgs decays
rare meson decays



- If, the U(1)d symmetry is broken by the introduction of a dark Higgs boson, then there could also be a mixing between the SM Higgs boson (H) and the dark sector Higgs boson (S)

Dark Photon (A'), or Dark Z (Zd)
same thing …

The mixing parameter κ between H and S, can be extracted from H → Zd Zd → 4l, a unique channel to access this parameter

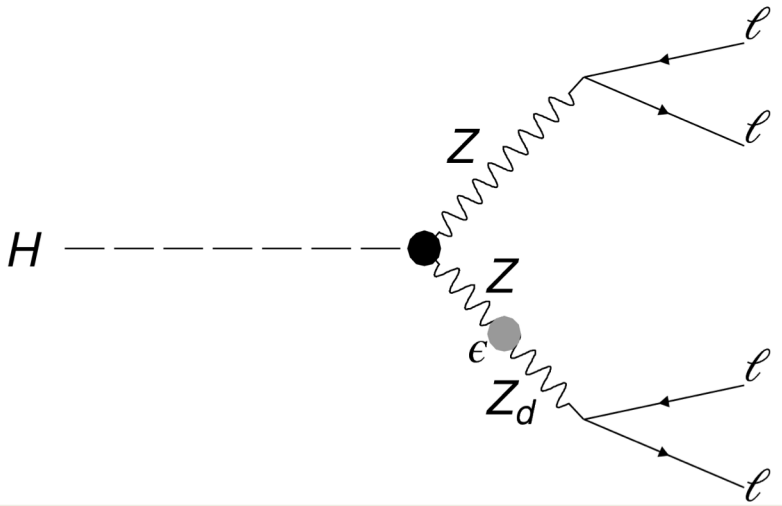
See the talk by Diallo Boye

Mass Mixing between SM Z and Zd

- In addition to kinetic mixing, there could be also a mass mixing between SM Z and Zd

Phys.Rev. D 88.1 (2013) 015022

Phys.Rev. D 85 (2012) 115019

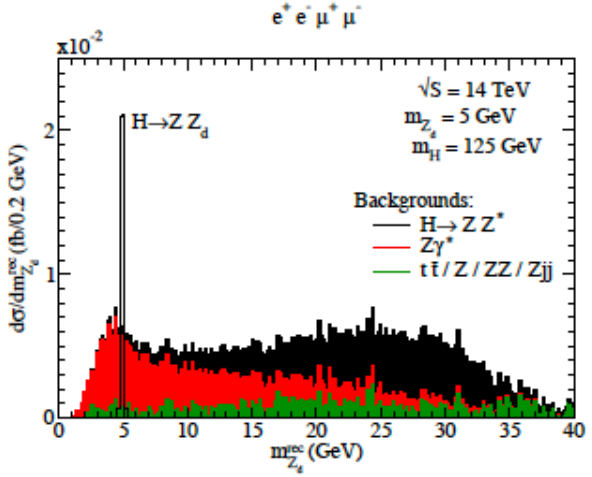


$$O_{A,X} = c_{A,X} H X_\mu Z_d^\mu \,, \qquad (2)$$

For operators of type $O_{A,X}$ in Eq. (2), we will focus on $X = Z$. Such interactions are typically associated with mixing. For example, the mass term for Z-Z_d mixing can be parametrized as $\varepsilon_Z \, m_Z^2 Z Z_d$, with

$$\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta \,, \qquad (4)$$

H → Z Zd → 4l is sensitive to the kinetic mixing parameter ε, and to Z-Zd mixing parameter δ. Unique channel to extract δ



See talk by Diallo Boye

Agenda – example of di2018

- **Theory:** Overview of light dark sectors
- **Experiments:** Overview of light dark sectors
- **Light (keV-GeV)** Dark Matter: Recent developments
- BSA Distinguished Lecture: "Illuminating Dark Matter"
- Indirect detection of dark matter
- Novel cosmic probes of dark matter
- **Ultralight** Dark Matter
- Cosmological and astrophysical probes of dark sectors
- Contributed Talks I
- Neutrinos and the dark sectors
- Colliders: Searches for dark sector states (I)
- Contributed Talks II
- Contributed Talks III
- Colliders: Searches for dark sector states (II)
- Direct Detections

di2020

- The 4th Dark Interactions workshop is currently in preparation
- Date: September 30 – October 2, 2020
- Scientific agenda under development
- Announcement in a few months
- I hope you will consider coming to BNL for di2020

Conclusions

- “Dark Interactions” is a series of workshop started in 2014
- Organized biennially
- At BNL
- On dark sector states and dark matter
- Next workshop, di2020, on September 30 - October 2, 2020