New Prospects in Fixed-Target Searches for Dark Forces

Susan Gardner

Department of Physics and Astronomy
University of Kentucky
Lexington, KY

Based, in part, on SG, Roy J. Holt,
Arun S. Tadepalli, arXiv: 1509.00050
[SeaQuest/E906/E1067 at Fermilab]

Visible Dark Photon Searches WG
Dark Sectors Workshop 2016
SLAC

Hidden Sector Portals

Only a Few "Sizeable" Portals Exist

$$\mathcal{L}_{\dim\leq 4} = \kappa B^{\mu\nu} V_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N L H N$$

[Batell, Pospelov, and Ritz, 2009; Le Dall, Pospelov, Ritz, 2015]

- Vector Portal
- Higgs Portal
- Neutrino Portal

All deserve systematic study;
N.B. low E Higgs portal
constrained by rare B, K decays
Here we focus on vector portals

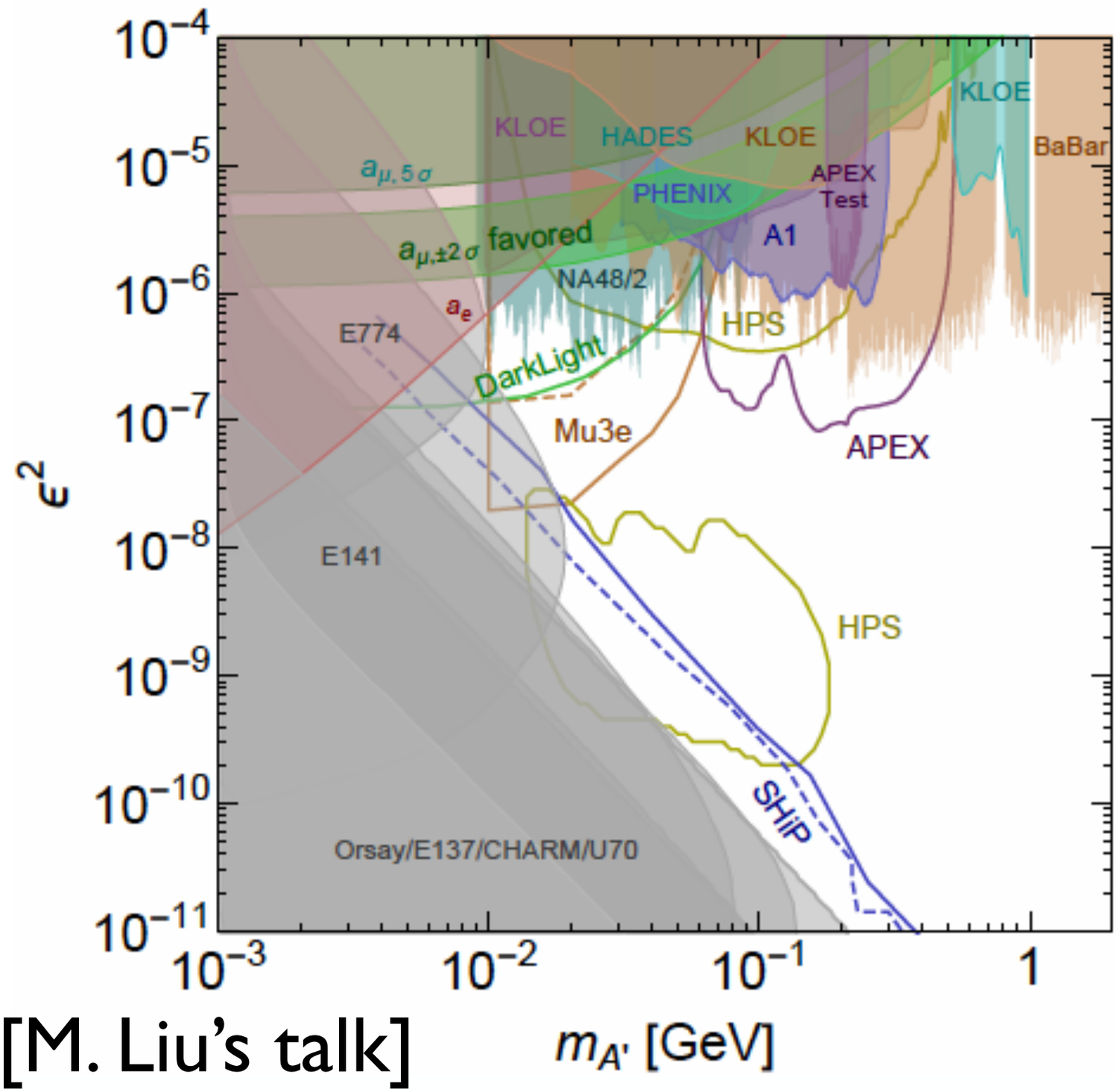
Enter the dark photon A´ and its field strength tensor $V^{\mu\nu}$

$$\mathcal{L}_{A'} = \frac{1}{2}\kappa B^{\mu\nu} V_{\mu\nu} - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'^{\mu} A'_{\mu}$$

→ Note "kinetic mixing" of visible & hidden sectors

Dark Photon Decays to Visibles (Only)

Exclude a "dark" explanation of the muon g-2 anomaly



But this may only speak to our assumptions…

[M. Liu's talk]

Vector Portals

Need not be...

mediated by dark photons...

nor have gauge bosons that decay to visible particles only...

nor even be vector-like...

How might one distinguish the possibilities experimentally?

Gauge Portals to a Hidden Sector

There are many possible vector portals – but fewer are anomaly free

Typical to consider Abelian groups as $F^{\mu\nu}$ is gauge invariant

- $U(1)_Y$ or $U(1)_{em}$: enter the dark photon and A-A' mixing [Holdom, 1986…]
- $U(1)_Y$ with an extended Higgs sector : now mixing with both the photon and Z occurs – enter the Z_d [Davoudiasl, Lee, Marciano, 2014]
- $U(1)_B$ but not anomaly free [Nelson & Tetradis, 1989; Tulin, 2014]
- U(1)x with particular couplings (leptophobic Z') [Dobrescu & Frugiuele, 2014]

$$\mathcal{L}_B = \frac{1}{3}\bar{q}\gamma^\mu q B_\mu$$

- $U(1)_{\mu\text{-}\tau}$ [Altsmannshofer, Gori, Pospelov, & Yavin, 2014]

Gauge Theories of the Hidden Sector

"Vector" portals need not be vector-like

For the dark photon...

$$\mathcal{L}_{A'} = \frac{1}{2}\kappa B^{\mu\nu} V_{\mu\nu} - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'^{\mu} A'_{\mu}$$

Diagonalization and field definition yields

$$A^\mu \longrightarrow A^\mu - \varepsilon A'^\mu \text{ but } Z - A' \text{ mixing } \mathcal{O}(\varepsilon m_{A'}^2 / M_Z^2)$$

[Bjorken, Essig, Schuster, and Toro, 2009...]

Thus the A' couples to SM fermions

Now with an extended Higgs sector…

$$\mathcal{L}_{\text{darkZ}} = -(\varepsilon e J^\mu_{\text{em}} + \varepsilon_Z \frac{g}{2\cos\theta_W} J^\mu_{\text{NC}}) Z_{d\,\mu}$$

[Davoudiasl, Lee, Marciano, 2014]

Higher-Mass Dimension Portals

Such portals can include QCD interactions

Enter non-Abelian portals... could BSM physics be hidden under non-perturbative QCD?

[Okun, 1980; Gupta & Quinn, 1982; Kang & Luty, 2009; Harnik, Kribs, & Martin, 2011...]

There are many possible connectors....

[Batell, Pospelov, and Ritz, 2009; Baumgart et al., 2009]

$$\frac{\kappa'}{\Lambda^2}\left(\bar{q}_{L(R)}\gamma_\mu q_{L(R)}\right)\left(\bar{q}_{L(R)}\gamma^\mu q_{L(R)}\right)$$

$$\frac{\kappa'}{\Lambda^2}\mathrm{tr}(\Phi^a F^a_{\mu\nu})\mathrm{tr}(\tilde{\Phi}^b \tilde{F}^b_{\mu\nu})$$

"hidden valley"

$$\mathrm{tr}(F^{a\,\mu\nu} F^a_{\mu\nu})\mathrm{tr}(\tilde{F}^{b\,\mu\nu} \tilde{F}^b_{\mu\nu})$$

[Strassler & Zurek, 2007]

"QCD" Portals

Model their emergence at low energy with a hadronic kinetic mixing model "vector meson dominance"

[SG & He, 2013]

$$\mathcal{L}_{\rm mix} = -\frac{1}{4}\rho^a_{\mu\nu}\rho^{a\,\mu\nu} - \frac{1}{4}\rho'^{\,a}_{\mu\nu}\rho'^{\,a\,\mu\nu} + \frac{\varepsilon}{2}\rho^a_{\mu\nu}\rho'^{\,a\,\mu\nu}$$
$$+\frac{m^2_\rho}{2}\rho^a_\mu\rho^{a\,\mu} + \frac{m^2_{\rho'}}{2}\rho'^{\,a}_\mu\rho'^{\,a\,\mu} + \kappa_\rho J^{\mu\,a}\rho^a_\mu$$

Diagonalization and field definition yields

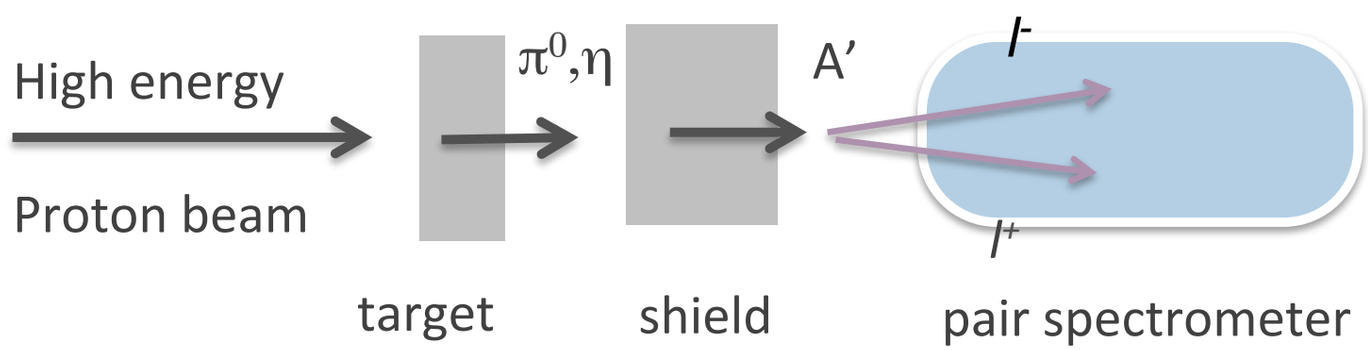
$$\rho^a_\mu \to \rho^a_\mu - \varepsilon\rho'^a_\mu$$

Thus a hidden non-Abelian sector can emerge through a weakly coupled ρ´

Distinguishing the Possibilities

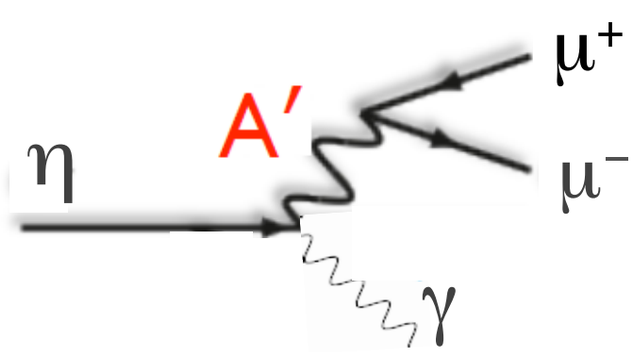
Enter, e.g., SeaQuest/E906/E1067 at Fermilab

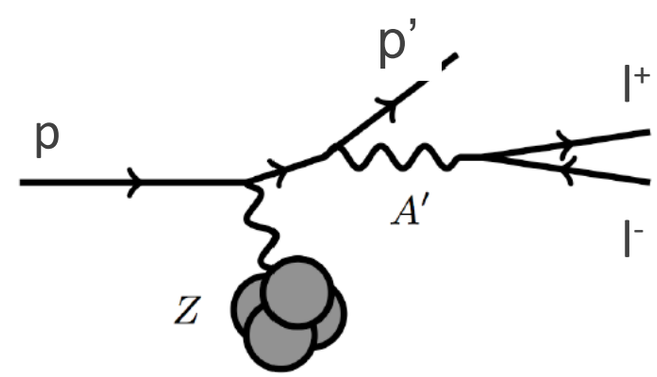
LOI, 2015; Liu & Reimer co-spokespersons



SeaQuest E906

Offering distinct windows on vector portals & more





Radiative π^0, η decays

[Batell, Pospelov, and Ritz, 2009; Gninenko, 2011]

Proton bremsstrahlung

[Bluemlein and Brunner, 2011 & 2013]

[SG, Holt, Tadepalli, 2015]

Also in Drell-Yan...

Dark Photon Parameter Space is Vast

SeaQuest/E906 is running now

N.B.
^{8}Be decay anomaly:
Krasznahorkay et al.
PRL (2016)
J. Feng et al.,
arXiv:1604.07411

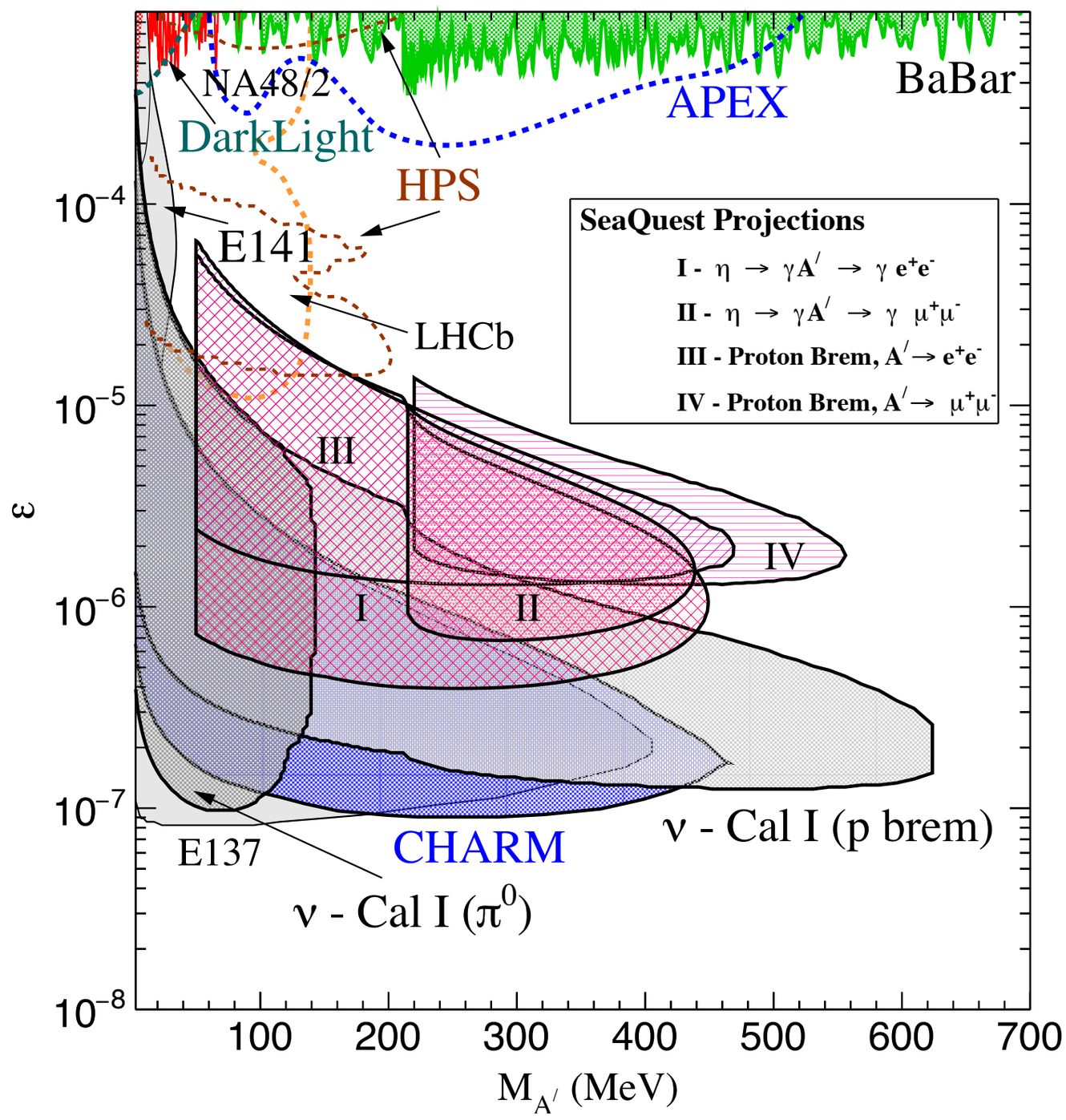
[P. Tanedo's talk]

[B. Fornal's talk]

Can test with…

$\eta \to \gamma e^+ e^-$

studies & more…



[SG, Holt, Tadepalli, 2015]

e^+e^- &
$\pi^+\pi^-$
final states
possible
after
Phase II
upgrade

[K. Liu's talk]

Distinguishing the Possibilities

Experimental handles include...

different detected final states

e vs. μ vs. π

utilization of polarized proton beams

vis-a-vis p bremstrahlung mechanism

Broader Prospects: Impact of Polarized Proton Beams

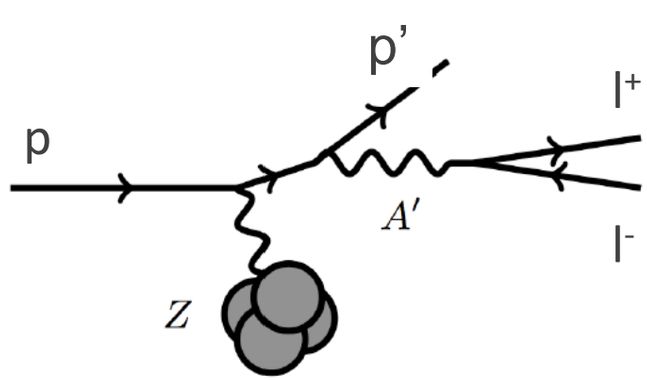
Searches for a dark photon also limit other possibilities

Parity violation studies could prove key

$$\mathcal{L}_{\mathrm{darkZ}} = -(\varepsilon e J^{\mu}_{\mathrm{em}} + \varepsilon_Z \frac{g}{2\cos\theta_W} J^{\mu}_{\mathrm{NC}}) Z_{d\,\mu}$$

[Davoudiasl, Lee, Marciano, 2014]

If the hidden gauge boson is a dark Z, then ...



The dilepton yield can change with proton polarization: the asymmetry can be O(1)!

Polarized proton beams under R&D at FNAL

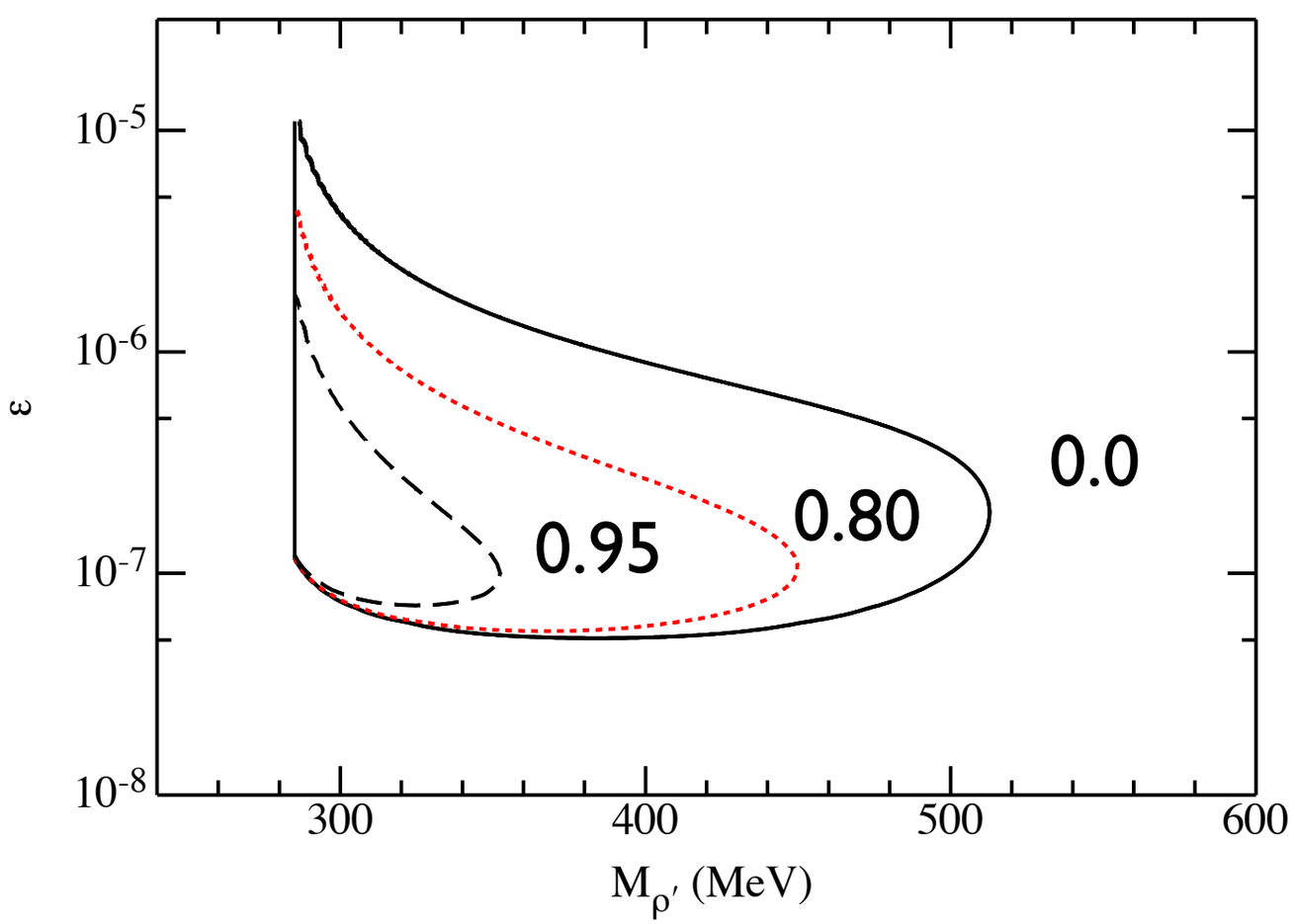
Broader Prospects

Assuming hidden vector forces...

Searches for leptophobic gauge bosons

These can be generated in many ways....
Note through $U(1)_B$ and more

$\rho - \rho'$ mixing

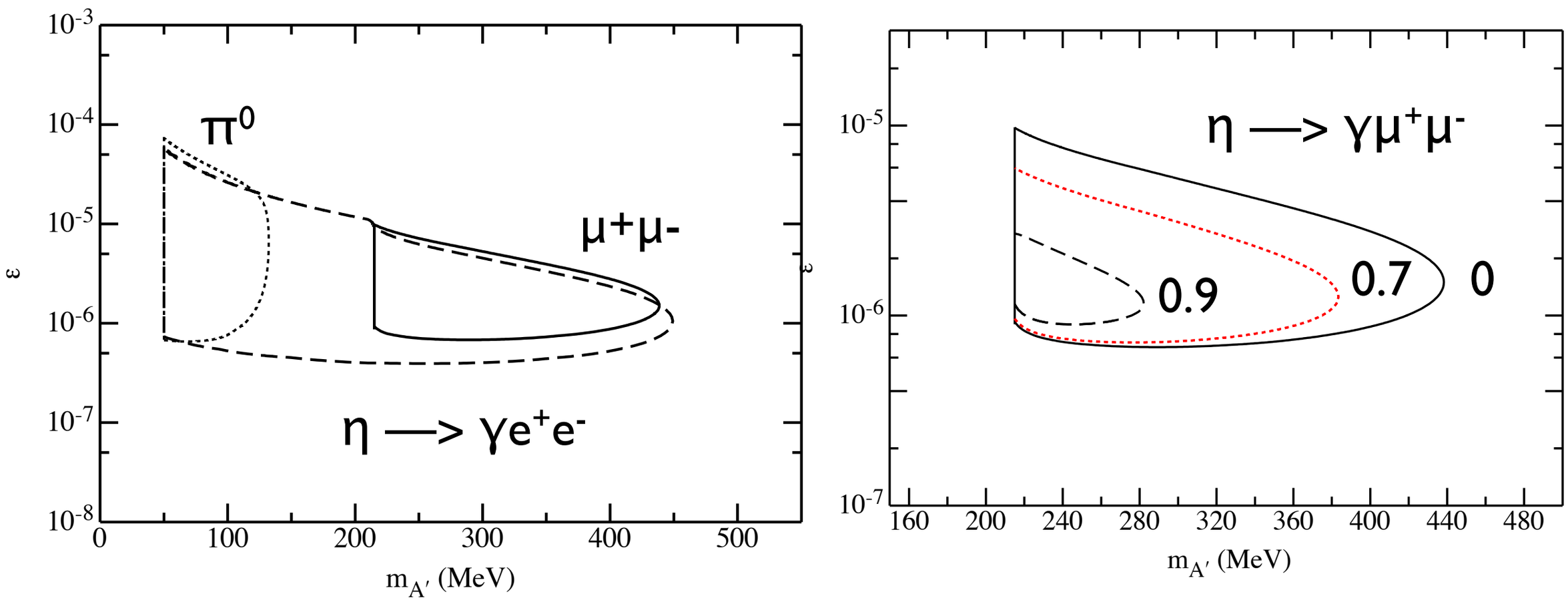


These can be probed at SeaQuest through $\pi^+\pi^-$ detection

Parameter Space is Vast

Note erosion of constraints through nonzero partial width to hidden sector final states

10 event contours



Constraints still possible even if only 10% can be seen!

Summary

Have considered the possibility of dark gauge forces mediated by a light [MeV-GeV] hidden sector

Such "long distance" effects would speak to the nature of particle dark matter

Theories of weakly coupled hidden sectors continue to evolve & are testable

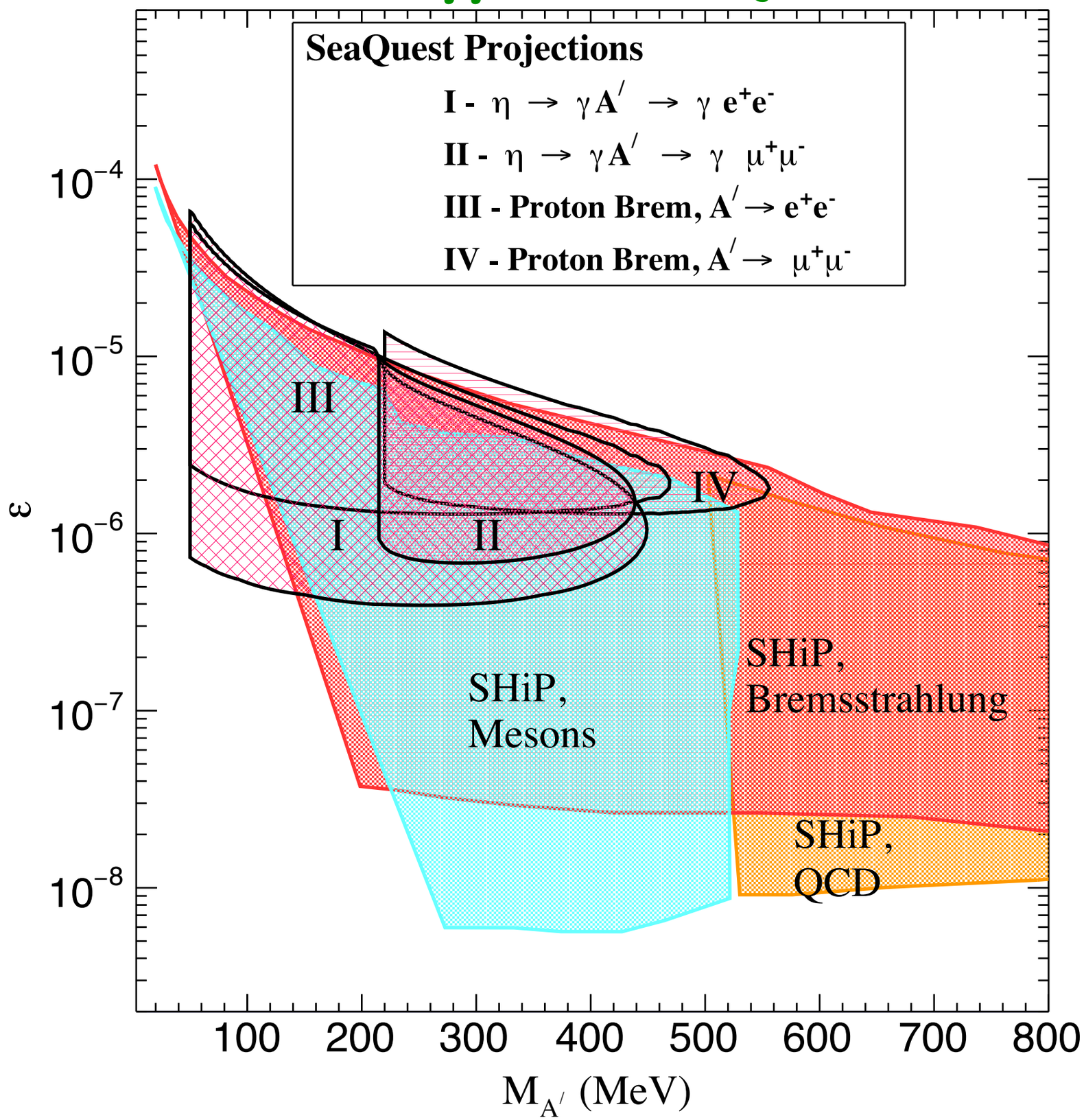
Studies at SeaQuest E906 /E1067 can open new windows on new physics…

- to possible parity-violating couplings
- to "strongly" weakly coupled hidden sectors

Backup Slides

Dark Photons: SeaQuest vs. SHiP

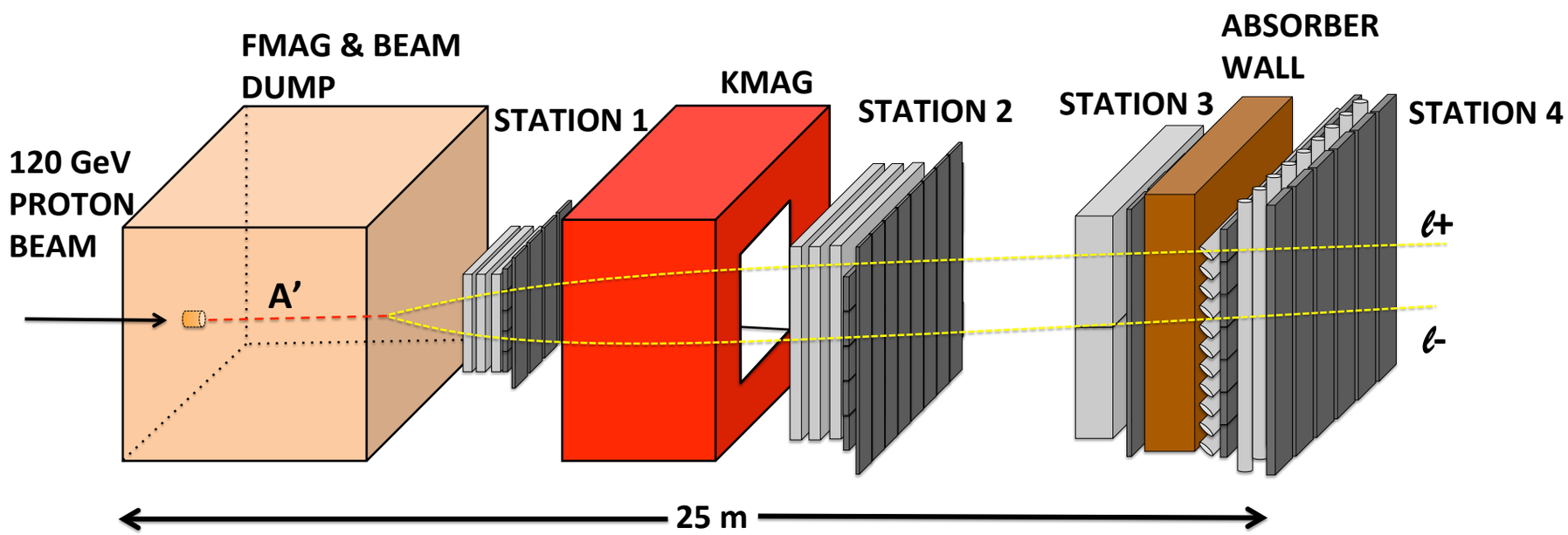
"apples & oranges"



5 yr exposure
400 GeV beam
opt. detectors
(SHiP)
vs.
1 yr exposure
120 GeV beam
SeaQuest spect.

Sharper constraints are possible!

Dark photon visibility estimates



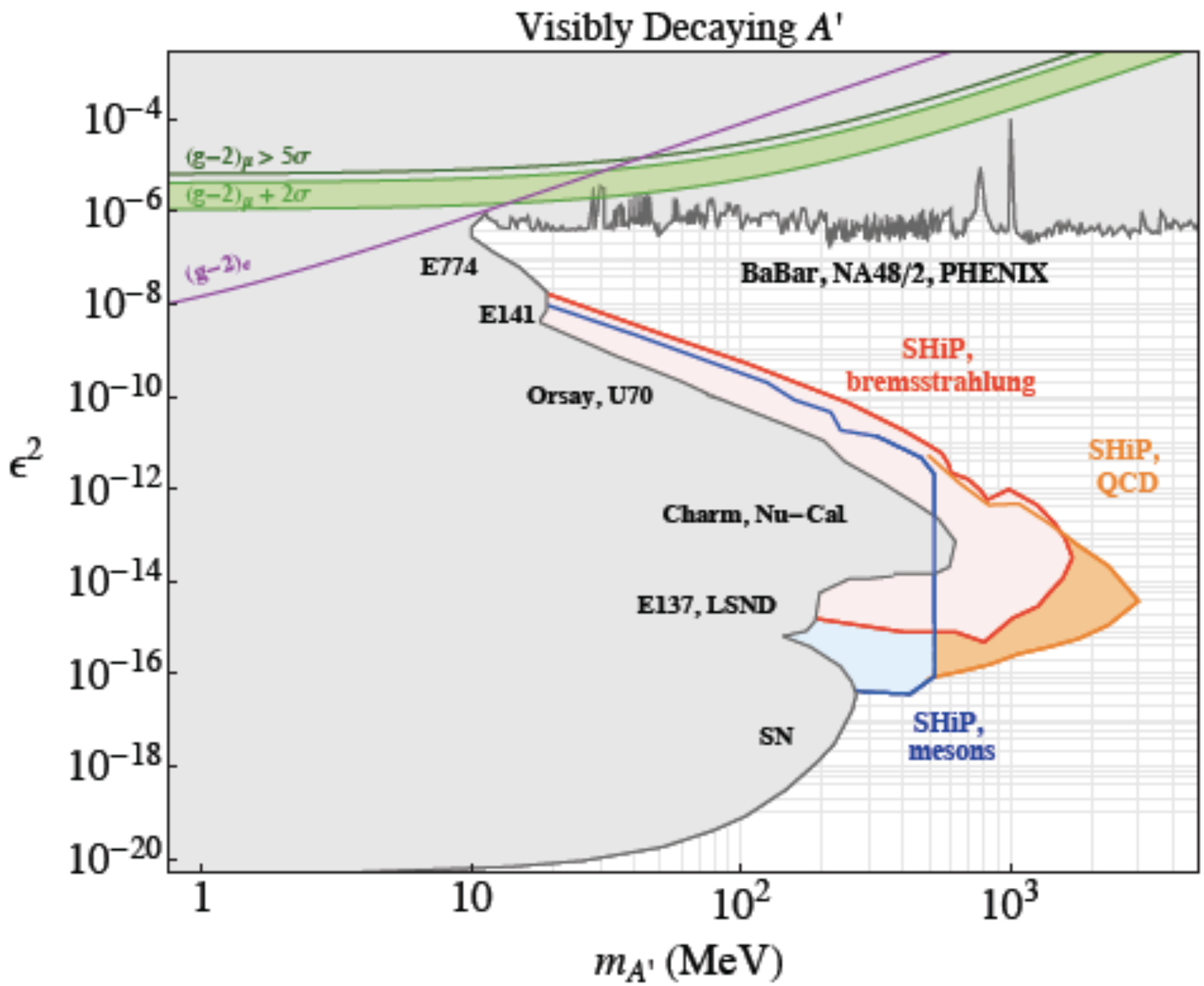
Utilize GEANT4 for eta & pion production yields

$$N_{\rm dec} = N_0 \mathcal{B}(A' \to \ell^+\ell^-) \exp\left(-\frac{l_{\rm dump}}{c\tau_{A'}}\frac{m_{A'}}{|\vec{p}_{A'}|}\right) \times \left[1 - \exp\left(-\frac{l_{\rm fid}}{c\tau_{A'}}\frac{m_{A'}}{|\vec{p}_{A'}|}\right)\right],$$

[Bluemlein and Brunner, 2011 & 2013]

Dark Photons at SHiP (CERN)

SeaQuest Projections are competitive



[Alekhin et al., arXiv: 1504.04855]

π and η radiative decays

Note decay chains sensitive to new dark gauge bosons

A′ search can include broader possibilities

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

$$\eta \to \gamma A' \to \gamma \ell^+ \ell^- \quad \text{with} \quad \ell \in e, \mu$$

$$\eta \to \gamma A' \to \gamma \pi^+ \pi^-$$

Could also search for a dark Higgs or particularly for a dark Z

$$\eta \to \pi^0 h_d \to \pi^0 \pi^+ \pi^-$$

$$K^\pm \to \pi^\pm Z_d \to \pi^\pm \ell^+ \ell^-$$

[Leutwyler & Shifman, 1990; Donoghue, Gasser, Leutwyler, 1990]

[Davoudiasl, Lee, Marciano, 2014]

π and η radiative decays

Note radiative decays are controlled by the axial anomaly in QCD

Validate procedures through cf. with SM partial widths; transitions form factors are important! [Masjuan, 2012...]

$$\Gamma(\pi^0 \to \gamma A' \to \gamma e^+ e^-) = \Gamma_0 \int_{r^2}^{1} dx \, \frac{\alpha}{\pi} \, \varepsilon^4 |f(1,0,x)|^2$$

$$\times \frac{2(1-x)^3 x}{\left((x - x_{A'})^2 + x_{A'} \tilde{\Gamma}^2_{A'}\right)} \beta \left(1 + \frac{r^2}{2x}\right)$$

$$x_{A'} = m^2_{A'}/M^2_\pi$$

$$\tilde{\Gamma}_{A'} = \Gamma_{A'}/M_\pi$$

We use the narrow width approximation throughout:

$$\Gamma(\pi^0 \to \gamma A' \to \gamma e^+ e^-) = |f(1,0,x_{A'})|^2 \, \Gamma(\pi^0 \to \gamma A') \, \mathcal{B}(A' \to e^+ e^-)$$