The Theory and Experimental Frontier of Dark Forces at the GeV Scale

Aspen Particle Physics Conference, January 2010

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Dark Forces at the GeV Scale

- Theory of New Vector Bosons (and hints from dark matter)
- e+e- Collider Searches (Babar, Belle, KLOE)
- Fixed-Target Experiments (e.g. @ JLab)

Is there structure beneath the Planck scale beyond known interactions?

Sector with new gauge interactions

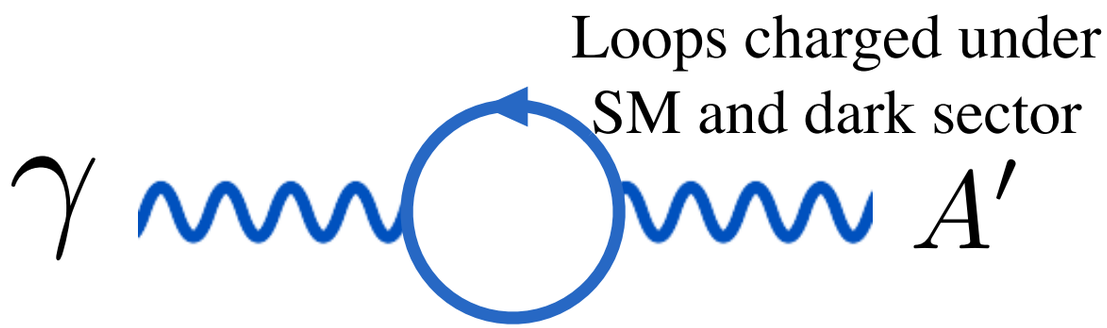
Standard Model gauge symmetries largely forbid couplings to other sectors

We nonetheless suspect that new sectors exist - SUSY breaking sectors...etc

A Simple U(1) Example

Gauge kinetic mixing is a "portal" that can link the Standard Model to new dark forces

$$\delta L = \epsilon F_Y F_{A'}$$



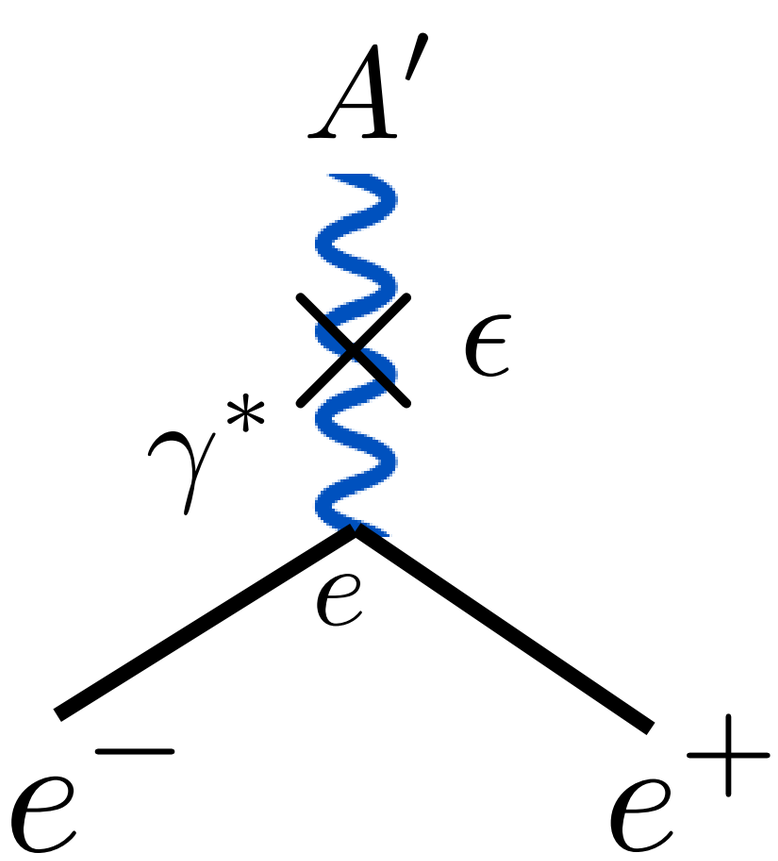
GUT or Planck scale quantum corrections

[Holdom '86]

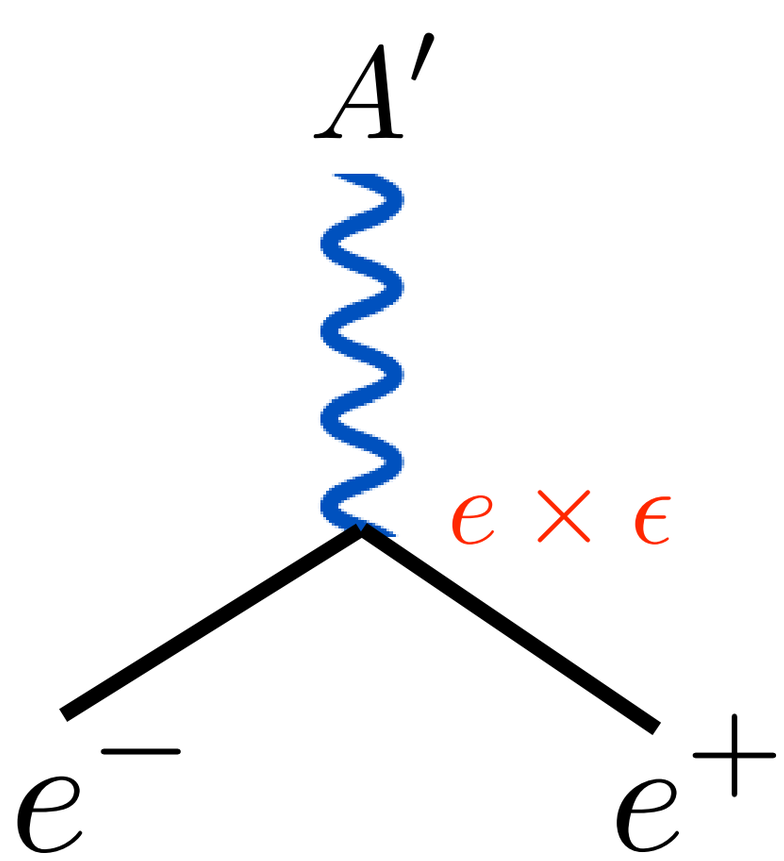
$$\epsilon \approx \frac{g_D g_Y}{16\pi^2} \sum_i q_{D,i} Y_i \ \ln \frac{\Lambda^2}{\mu_i^2} \ \sim 10^{-4} - 10^{-3}$$

Ordinary Matter and Dark Forces

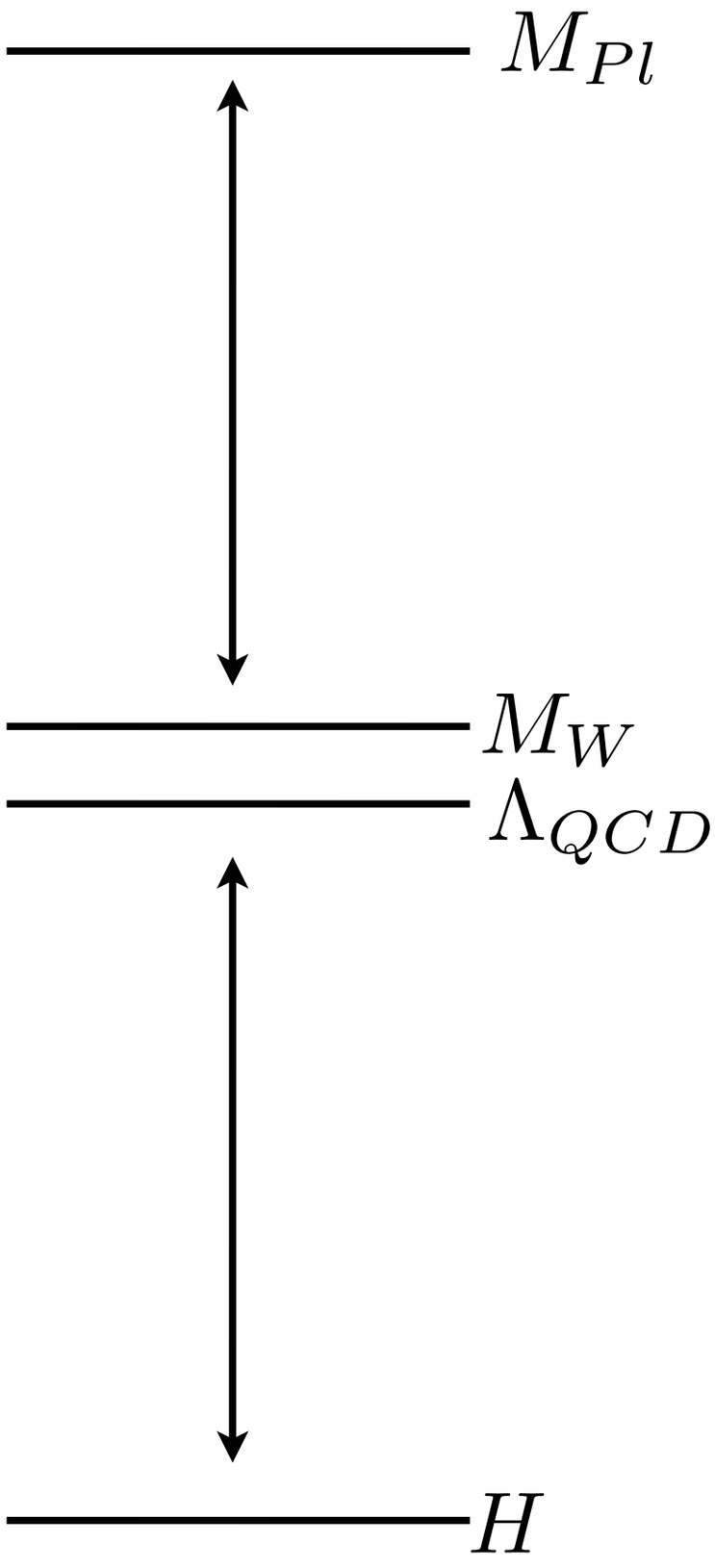
Photon mixing with massive A' is equivalent to electrically charged matter acquiring a milli-charge under the A'



(equivalent)



Mass Scales



Weak coupling to dark sector is natural,
but what about the mass scale?

GUT or Planck scale?

Nearly massless or massless?

Anywhere (technicolor like dark sector) ?

New U(1) Near The Weak-Scale

Assume that "weak-scale" SUSY exists, and couple the Standard Model to a dark sector via kinetic mixing.

Supersymmetric kinetic mixing:

$$\mathcal{L} \supset \int d^2\theta \frac{\epsilon}{2} W_Y^\alpha W_{A'\alpha} + \text{h.c.}$$

[Dienes, Kolda, March-Russell]

Dark sector matter:

$$W = \mu_D H_+ H_- \qquad \text{or} \qquad W = \lambda S H_+ H_-$$

[Cheung, Ruderman, Wang, Yavin; Katz and Sundrum; Morrissey, Poland, Zurek]

New U(1) Near The Weak-Scale

Dark U(1) and hypercharge U(1) D-terms mix

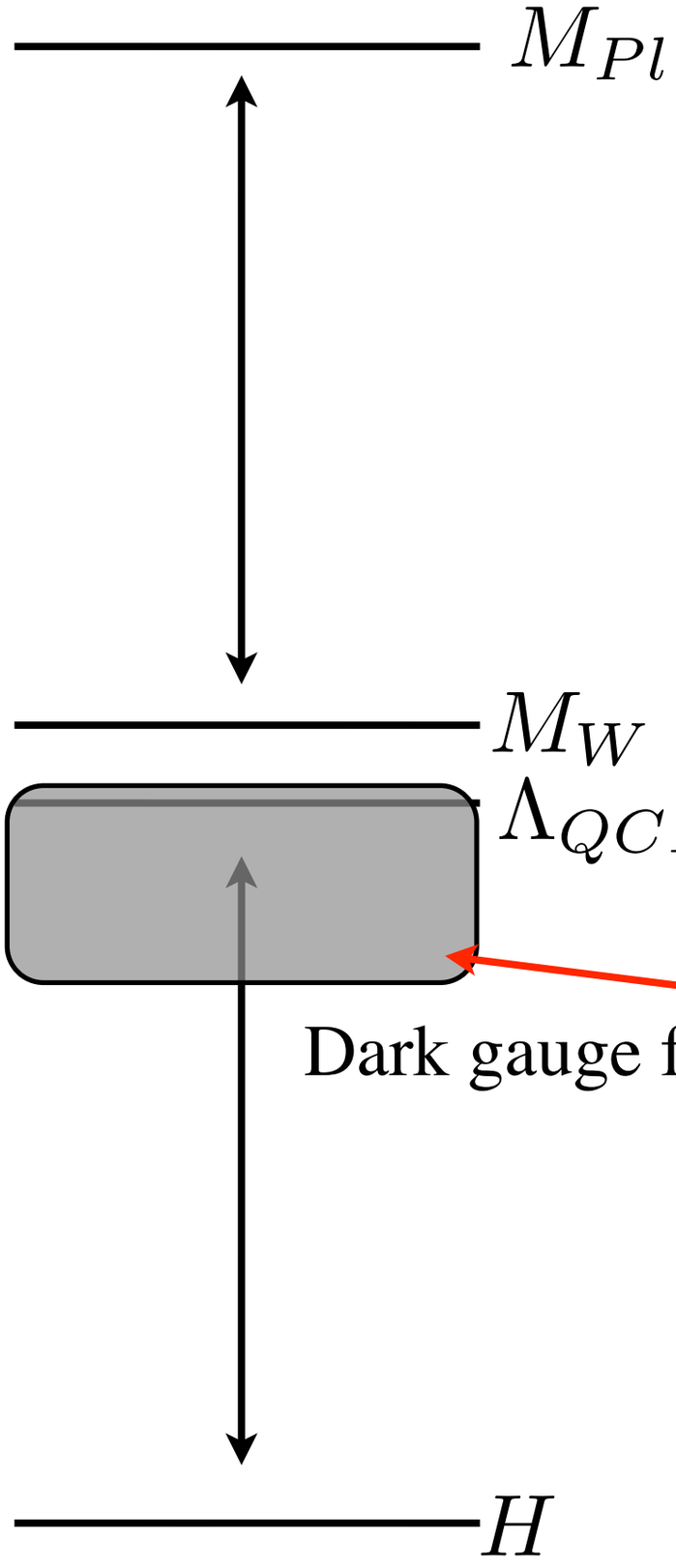
Dark Sector D-term Potential:

$$V_D \sim g_D^2(|\phi_D|^2 - \frac{\epsilon g_Y}{g_D}|H_{SM}|^2)^2$$

Electro-weak symmetry breaking triggers dark U(1) breaking:

$$m_{A'}^2 \sim \epsilon \frac{g_D}{g_Y} M_W^2 \lesssim (1\mathrm{GeV})^2$$

New Dark Gauge Forces - Where to Look?



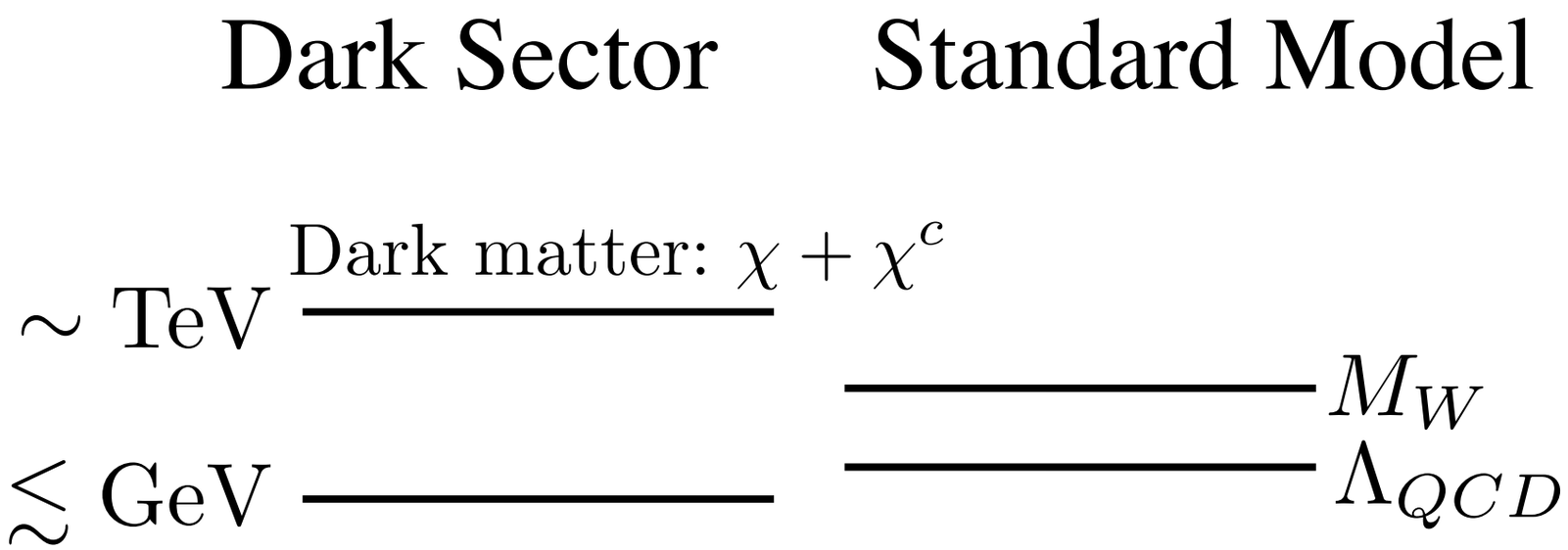
Theoretical Region of Interest:

New weakly coupled gauge interactions with mass scale beneath the weak scale

A good place to explore!

What if dark matter belongs to a dark sector

Suppose that dark matter is a TeV mass thermal relic charged under a dark U(1) that kinetically mixes with the photon



Existing astro/direct-detection anomalies, if true, provide evidence for this picture!

Striking cosmic ray signals!

[Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Cholis, Finkbeiner, Goodenough, Weiner; Pospelov & Ritz]

Inelastic dark matter scattering in direct detection experiments!

[Tucker-Smith and Weiner; Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Alves, Behbahani, PS, Wacker]

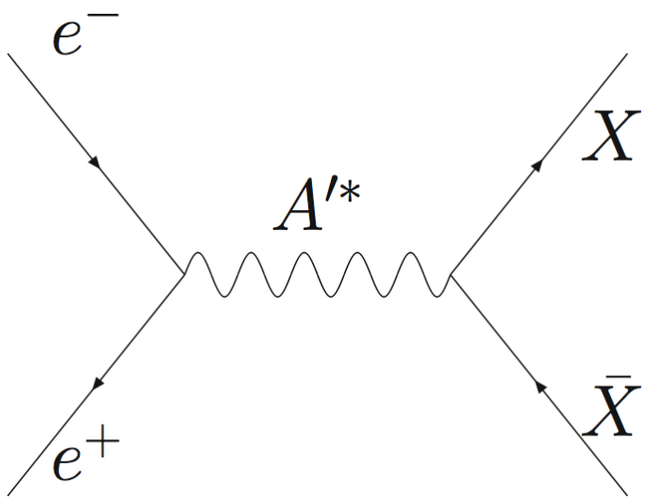
New Gauge Forces

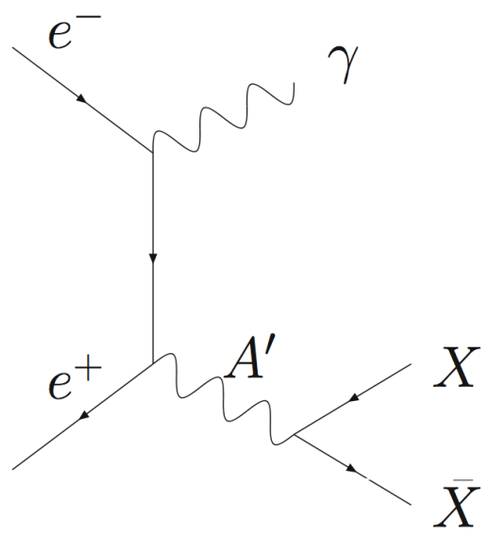
Are there new gauge forces? – an intriguing possibility

Do new gauge forces explain astro/direct-detection data?

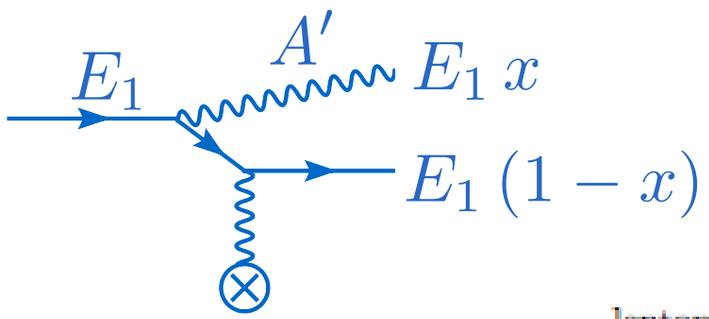
Insight from laboratory experiments needed!

Broad Array of Signatures and Searches!

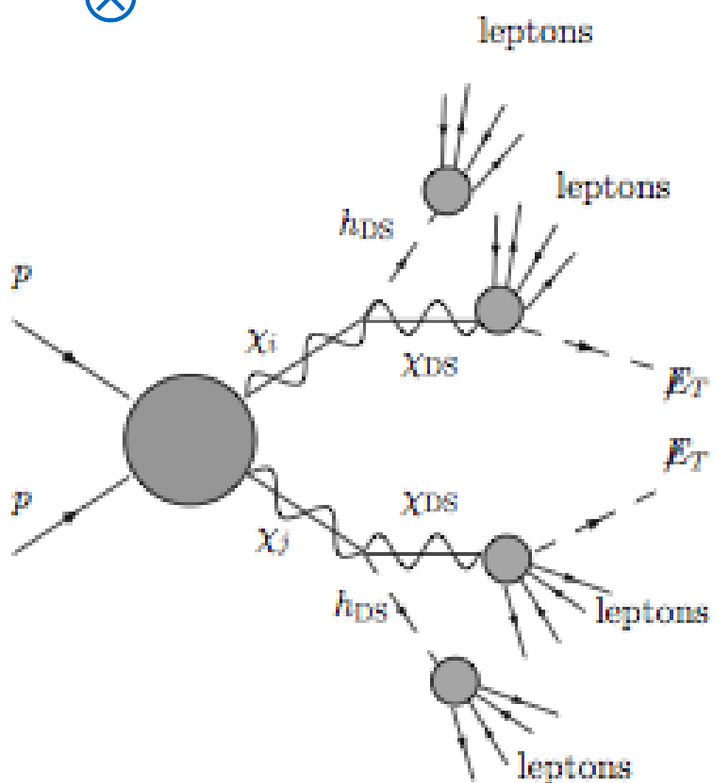




Colliding e+e-: On- or Off- shell A',
X=dark sector or leptons & pions
(BELLE, BaBar, BES-III,
KLOE, CLEO)



Fixed-Target: Electron or Proton collisions,
A' decays to di-lepton, pions, multiple channels
(Jefferson Lab (Hall A, Hall B/CLAS), SLAC,
MAMI (Mainz), ELSA (Bonn), XFEL (DESY),
COMPASS (CERN), FNAL, ...)



High Energy Hadron Colliders:
New heavy particles decaying into
dark sector (lepton jets) (CDF & D0)

(very interesting, but no time in this talk)

Dark Forces at the GeV Scale

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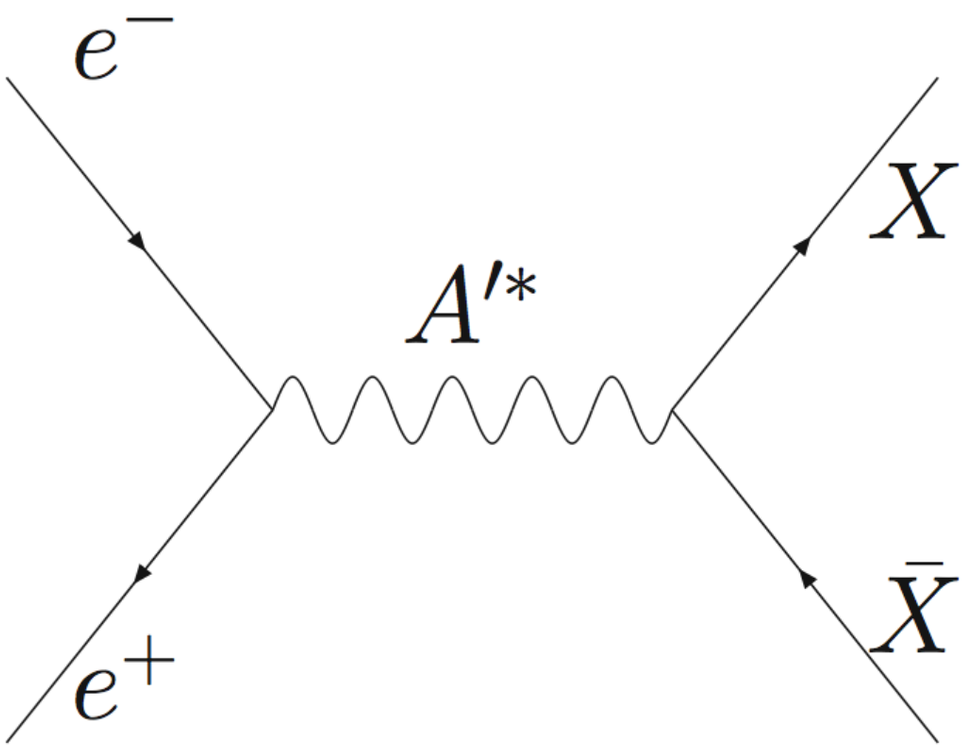
- Fixed-Target Experiments (e.g. @ JLab)

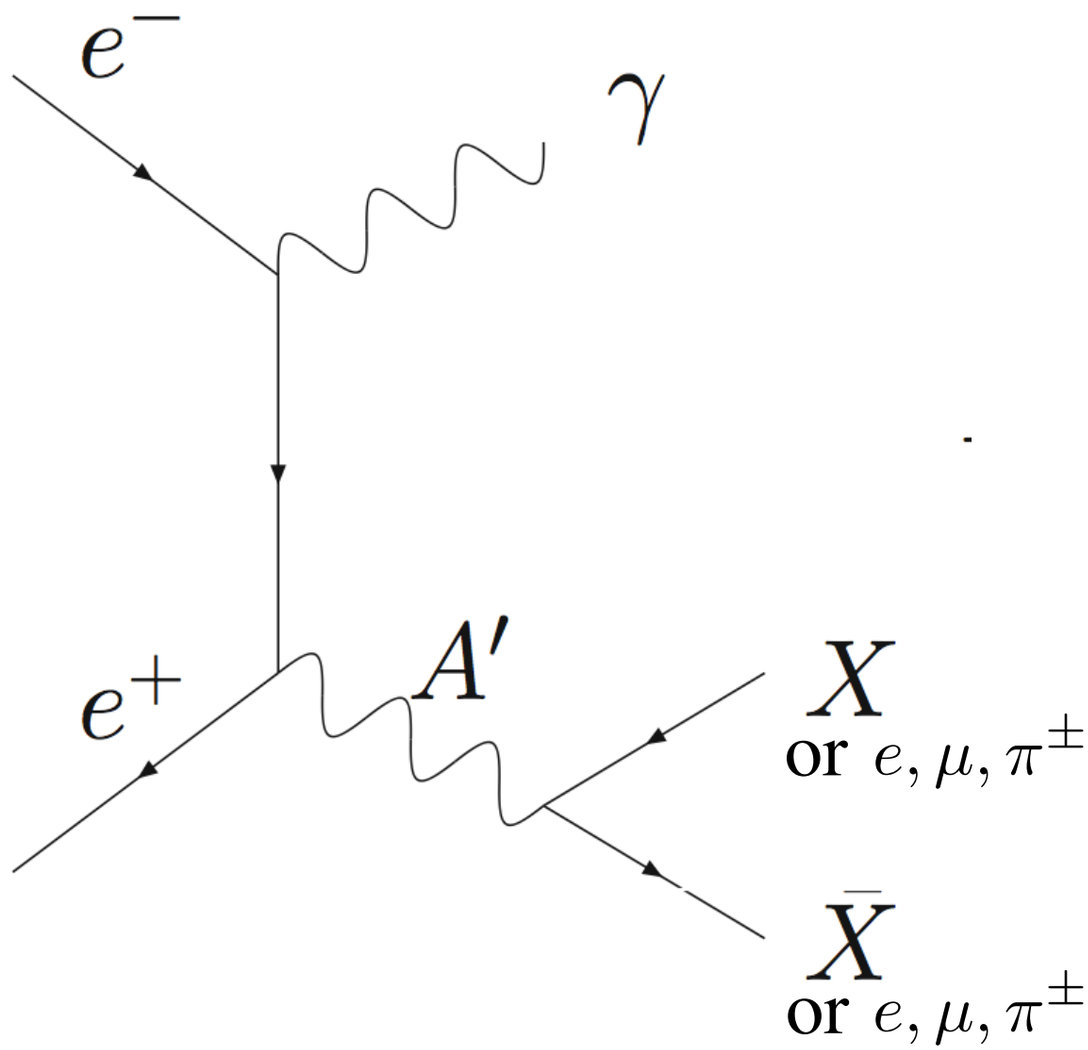
Dark Sector Collider Production

Off-Shell A′



X = dark sector particles

Radiative return



$$\sigma \propto \epsilon^2 / s \quad \rightarrow$$

High-luminosity
GeV-scale colliders

GeV-Scale Colliders

Figure of Merit is: $\mathcal{L}_{int}/s$

BELLE	BaBar	KLOE	CLEO-C	BES III
$\frac{725\ \text{fb}^{-1}}{(10.6\ \text{GeV})^2}$	$\frac{430\ \text{fb}^{-1}}{(10.6\ \text{GeV})^2}$	$\frac{2.5\ \text{fb}^{-1}}{(1\ \text{GeV})^2}$	$\frac{\approx 1\ \text{fb}^{-1}}{(4\ \text{GeV})^2}$	$\frac{??\ \text{fb}^{-1}}{(4\ \text{GeV})^2}$

No. of events for $\alpha_D = \alpha$, $\epsilon = 10^{-2}$ (approx):

170,000	100,000	50,000	1,000

Missing from numerical comparison:

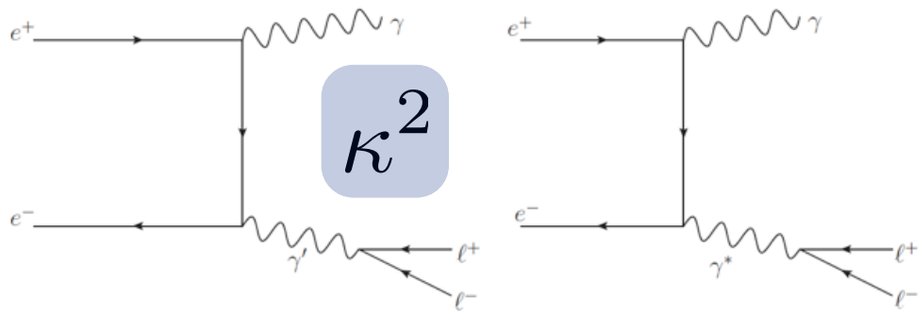
– accessible mass range

– kinematic acceptance & **visibility** of events

Broad range of searches needed

Final States (direct production)

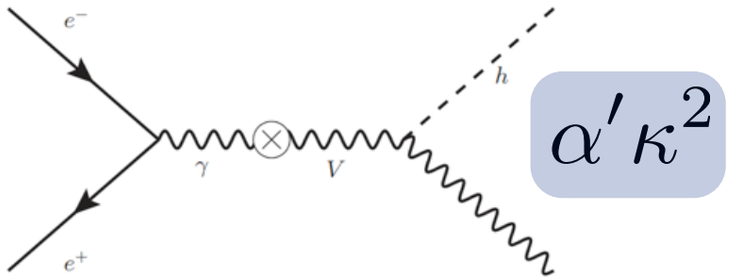
- "Generic": $e^+e^- \to \gamma l^+ l^-$



- BaBar [via Υ-decay search, H. Kim] ✓?
- Belle [Y. Kwon, J. Rorie]
- BES-III [H. Li, Y. Zheng]
- KLOE [F. Bossi]

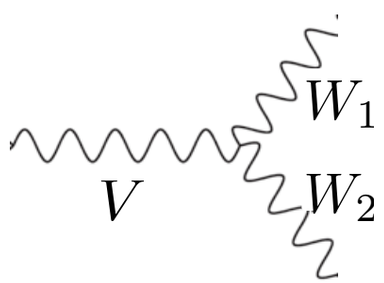
- "Generic + higgs": $e^+e^- \longrightarrow Vh' \longrightarrow 6l \ \ (or\ 2l + \not{E})$

Reach: $\epsilon \sim 10^{-3}$



- not yet!
  [interest from BaBar, Belle, BES-III, KLOE]

- "Nonabelian": $e^+e^- \to V^* \to 4l$



Reach: $\epsilon \sim 10^{-4}$

- BaBar [4l, M. Graham] ✓

Also: higher multiplicity (confining), 4l + $\not{E}_T$, ...

From e+e- working group summary (SLAC Dark Forces workshop)

Rare Meson Decays

Existing data sets provide sensitivity to $\epsilon \sim 10^{-3}$

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	BR($X \to Y + \gamma$)	BR($X \to Y + \ell^+\ell^-$)	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8a}	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

[Reece & Wang '09]

Good sensitivity in additional channels:

$\pi \to ee\gamma$ Sensitivity to $\epsilon \lesssim 10^{-3}$ (Babar, Belle, kTeV)

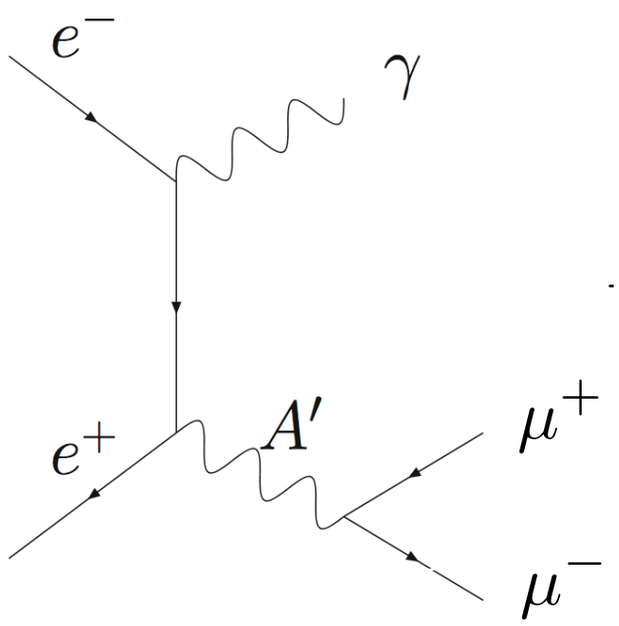
$J/\psi \to 6l$ Sensitivity to $\epsilon \sim 10^{-4} - 10^{-3}$ (BES-III in 1 year)

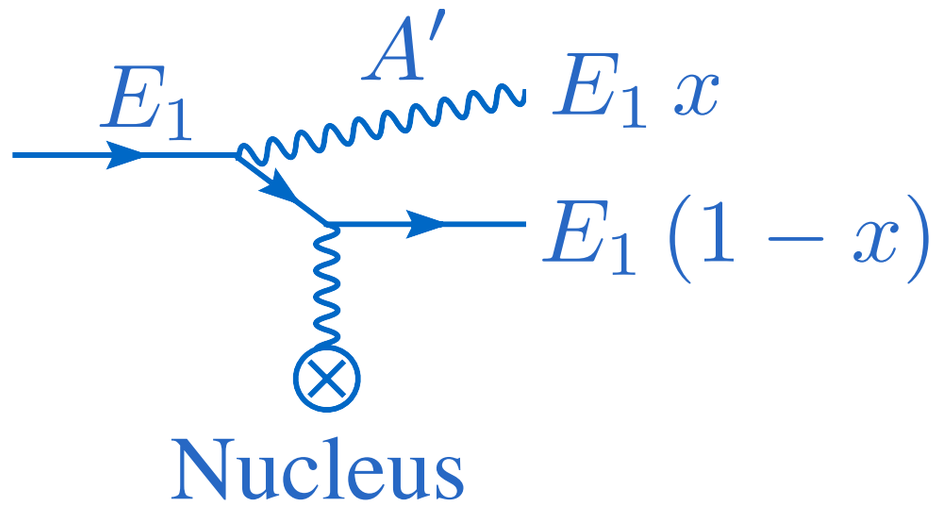
Searches ongoing...

Dark Forces at the GeV Scale

- Theory of New Vector Bosons (and hints from dark matter)
- e+e- Collider Searches (Babar, Belle, KLOE)
- Fixed-Target Experiments (e.g. @ JLab)

Collider vs. Fixed-Target





$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

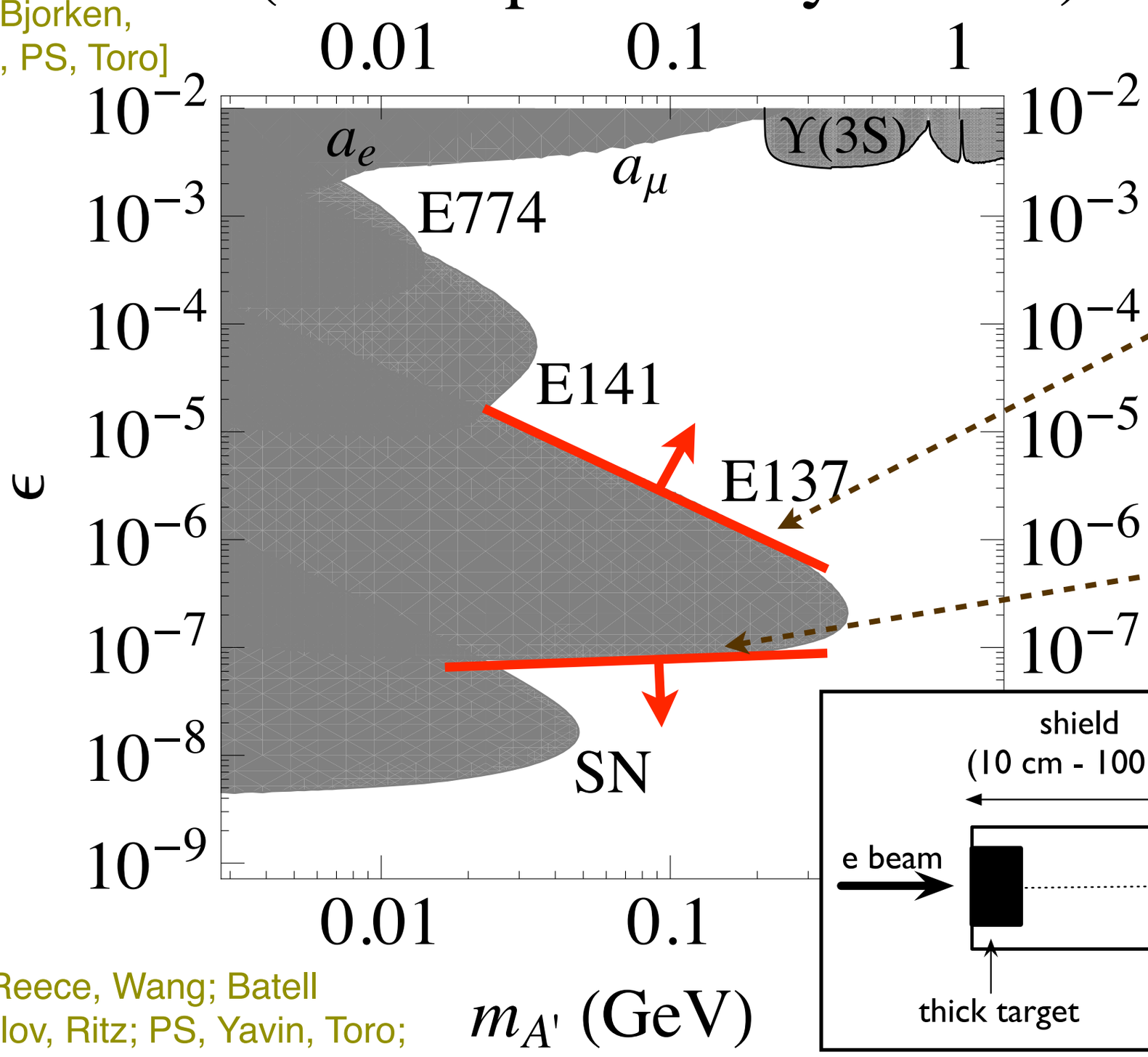
O(few) ab^{-1} per decade

O(few) ab^{-1} per day

Past Beam Dump Limits

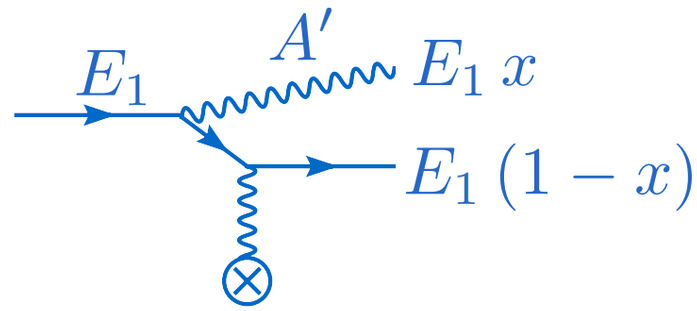
(A' di-lepton decay modes)

[see: Bjorken, Essig, PS, Toro]



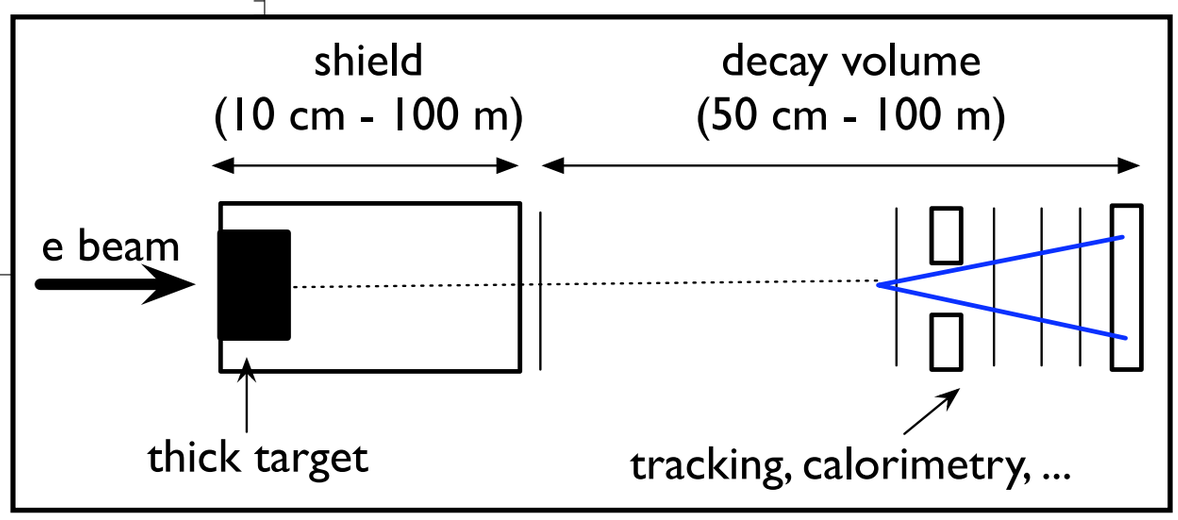
[see; Reece, Wang; Batell Pospelov, Ritz; PS, Yavin, Toro; Batell, Pospelov, Ritz, Shang for additional constraints]

Production Mode:



Lifetime small compared to shield length: decay products stop

Lifetime large compared to shield length, and lower cross-section: run out of statistics



SLAC E137: 10^{20} e^- (30 C) at 20 GeV, 200m shield

Approaches for New Experiments

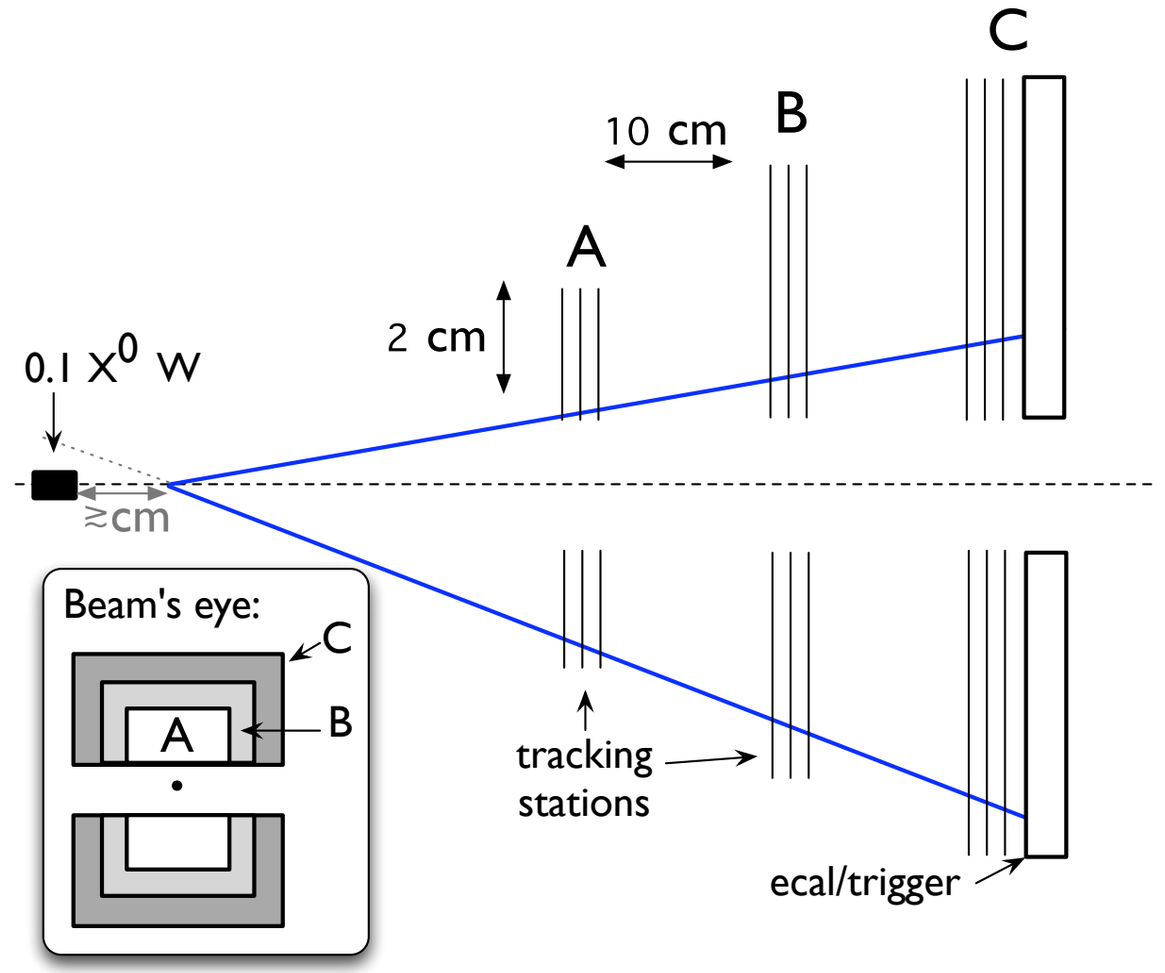
- Electron beam dump experiments set strongest bounds.
- To see higher ϵ, m_A (best DM region) need thinner target – now beam gets through, too!

- Two strategies:
  - Resonance Search
  - Vertex and recoil tagging

Features of conceptual design:

- Very good forward coverage
  (signal production is peaked forward)
- Fast trigger (high event rate)
- Fast detector and continuous beam
  (control coincidence backgrounds)
- 1% or better mass resolution
  (kinematic discrimination)
- Silicon good for fast precision tracking
  (use vertex discrimination)

Two-arm spectrometer



Small with variable geometry

JLab Hall A Experiment

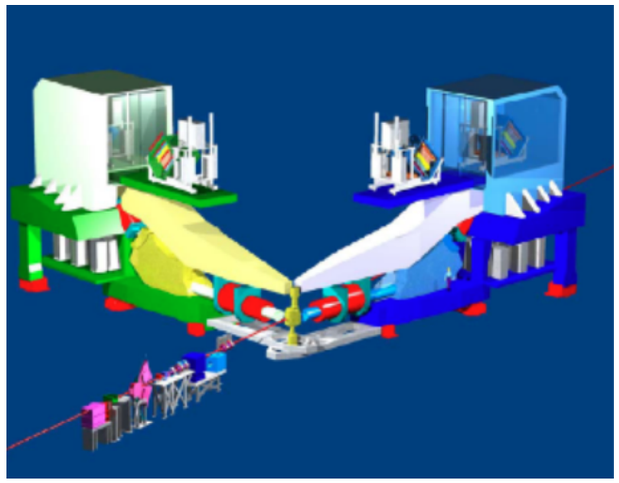
Proposal by:

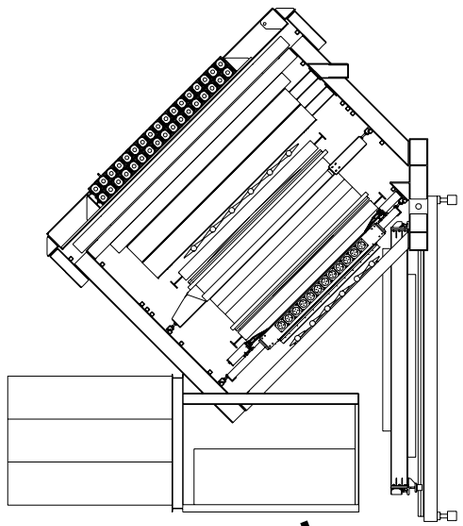
R. Essig, PS, N. Toro,

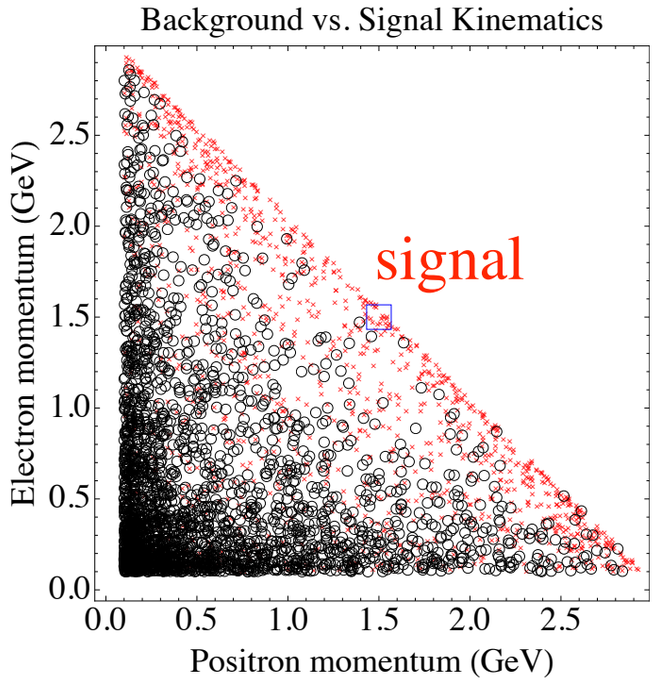
B. Wojtsekhowski (spokes)

~40 person collaboration

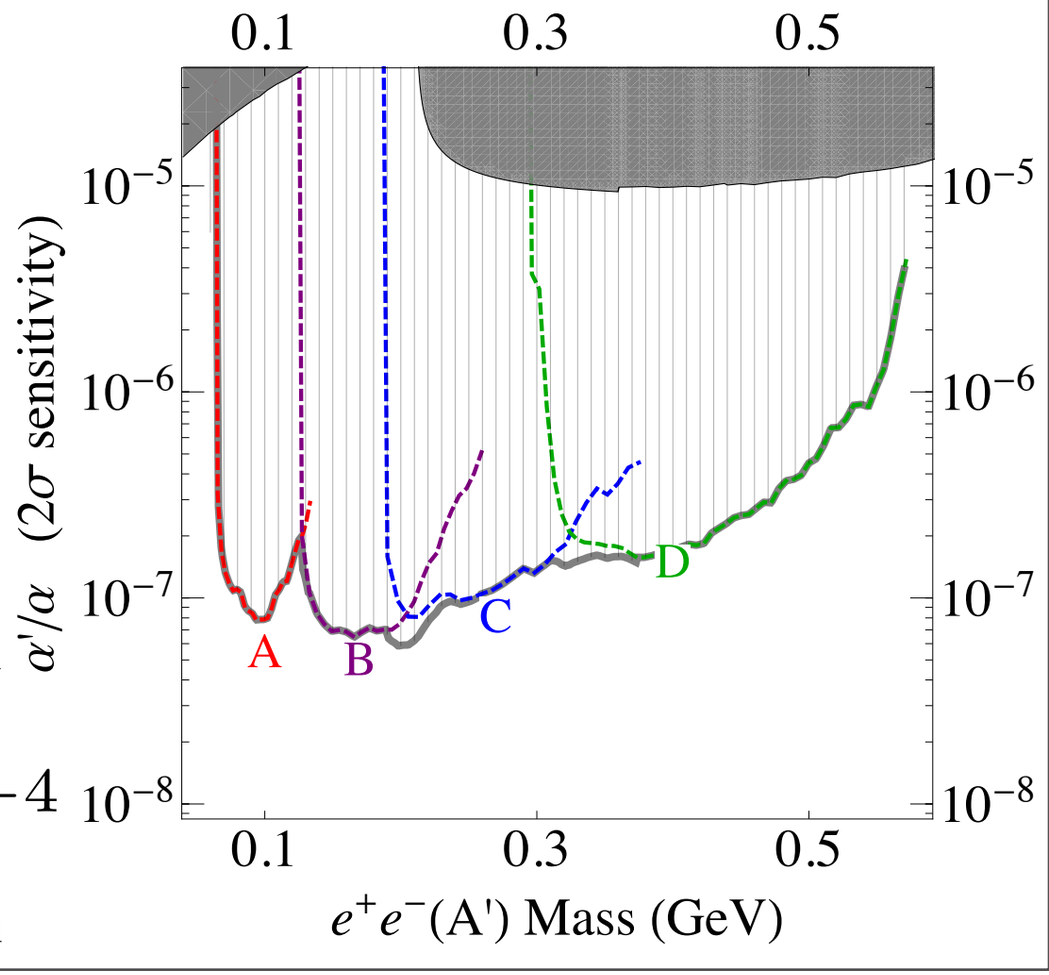
[see: arXiv 1001.2557]







Sensitivity of Early Run Plan



$$\epsilon_{sens} \sim (2-3) \times 10^{-4}$$

for the final reach

Heavy Photon Search Working Group

SLAC
R. Essig
C. Field
M. Graham
J. Jaros (Chair)
C. Kenney
T. Maruyama
K. Moffeit
A. Odian
R. Partridge
P. Schuster
J. Sheppard
C. Spencer
N. Toro

FNAL
M. Demarteau

JLab
P. Bosted
S. Stepanyan
L. Weinstein
B. Wojtsekhowski

U. Oregon
R. Frey

Developing: New experiment (parasitic) in JLab Hall B

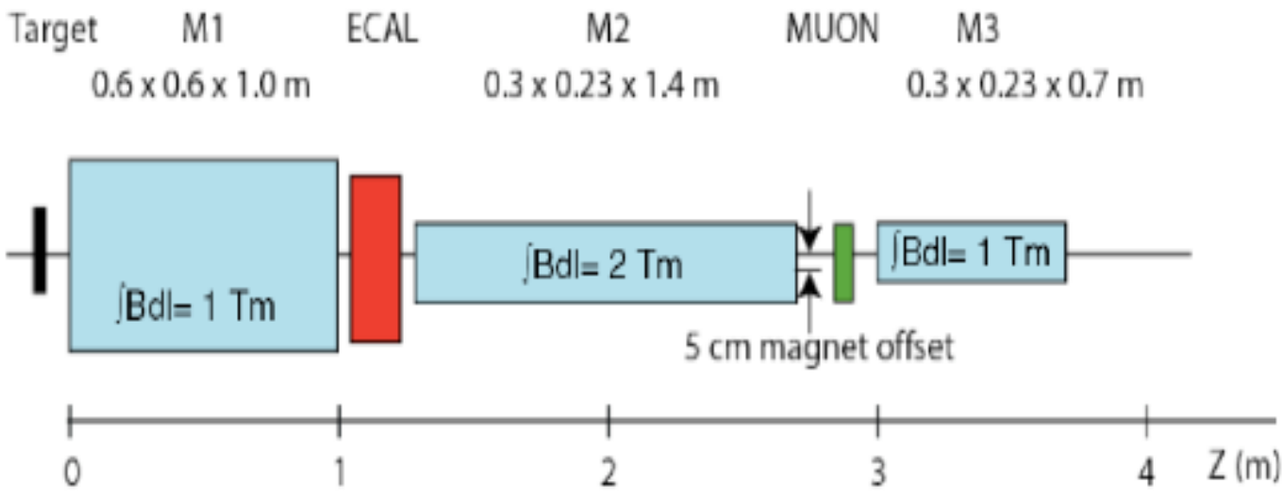
The main strategy is to exploit fast tracking using silicon

Optimizing singularly requires pushing the luminosity boundary

New Parasitic Experiment in JLab Hall B

- Introduction
- Available beam
- JLab Hall B "Photon Dump"
- Experimental Apparatus
- Simulation
- Backgrounds
  - Occupancy
  - Track multiplicity
- Performance
  - Acceptance
  - Mass resolution
  - Vertex resolution
- Experimental reach
- Conclusions

Experimental Apparatus

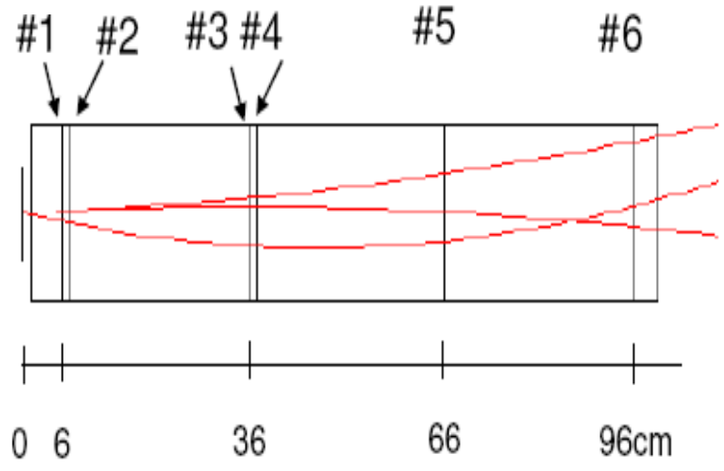


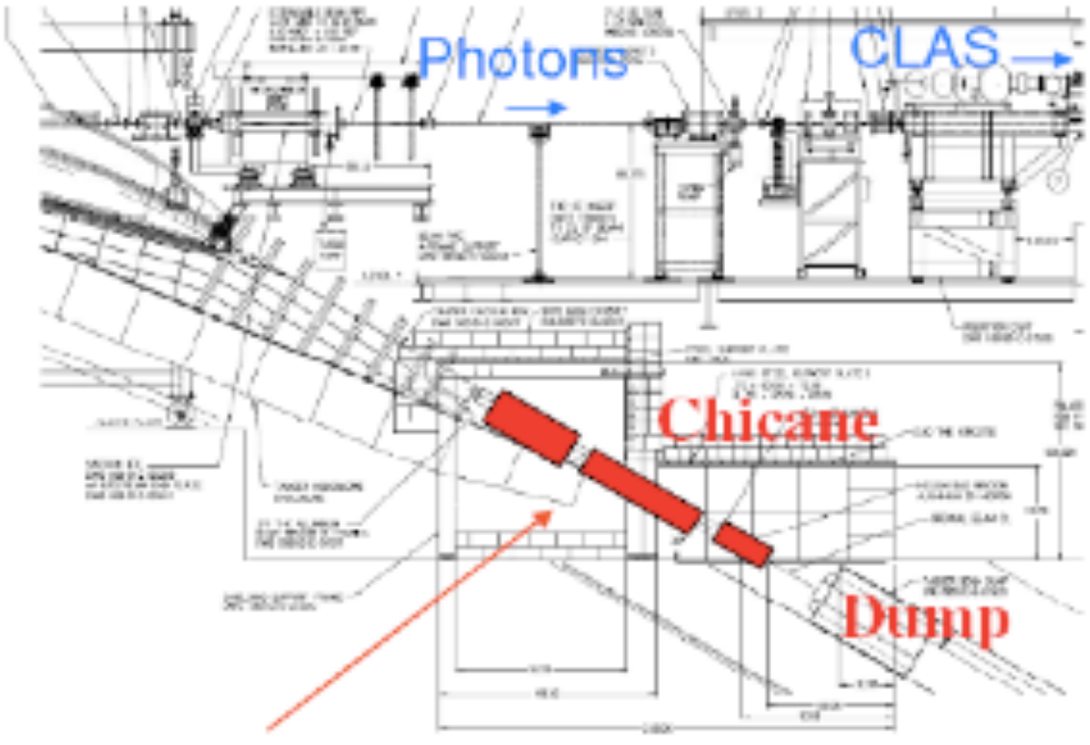
Beam:

- 6 GeV e- 100 nA

Target:

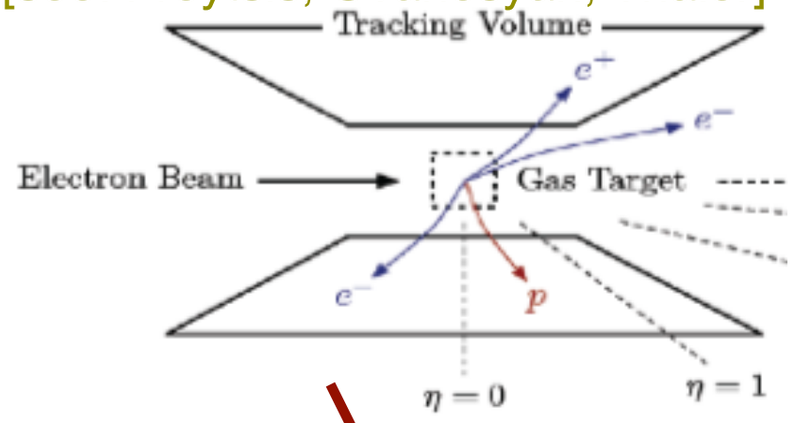
- 0.01 X_0 Tungsten



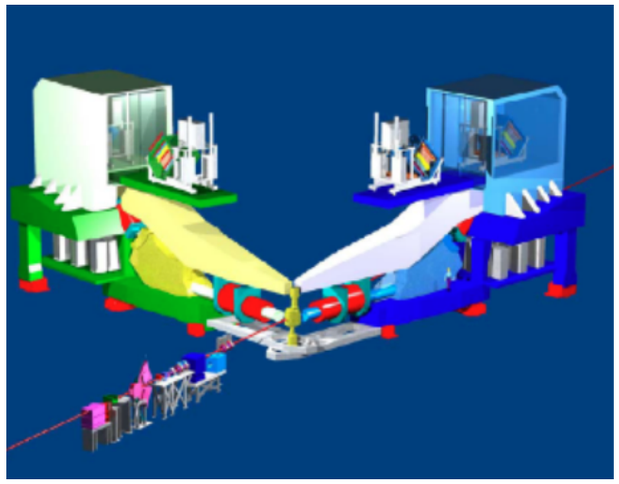


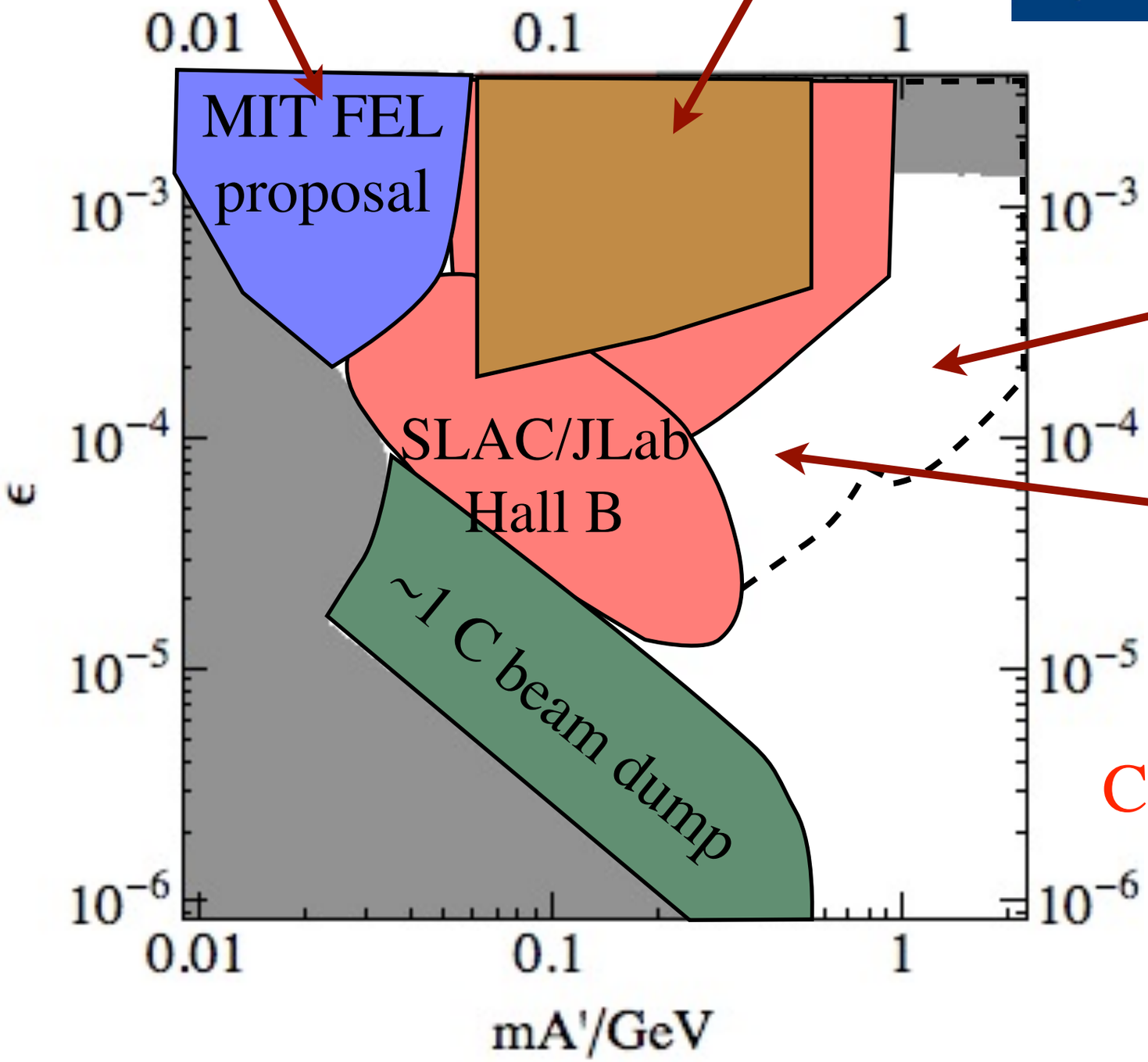
See T. Maruyama Talk at the SLAC Dark Fores Workshop

[see: Freytsis, Ovanesyan, Thaler]



JLab
Hall A
(24 days)





Improvements:

Sensitivity with existing beams but better acceptance

Pixel tracking extends reach

Final version of SLAC/JLab experiment may have extended reach

Complementary coverage from B-factories: higher mass, multi-lepton channels

Summary

- Dark forces are an intriguing possibility, well-motivated by existing data
- Laboratory tests are crucial and complementary to astro/direct-detection hints and upcoming data

- Broad array of experimental investigation is possible
- Sensitivity to many decades in mass and cross section with existing data and new small-scale experiments

New searches and experiments on ~1-2 year timescale!