Laboratory Searches for Dark Matter Signatures with Electron Beams at JLab

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IDM 2010, Montpellier, France
July 26-30, 2010

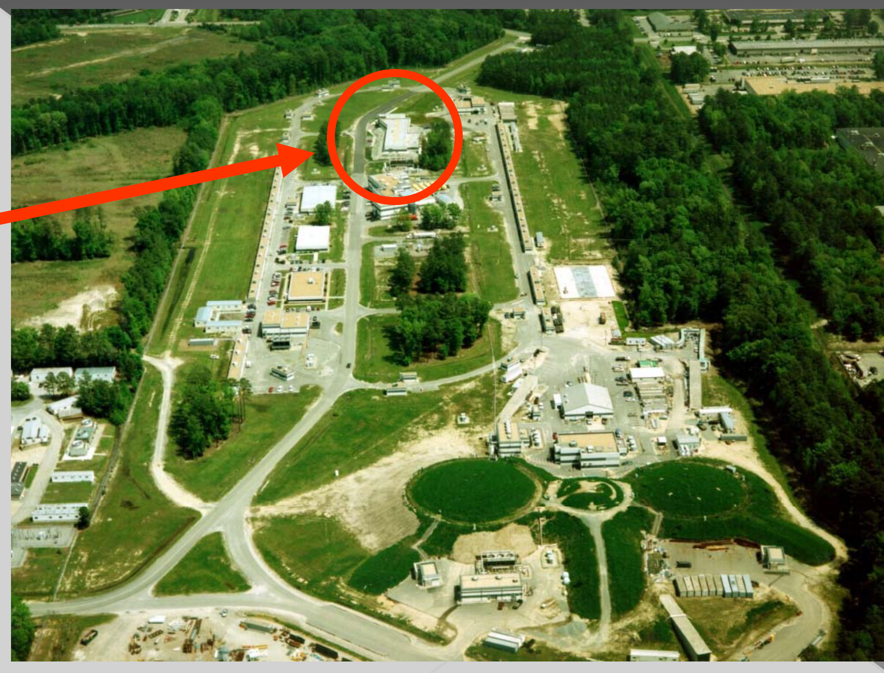
Plan of Talk

- Laser-based laboratory search for axion-like particles (LIPSS at JLAB)
- Planned fixed-target searches for A'
  - What electron accelerators can do?
    - APEX, ...
    - Beam-dump

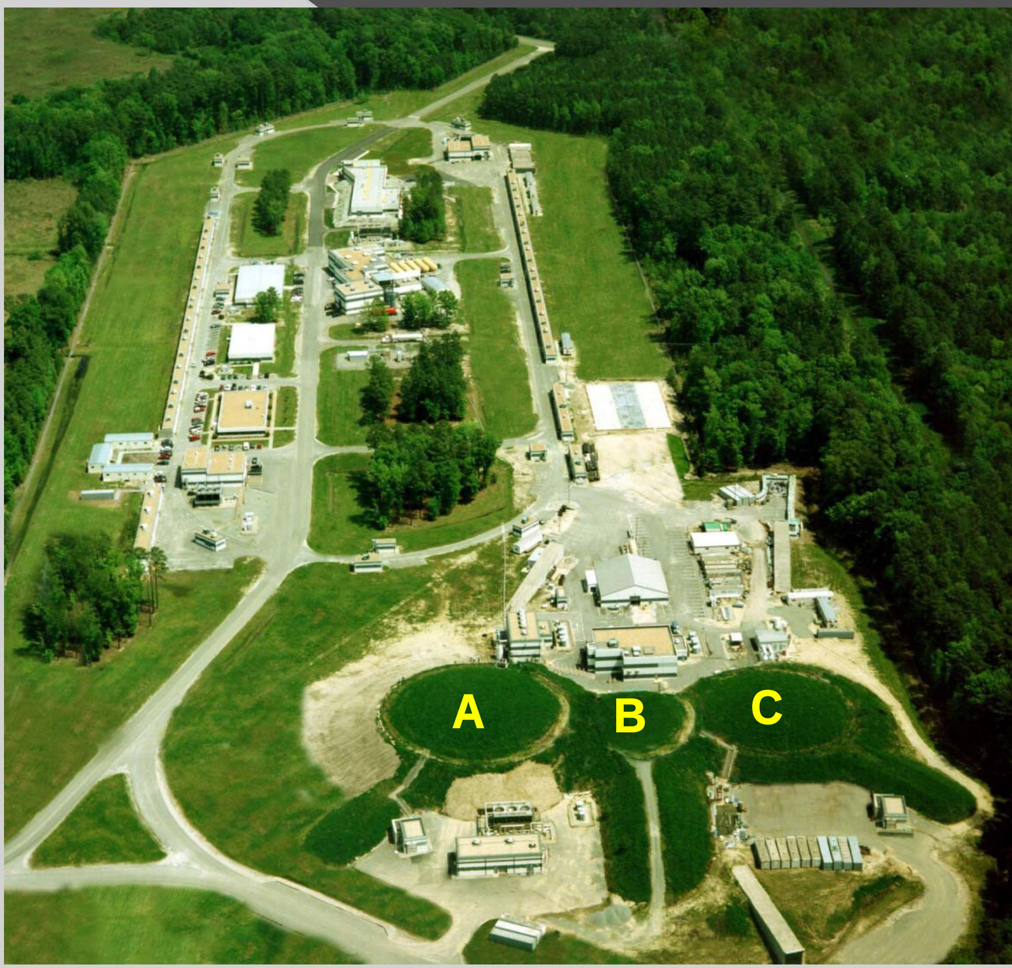
Jefferson Lab is Located in Newport News, Virginia

JLAB's Free Electron Laser

Produced up to 14kW of continuous light at 1.6 micron wavelength



CEBAF Accelerator

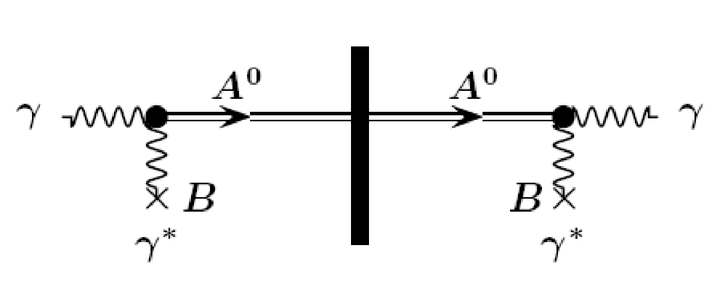


- Re-circulating linac design
- Up to 5 pass, 0.3 to 1.2 GeV per pass.
- 6.0 GeV max beam energy
- 100% duty cycle
  - .2ns microstructure
- $\Delta E/E < 1 \cdot 10^{-4}$ (Halls A & C)
- Beam polarization up to 85%
- 180 μA max current
- CEBAF energy will be doubled to 12GeV after 2012

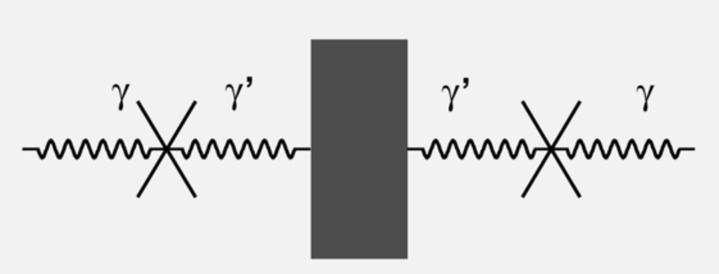
- Well-suited to measure picobarn-level cross sections

Photon Regeneration in `Light Shining through a Wall' (LSW)

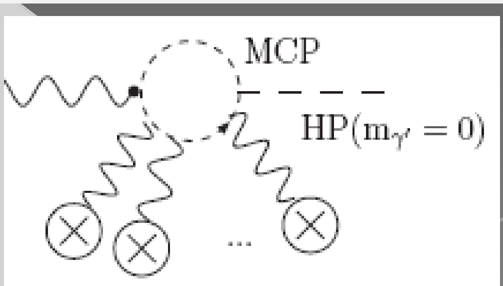
- Photon-axion conversion in presence of magnetic field



- Photon-(massive) paraphoton oscillation (no magnetic field)

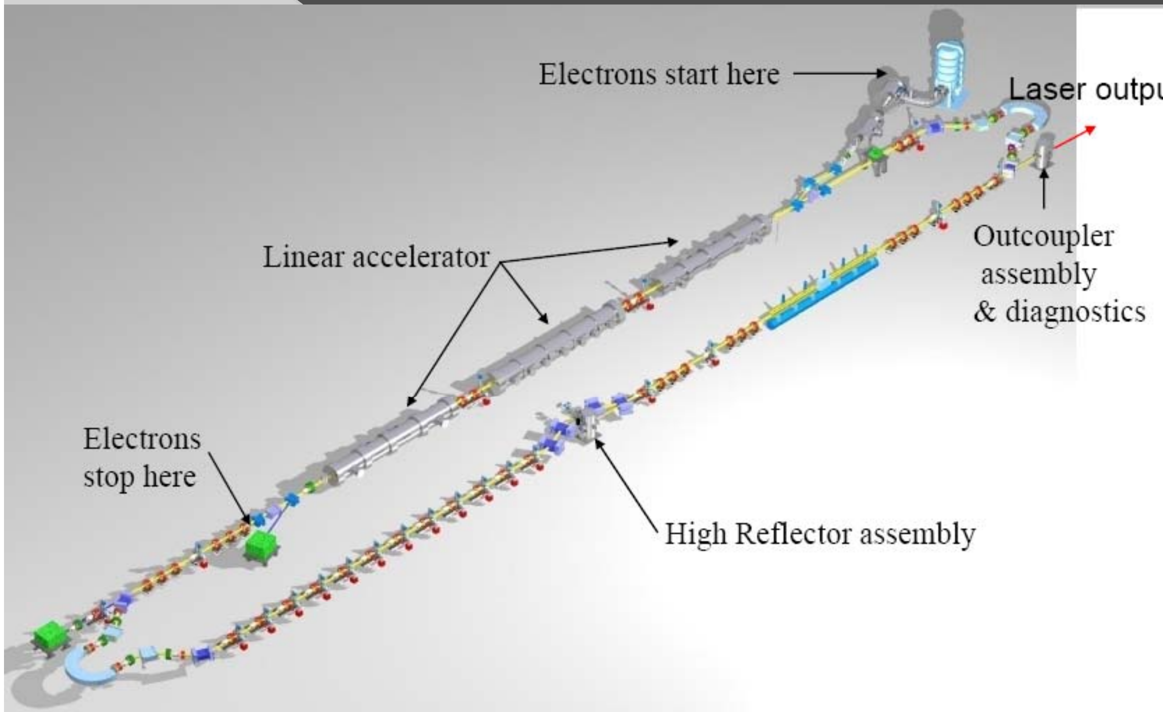


- Photon-(massless) paraphoton conversion in magnetic field via quantum loop of mini-charged particles (MCP)



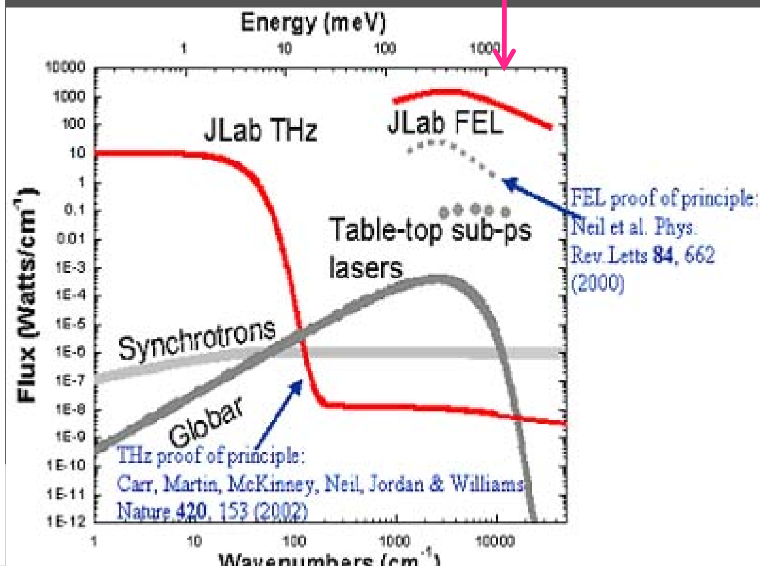
Experimental that use LSW: LIPSS(Jlab, this talk) , BFRT (BNL), BMV(LULI), GammeV (Fermilab), ALPS(DESY), OSCAR (CERN), PVLAS (INFN)

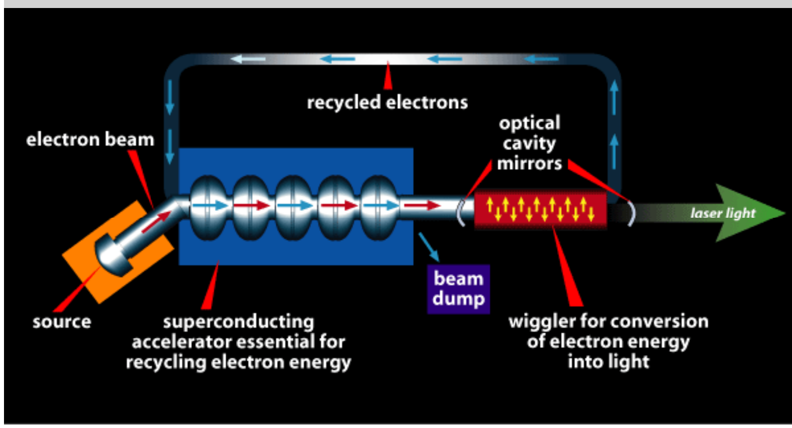
JLAB FEL: Used for LIPSS experiment



Accelerator is over 200 ft long

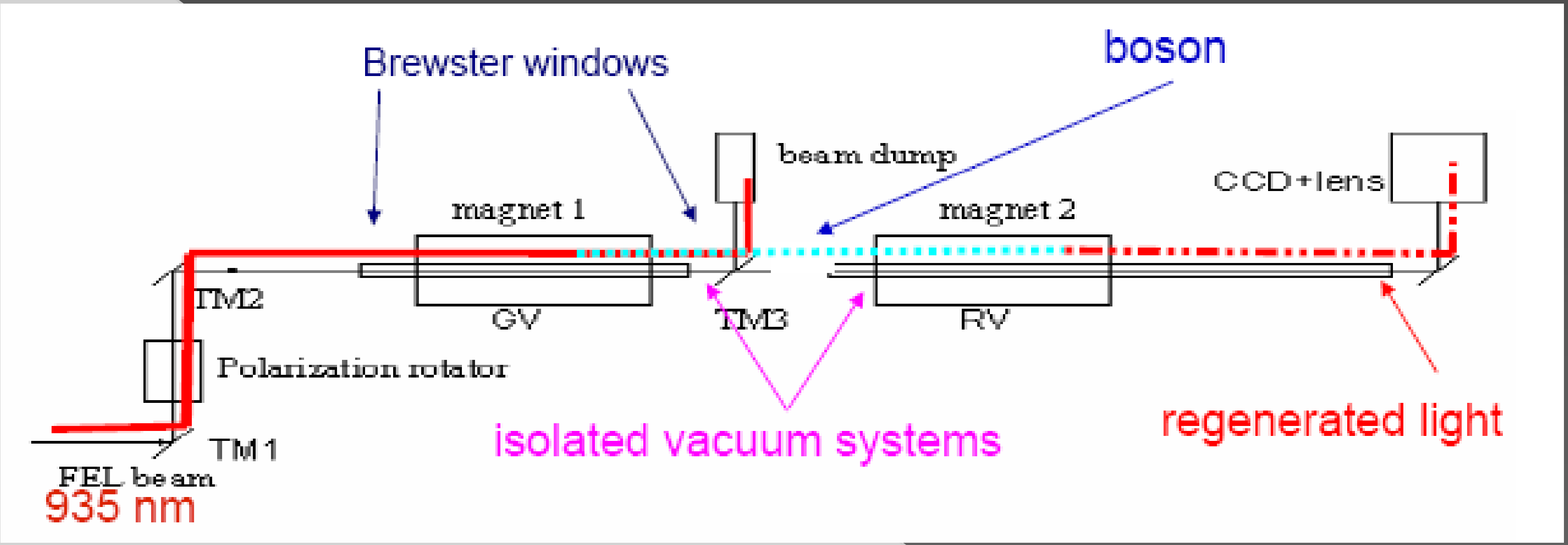
LIPSS IR run at 0.935 micron

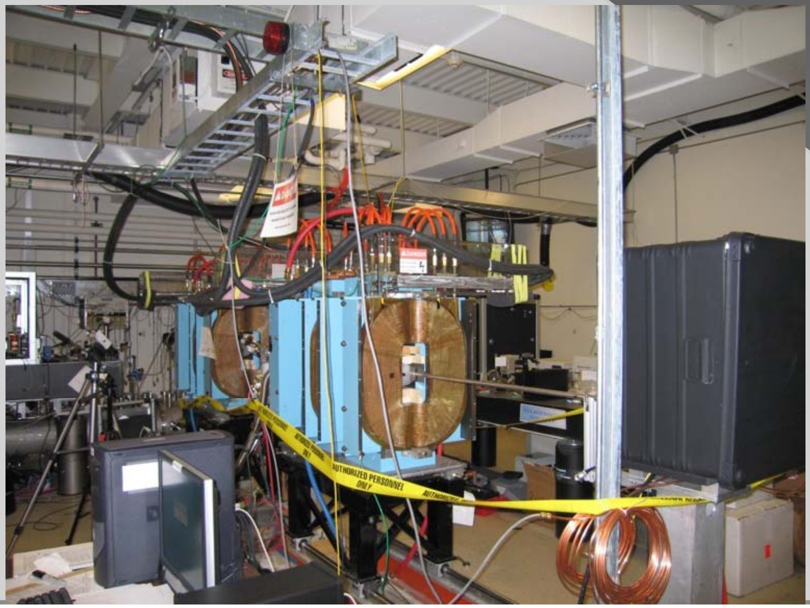




- 150 fs wide pulses
- 75 MHz rep rate
- 100 % df
- 935. +/- 005 nm
- 200 watts avg power
- >99% linearly polarized

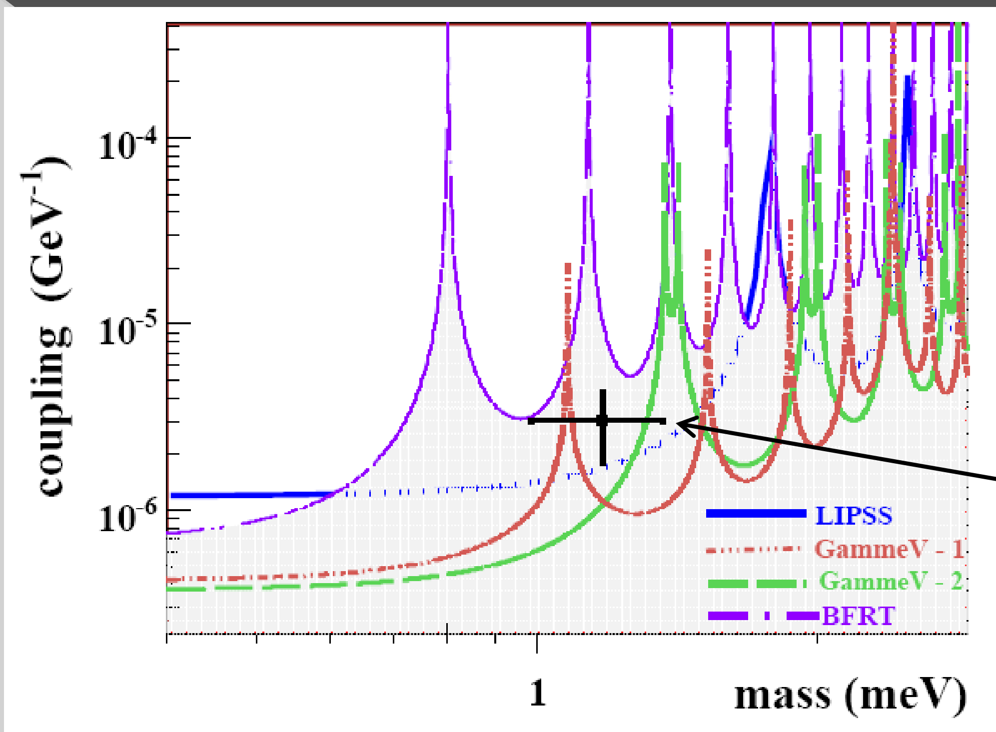
LIPSS experiment schematic





LIPSS Result on Axion-Like Particle

AA et al (LIPSS Collab), Phys Rev Lett 101, 120401 (2008)



PVLAS'05 (now disclaimed)

- No signal observed, regions above the curves are excluded by the experiment(s) at 95%CL
- Scalar coupling probed (`B^2' interaction)

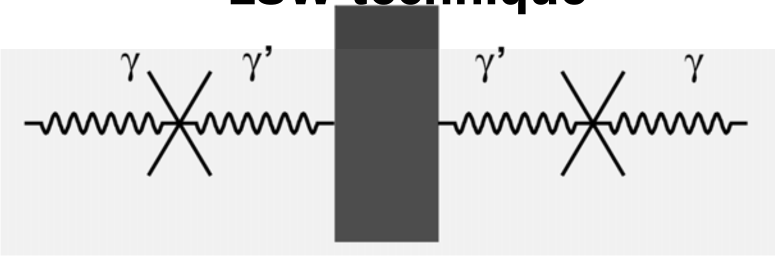
New Constraint on Photon Paraphoton Mixing

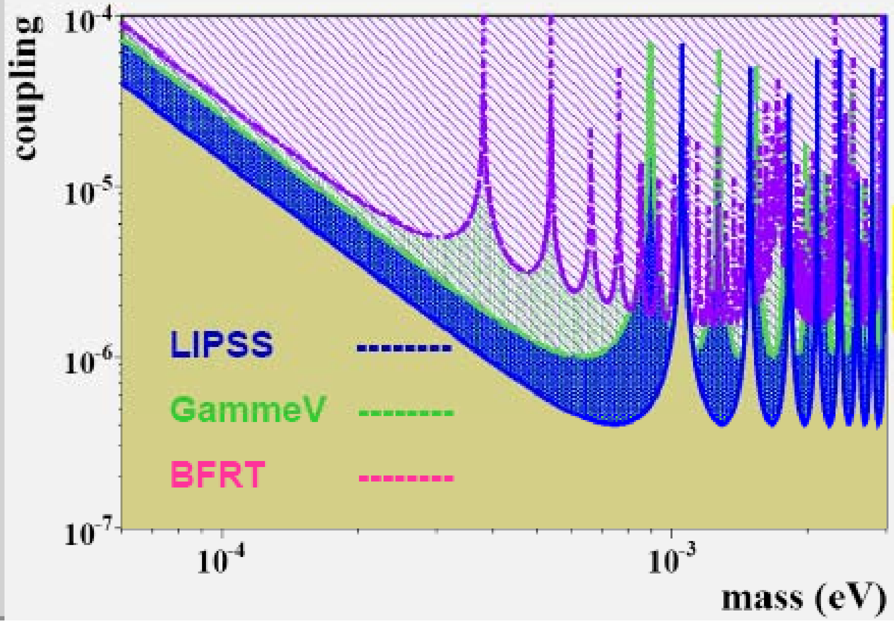
- Hidden-sector $U(1)_H$ symmetry: Paraphotons L.B. Okun, Sov Phys JETP 56, 502 (1982); B. Holdom, Phys Lett B 166, 196 (1986)
  - For the latest, see Ahlers et al, PRD 78, 075005 (2008) ; Abel et al, JHEP07, 124 (2008)

$$L_{mix} = -\frac{1}{2}\chi F^{\mu\nu}B_{\mu\nu}$$

$$P = 16\chi^4\left[\sin\left(\frac{\Delta k L_1}{2}\right)\sin\left(\frac{\Delta k L_2}{2}\right)\right]^2$$

LSW technique

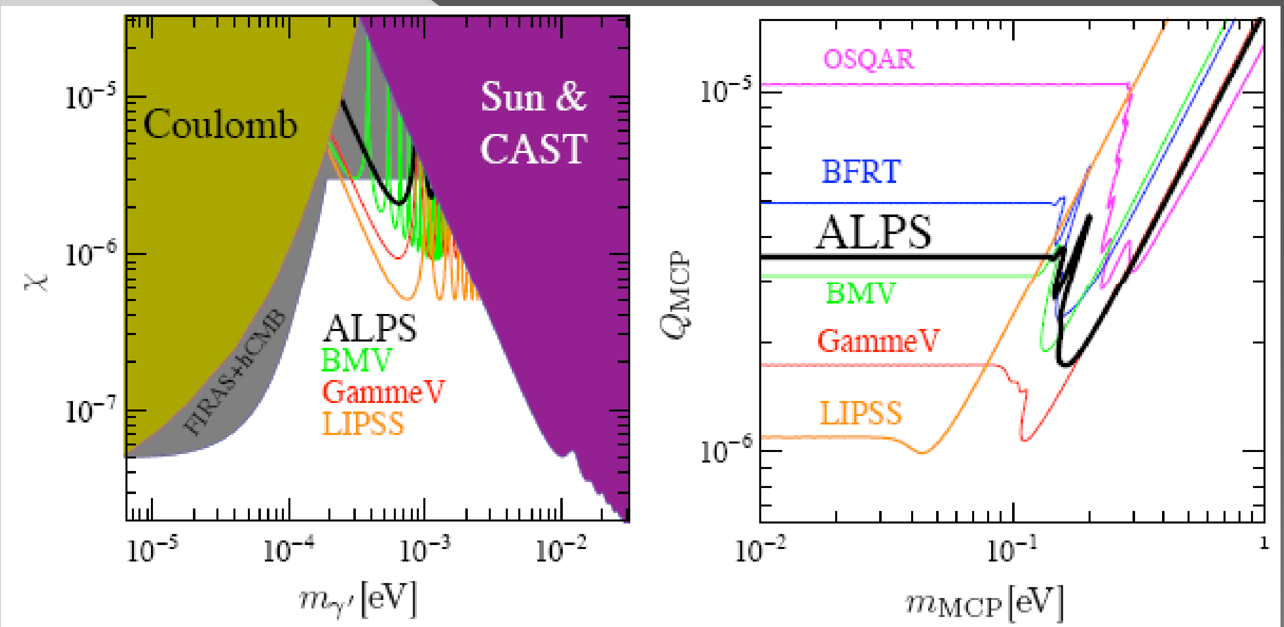




- AA et al, Phys.Lett.B 679, 317 (2009) LIPSS observed no oscillations
- Best LSW constraints due to high initial photon flux
- Region above the curves excluded at 95% CL

Photon-Paraphoton Mixing

- LIPSS results Phys.Lett. B679, 317(2009) vs other constraints:
  - As of 2009, achieved the highest sensitivity in milli-eV mass range (plot compiled in arXiv:0905.4159)



- Also leads to a new constraint on mini-charged particle (MCP) mass and charge, see formalism in Ahlers et al, PRD 78, 075005 (2008) ;
- New results from ALPS: Phys. Lett.B 689:149-155,2010.

Dark Forces Workshop

Searches for New Forces at the GeV-scale

SLAC, September 24th to 26th, 2009

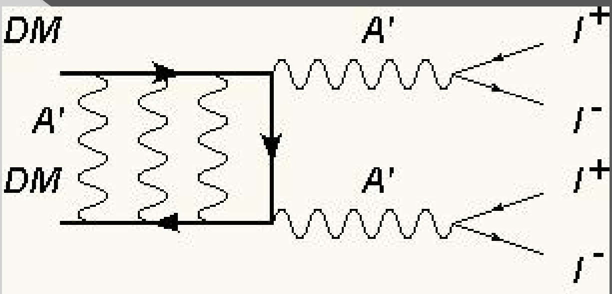
Theoretical models related to dark matter have proposed that there are long-range forces mediated by new gauge bosons with masses in the MeV to GeV range and very weak coupling to ordinary matter. The experimental constraints on the existence of these new gauge bosons are quite weak. This workshop will bring together theorists and experimentalists to stimulate progress in searching for these "dark forces" in three arenas:

- New fixed-target experiments at electron and proton accelerators such as JLab, SLAC, and Fermilab;
- Searches at high-luminosity e+e- experiments, including BaBar, BELLE, CLEO-c, KLOE, and BES-III;
- Searches at the Tevatron experiments

Talks available at http://www-conf.slac.stanford.edu/darkforces2009/

Motivated by observations

- PAMELA positron excess (with no antiproton excess)
- In combination with Fermi, ATIC, HESS

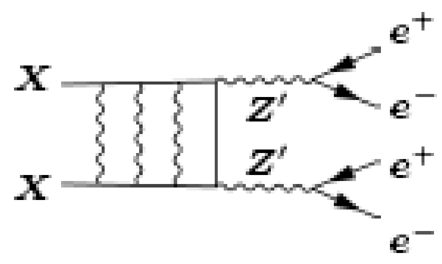


- Sommerfeld enhancement: to reconcile DM relic abundance with observed cosmic ray flux
- Laboratory search strategy: Look for A’ boson coupling to charged leptons

Sommerfeld enhancement

- A heavy DM particle X (100s GeV) could annihilate into GeV Z', which would decay preferentially into light SM particles because of its small mass. The necessary large enhancement in the XX annihilation cross section (needed in all such models) could be accounted for by the Sommerfeld enhancement (from the distortion of the wave functions at low energy), due to repeated Z' exchange

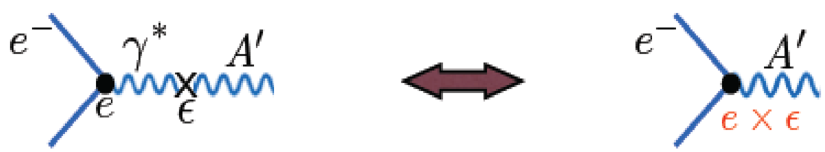
$$XX \to Z'Z' \to \text{light SM}$$



Searching for Dark Forces in Electron Scattering Experiments on Fixed Targets

- Bjorken et al, Phys.Rev.D80:075018,2009

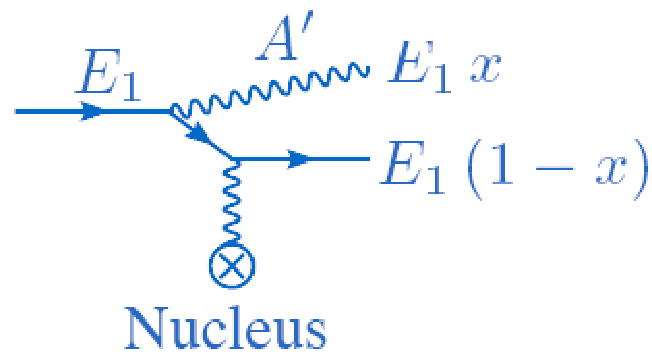
- Dark gauge boson A´ mixing with photon, Mass $m_{A'}$ = 1 MeV – few GeV



- This vertex allows A´ production in any charged-particle scattering.

- Assume A´ decays (only) through photon mixing, i.e. to e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, etc. depending on mass
$c\tau \sim (m_{A'}\epsilon^2)^{-1}$

Fixed-Target



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

Constraints on mass vs coupling for A’

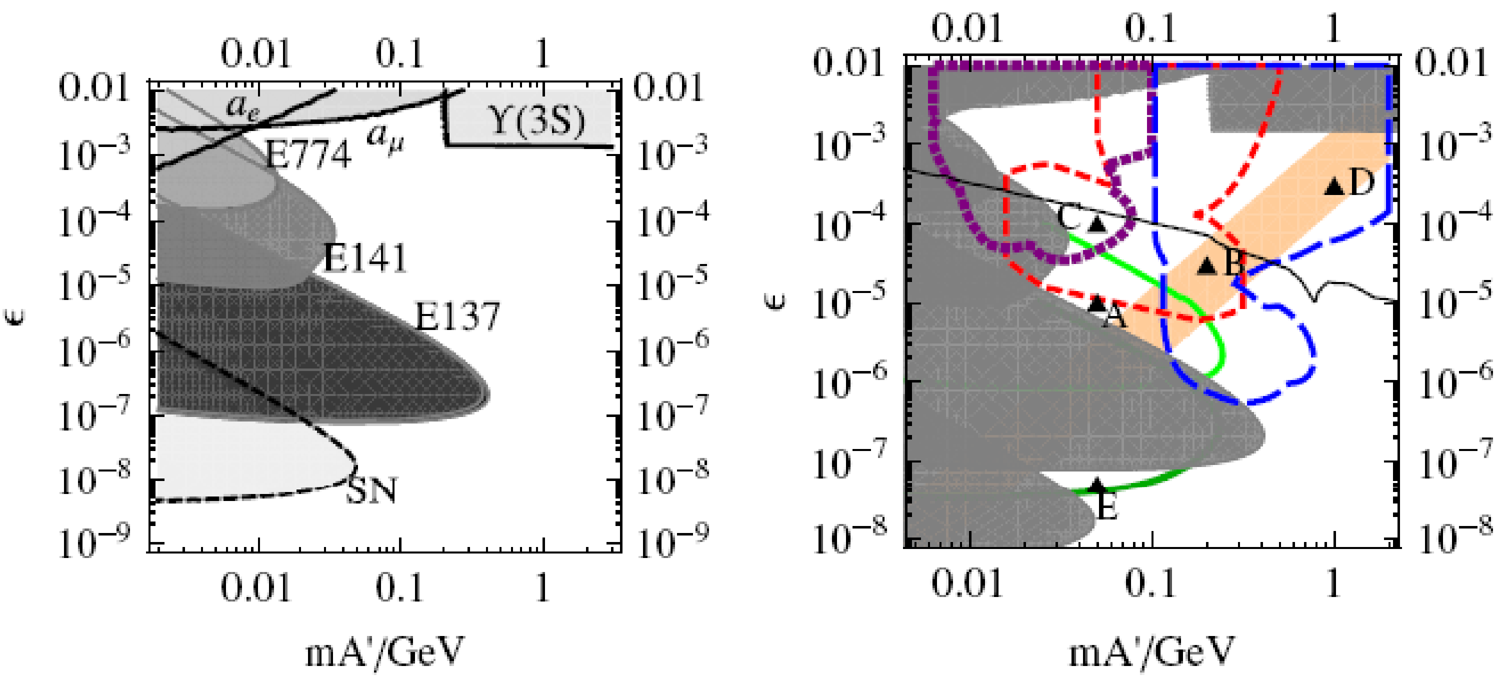
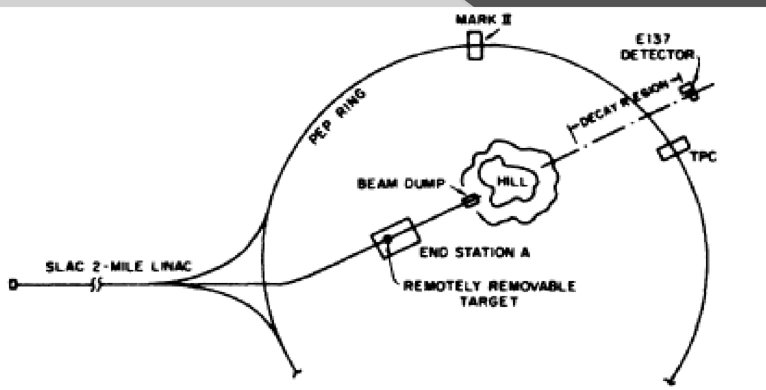
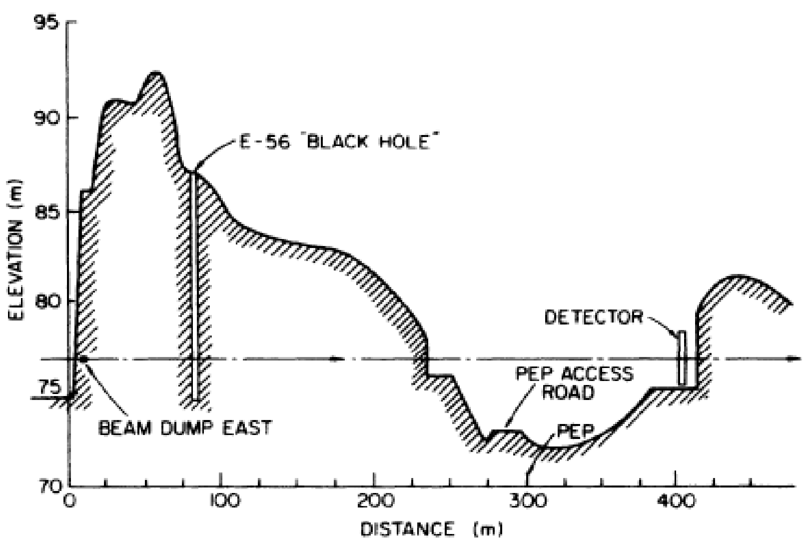


FIG. 1 (color online). *Left:* Existing constraints on an A'. Shown are constraints from electron and muon anomalous magnetic moment measurements, a_e and a_μ, the *BABAR* search for $\Upsilon(3S) \to \gamma\mu^+\mu^-$, three beam-dump experiments, E137, E141, and E774, and supernova cooling (SN). These constraints are discussed further in Sec. III. *Right:* Existing constraints are shown in gray, while the various lines—light green (upper) solid, red short-dashed, purple dotted, blue long-dashed, and dark green (lower) solid—show estimates of the regions that can be explored with the experimental scenarios discussed in Secs. IV A, IV B, IV C, IV D, and IV E, respectively. The discussion in Sec. IV focuses on the five points labeled “A” through “E.” The orange stripe denotes the “*D*-term” region introduced in Sec. II A, in which simple models of dark matter interacting with the A' can explain the annual modulation signal reported by DAMA/LIBRA. Along the thin black line, the A' proper lifetime $c\tau = 80$ μm, which is approximately the τ proper lifetime—see Eq. (11).

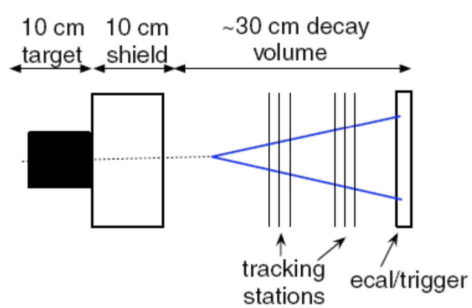
Beam Dump Experiments

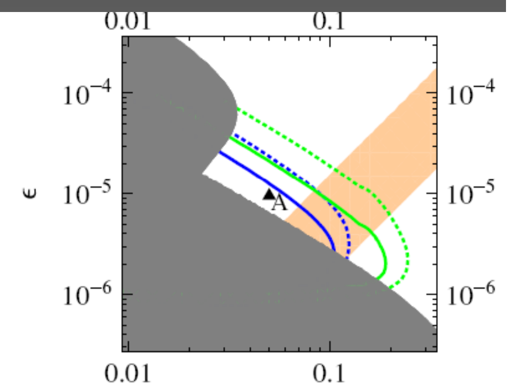
- Sample layout: SLAC E137, Bjorken et al, PRD38, 3375 (1988)





•Dumped ~30 Coulomb of 20-GeV electrons
•New scenario and reach analyzed in BEST (contours indicate sensitivity for 0.1-0.3C at electron energies





•JLAB/CEBAF electons : I<180uA (<6 GeV)
•JLAB/FEL : I<10mA at ~150MeV
•SLAC's 30C benchmark can be reached
  -In ~2days for 6GeV and
  -In ~1hour at 150MeV@FEL

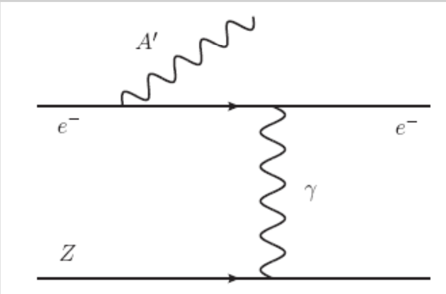
Upcoming JLAB experiments (in preparation)

- Wojtsekhowski, Bjorken et al (Hall A); JLAB Proposal PR-10-009 (**test run underway June-July 2010**)
- Thaler, Fisher, Ent (Berkley, MIT, JLAB): (LOI 10-006): Use gas jet target at JLAB FEL beam
- Jaros, Stepanian, Maruyama et al (Hall B photon dump)
- Baker, Afanasev, et al (Beam dumps: Hall A/C, FEL)
- Also planned at DESY (PETRA) and Mainz (MAMI)

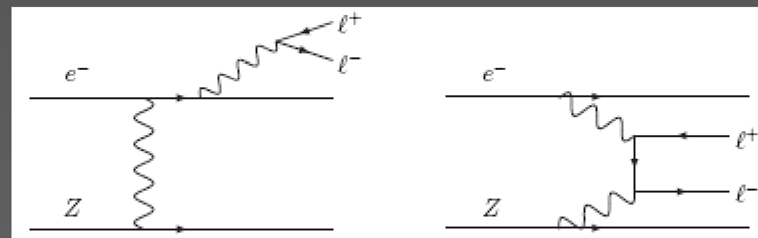
Search for a New Vector Boson A' Decaying to e^+e^-

Experiment JLAB E-10-009

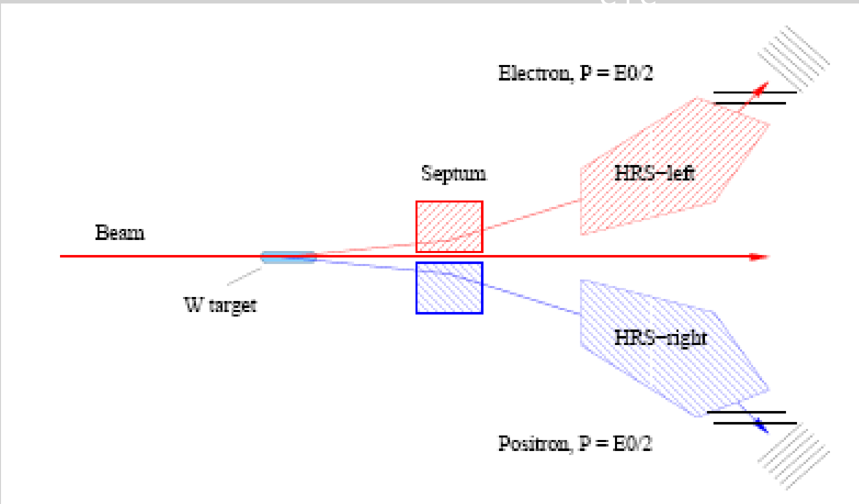
For details of planned experiment, see Essig et al, arXiv:1001.2557

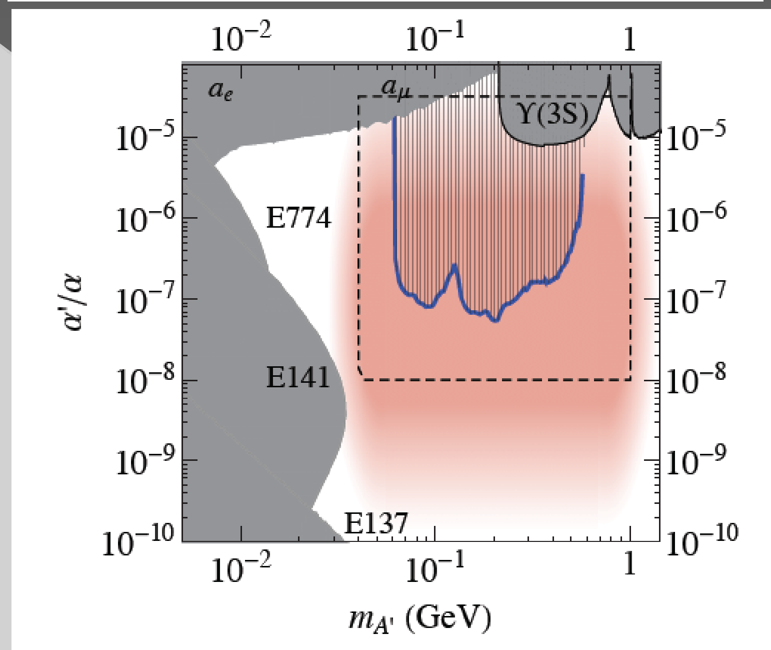


- A' is produced in electron scattering on a fixed target with a charge Z, its decay into e+e- pairs is searched for (upper plot);
- Major background: Standard QED processes :Bethe-Heitler pairs



Experimental setup: W target, septum magnet, High-resolution spectrometers (HRS)
Rate of e+e- pair production is measured as a function of invariant mass W_{e+e-}





Experiment JLAB E-10-009

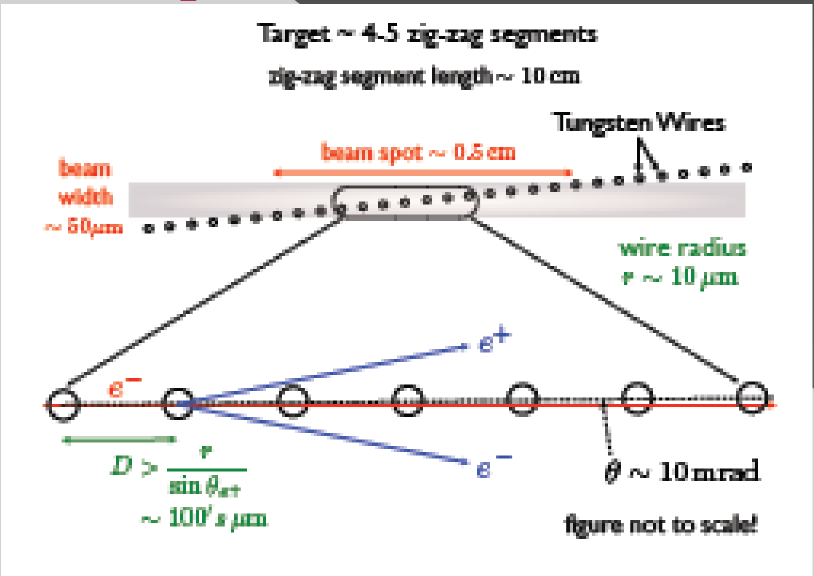
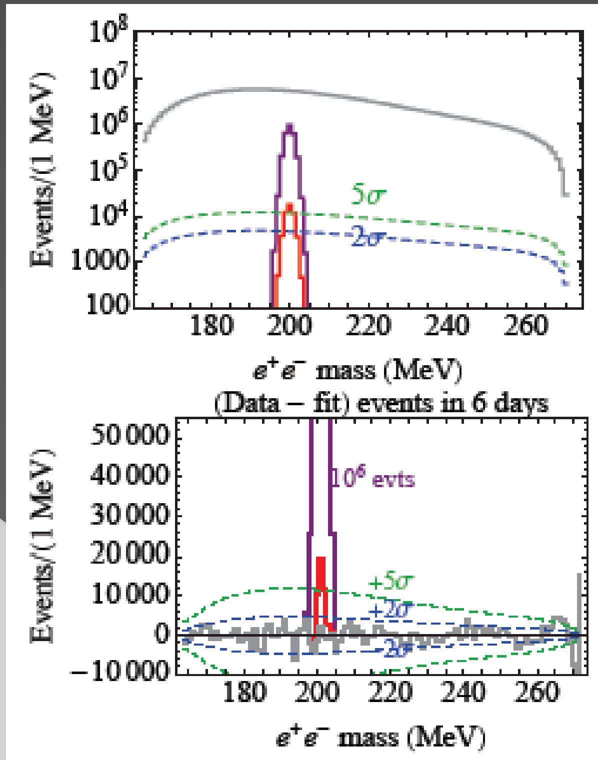


FIG. 7: A schematic close-up view of the target. The figure is not to scale. The target consists of 4–5 zig-zag planes, with each plane consisting of tungsten wires strung together. Each zig-zag plane is ~ 10 cm long, and lies at an angle of ~ 10 mrad with respect to the beam line. The tungsten wires have a radius of $\sim 10\mu$m and are spaced at a distance of ~ 100's μm. While each beam electron can traverse up to ~ 10 wires, the production and prompt decay of an A' in a wire produces e^+e^- pairs that have an angle of $\sim m_{A'}/E_{\rm beam}$, large enough for them to miss the next wire — this greatly reduces the multiple scattering, and is the reason for not using a target foil. The beam width is $\sim 50\mu$m, which translates into a ~ 0.5cm large beam spot along the target plane. The vertical rastering of the beam of ~ 0.5mm moves the beam spot ~ 5cm back-and-forth along the target plane — this helps to prevent the beam from melting the target.

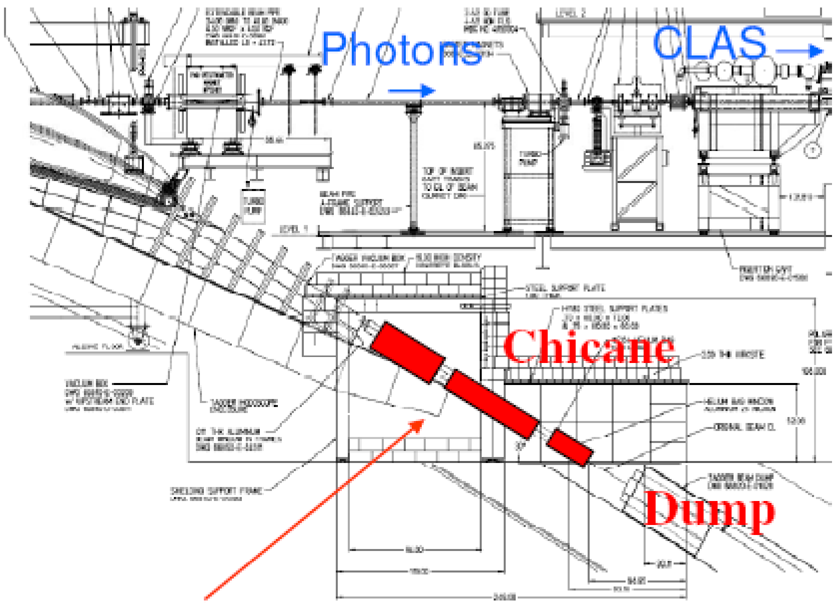


Simulated signal in APEX experiment:
6 days of running time, mA'=200MeV,
$\alpha'/\alpha = 6.5\times10^{-6}$(magenta), 1.3×10^{-7}(red)
Background is from QED pair production

Proposed Experiment at JLAB Hall B

- As reported by Takashi Maruyama (Sept.09)
  - For additional information contact S. Stepanian, J. Jaros

JLab Hall B "Photon Dump"

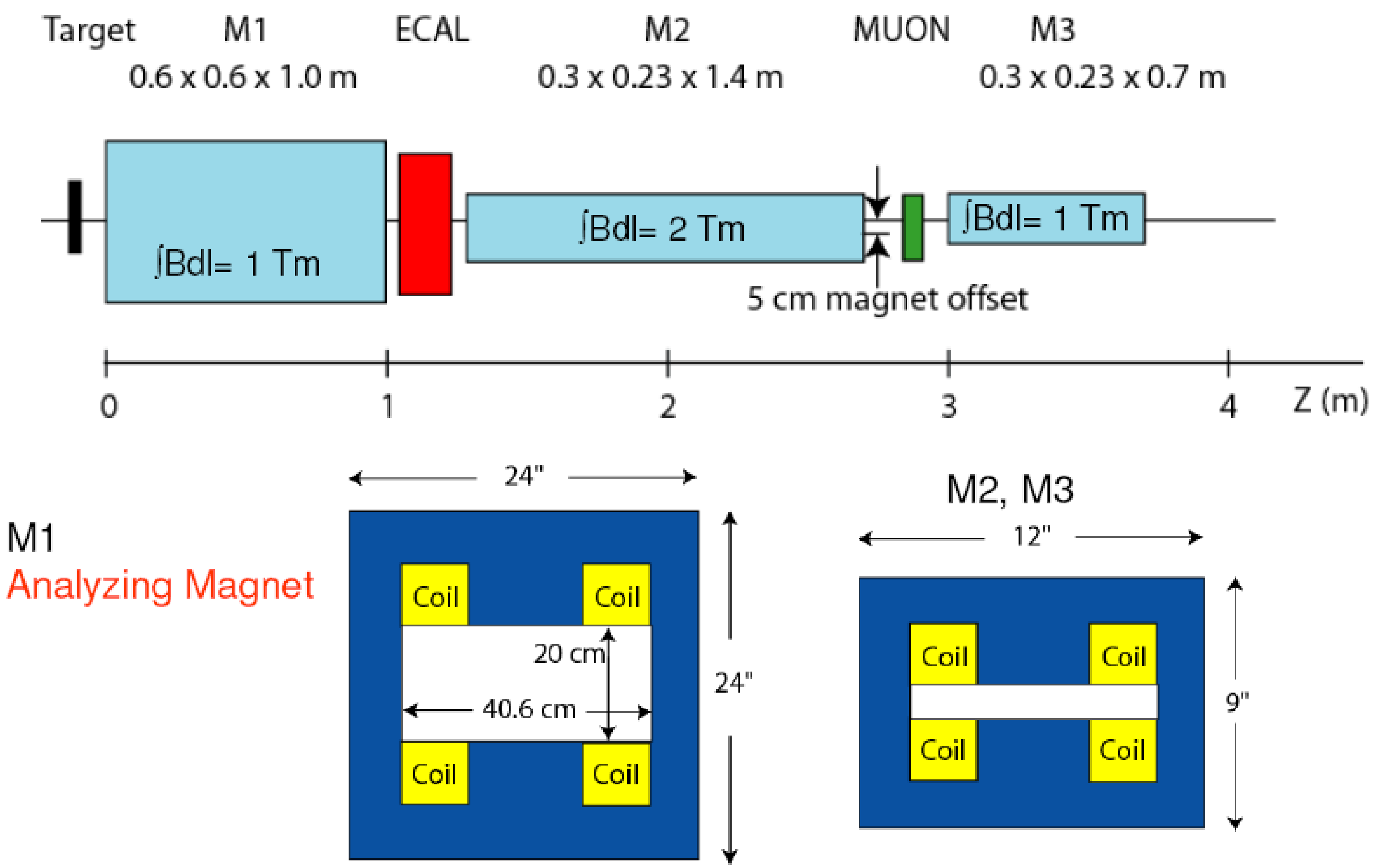


Possible location for heavy photon search

- 100 nA, 6 GeV e-, post-radiator "primary beam"
- Beam size ≤ 100 μm
- Tight ~5m space
- Avoid vertical bending plane containing primary beam, sync radiation, degraded electrons
- Beam must be directed to the dump.
  - Chicane magnets
- Parasitic run with CLAS

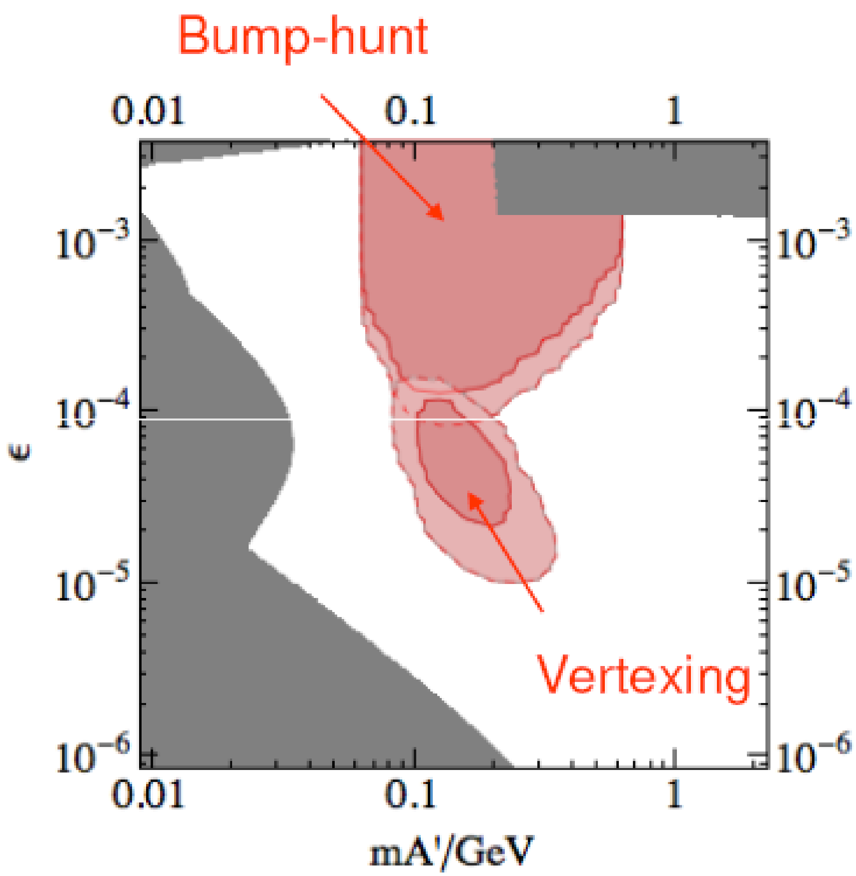
Hall B `Photon Dump'

Experimental Apparatus



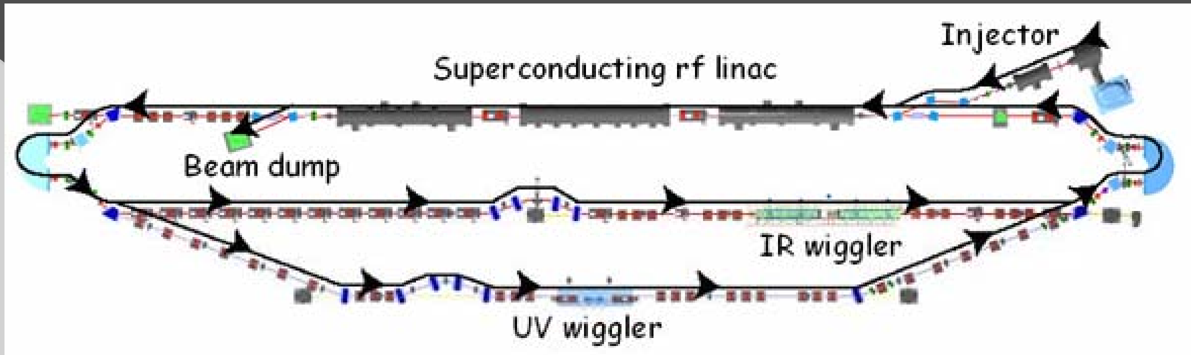
Hall B `Photon Dump' Simulated Sensitivity

Experimental Reach



- Bump-Hunt
  - Require S/sqrt(B) > 5 in 100 nA x 10^7 sec
- Vertexing
  - Require 10 events with z > 5•σ in 100 nA x 10^7 sec

Using a high-current JLAB FEL electron beam



Jefferson Lab FEL Output Light Parameters

	IR Branch	UV Branch
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser energy / pulse (microJoulesJ)	100 - 300	25
Laser power (kW)	> 10	> 1
Repetition Rate (cw operation, MHz)	4.7 - 75	4.7 - 75

Jefferson Lab FEL Electron Beam Parameters

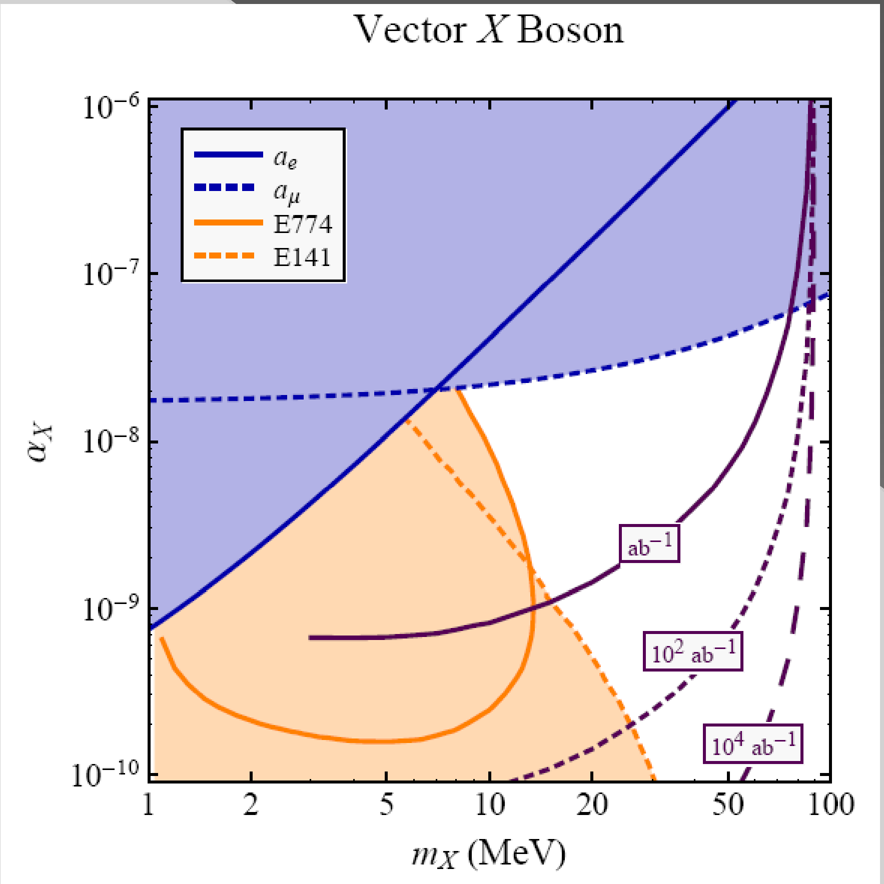
Energy (MeV)	80-200	200
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50%	0.13%
Normalized emittance (mm-mrad)	<30	<11
Induced energy spread (full)	10%	5%

See G. Neil et al.,
NIM A 557, 9 (2006);
www.jlab.org/FEL

JLAB LOI 10-006

Contact: P. Fisher (MIT)

- To install an internal gas target in FEL's electron beam;
- For theoretical justification and computed sensitivity, see Freytis et al, JHEP 1001:111,2010 (arXiv:0909.2862)



DESY Beam Dump (planned)

- See talk by Sarah Andreas at Axion-WIMP 2010, http://axion-wimp.desy.de/

Constraints

Muon & Electron $g-2$

one-loop contribution from hidden photon[Pospelov 2009]

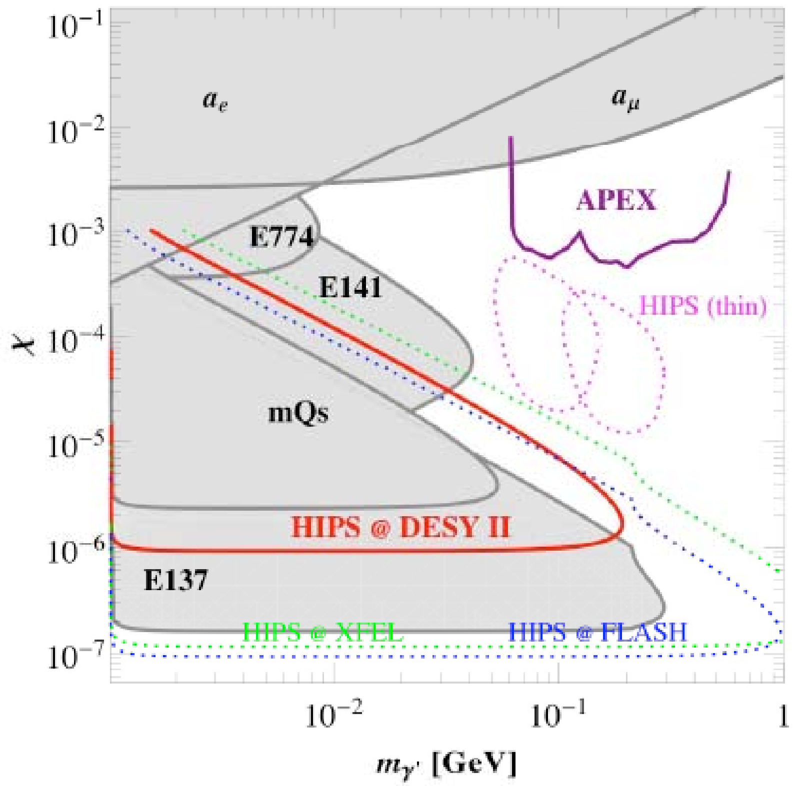
past beam-dump experiments

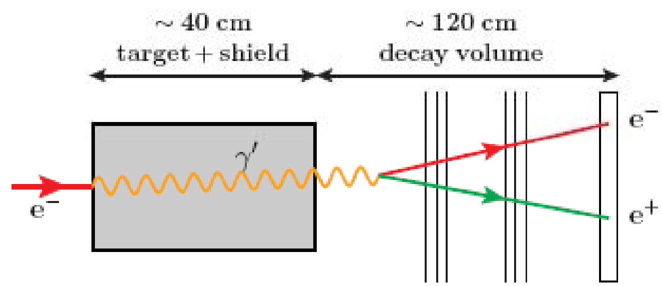
γ' emitted via bremsstrahlung from e-beam[Bjorken et al. 2009]

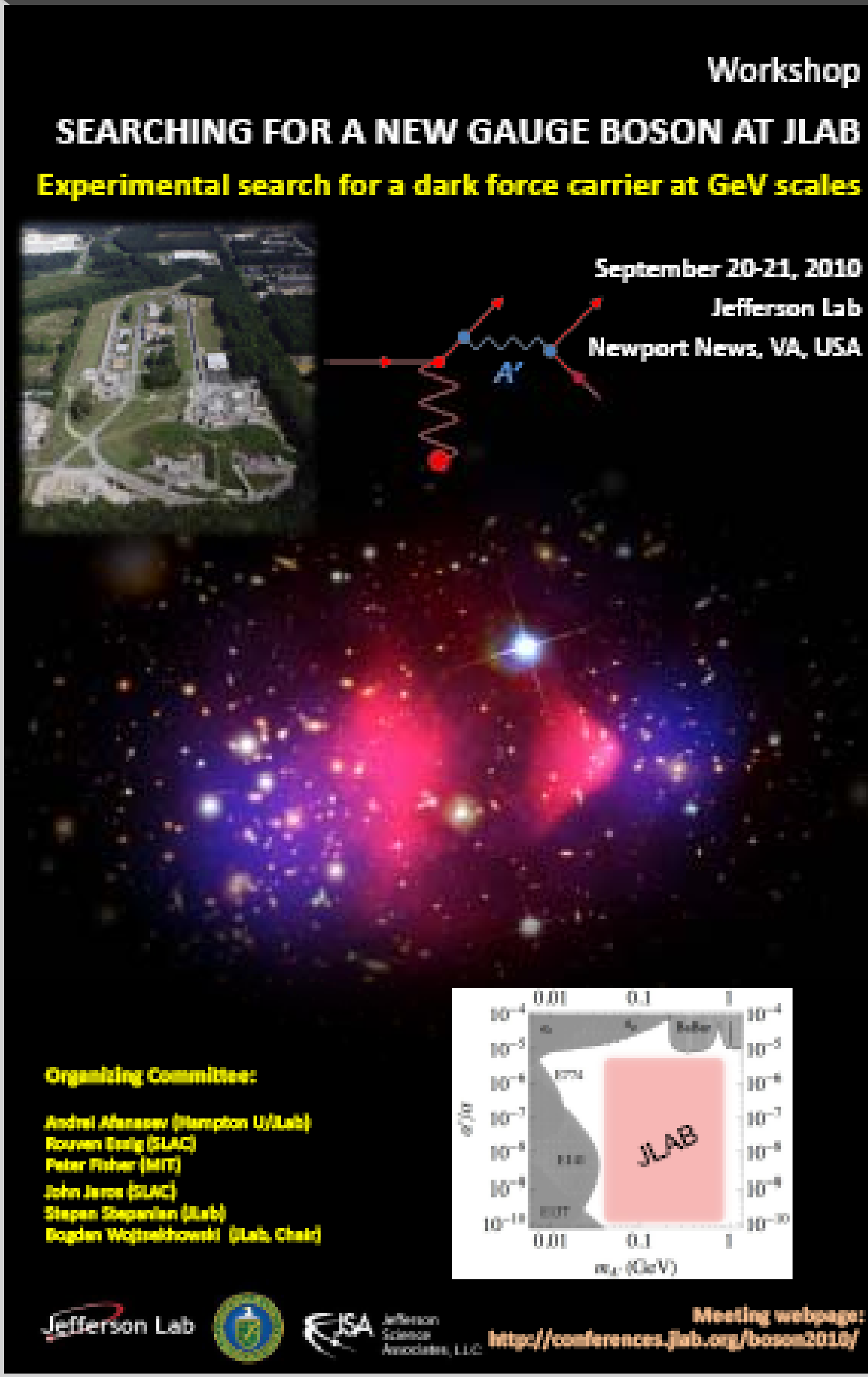
search for decay $\gamma' \to e^+e^-$

sensitivity of future experiments

- JLab experiments e.g. APEX
- thick target at DESY: HIPS







- The workshop will be held at Jefferson Lab later this year (September 20-21, 2010)
- Purpose: Planning experiments to search for a new gauge boson at MeV-GeV scales
  - Additional theoretical motivation is not needed at this stage (!)
  - Focused on experimental techniques, equipment and priorities in scheduling

Electrodynamics of Dark Matter

(AA, Carlson, in preparation)

Dark Compton Scattering, polarizability of WIMPS
in electromagnetc fields
Dark Delbruck effect:
Light absorption+dispersion at astrophysical distances

<- Photo-convertion of dark bosons
into electron-positron pairs

Dark Bethe-Heitler pair production:
Electron-positron pair production
on a dark field of a WIMP->

Summary

- Newly observed astrophysics anomalies can be interpreted in terms of Dark-Matter particles at ~TeV scale and force-carrying particles at MeV-GeV scale
- This is within reach for JLAB
  - APEX experiment is running
  - More experiments being planned