Extending DarkLight's Reach

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For the DarkLight Collaboration

CSS 2013 / Snowmass on the Mississippi (Minnesota)
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University of Minnesota

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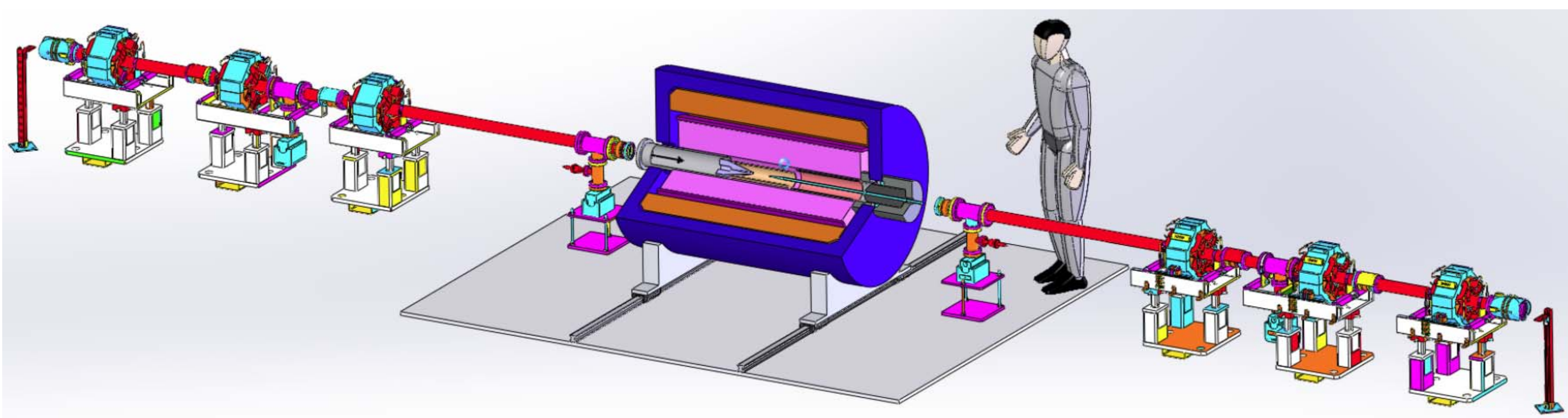
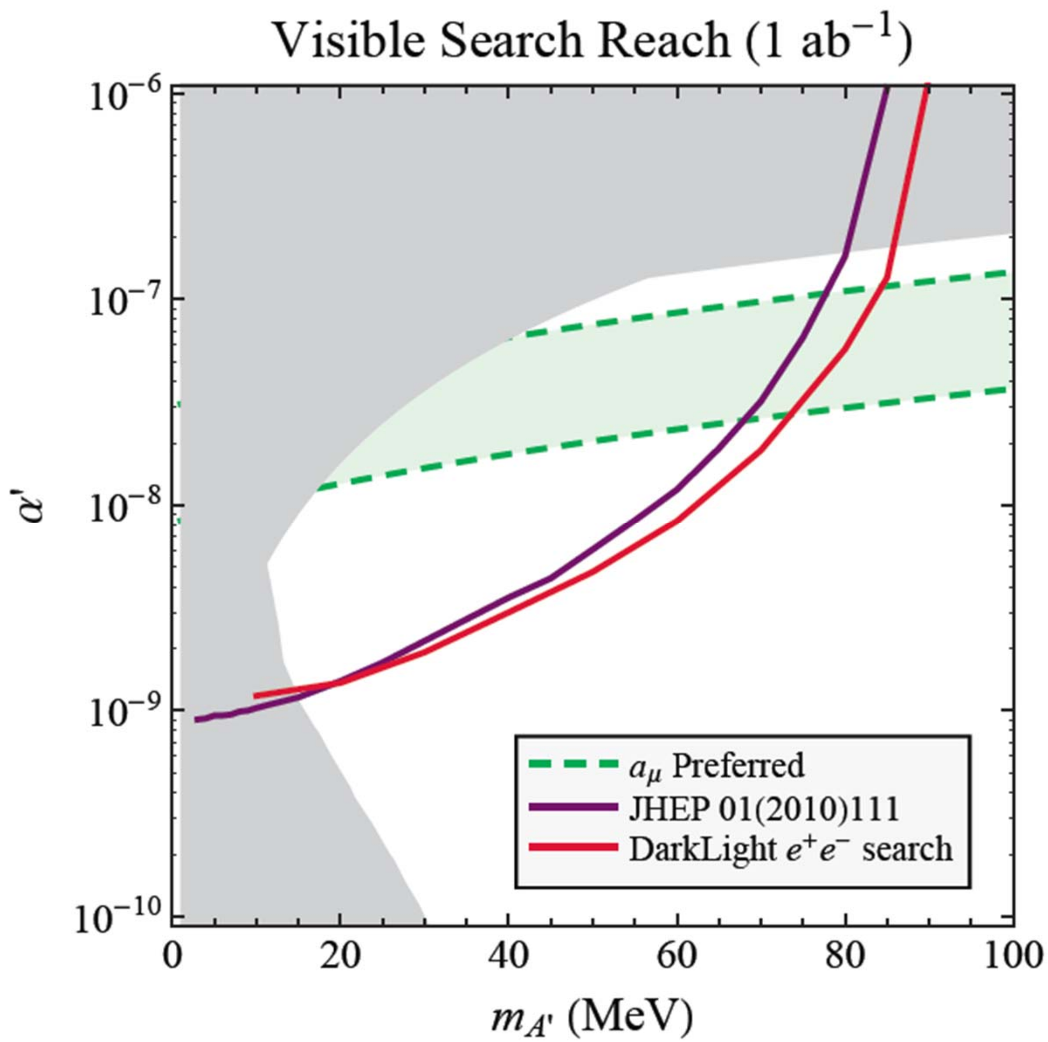
Outline of Talk

- Overview of DarkLight
- Plasma windows for gas targets
- Invisibly decaying particles
- Other possibilities from the *Physics of Electron Beams Workshop*
- Summary



Overview: DarkLight's reach

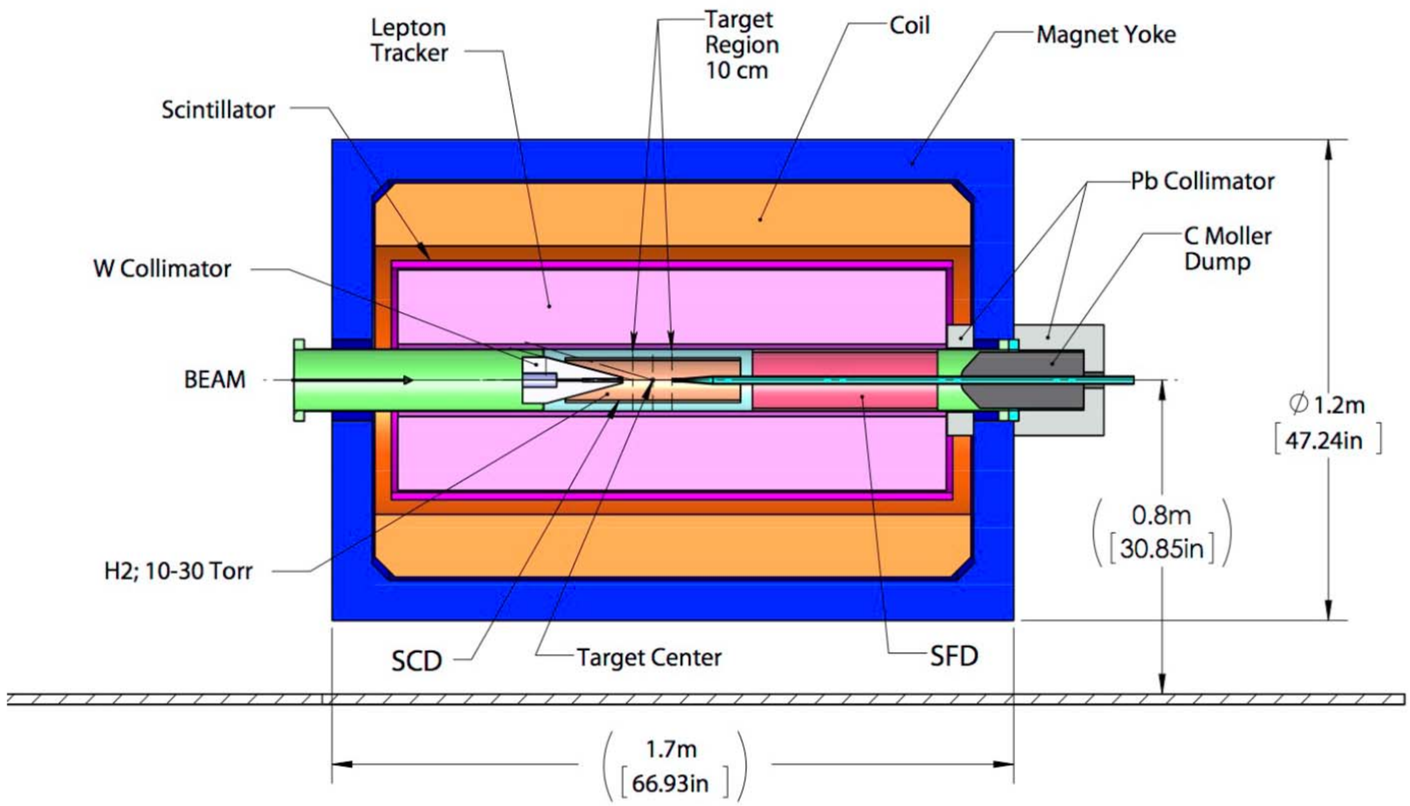
- Goal: search for heavy photon *A'*
  - With a mass between 10 – 90 MeV/c^2
    - In $e^- + p \rightarrow e^- + p + e^- + e^+$ events
  - Signal is a narrow peak in e^-e^+ invariant mass
    - At the *A'* mass
  - Above QED and other backgrounds
    - Backgrounds minimized by
      - Reconstruction of all four final-state particles
      - Excellent detector resolution, and kinematic cuts
- Reach is complementary to other planned experiments
- Such as APEX and the Heavy Photon Search (HPS) at JLab CEBAF machine



DarkLight's main components

1. Gas hydrogen target & beamline components
2. Recoil proton silicon detectors
3. Lepton tracker
4. Solenoidal field magnet

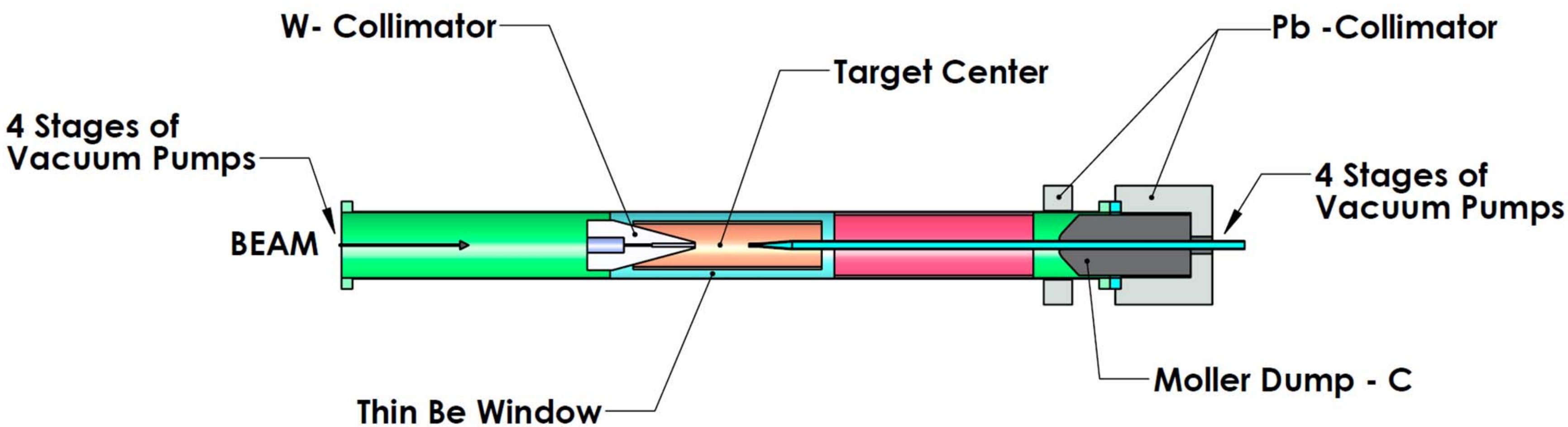
- Plus auxiliary items
  - Readout DAQ
  - Electrical services
  - Mechanical support



Extending DarkLight's Reach

- Scientific reach
  - DarkLight proposal based on 1 ab^{-1} = 1 month of running
  - If given funding 10 months => 10 ab^{-1}
  - JLab FEL beam energy is 130 MeV maximum at present
    - DarkLight proposal only considers 100 MeV running, 10 MeV/c^2 < m(A') < 90 MeV/c^2
      - Could go up to 130 MeV, raises *m*(*A'*) upper limit to 120 MeV/c^2
    - There is a proposal to increase FEL beam energy to above pion threshold
      - Would extend DarkLight's reach, but would require addition of particle ID
      - Require major upgrade to the apparatus
- Technological "reach"
  - Development of a TPC that can handle the high rates of DarkLight has technological value for other experiments
    - The next step for BONUS and other experiments similar to DarkLight
  - With an apparatus like DarkLight, you can also do
    - Nuclear physics
      - Example: study $^{12}C(\alpha,\gamma^*)^{16}O$ inverse reaction to obtain information on the *s*-factor at astrophysical energies (suggested by N. Kalantarians)
    - Fundamental asymmetries
    - Charge radius of the proton
    - Precision measurements of elastic and other QED processes

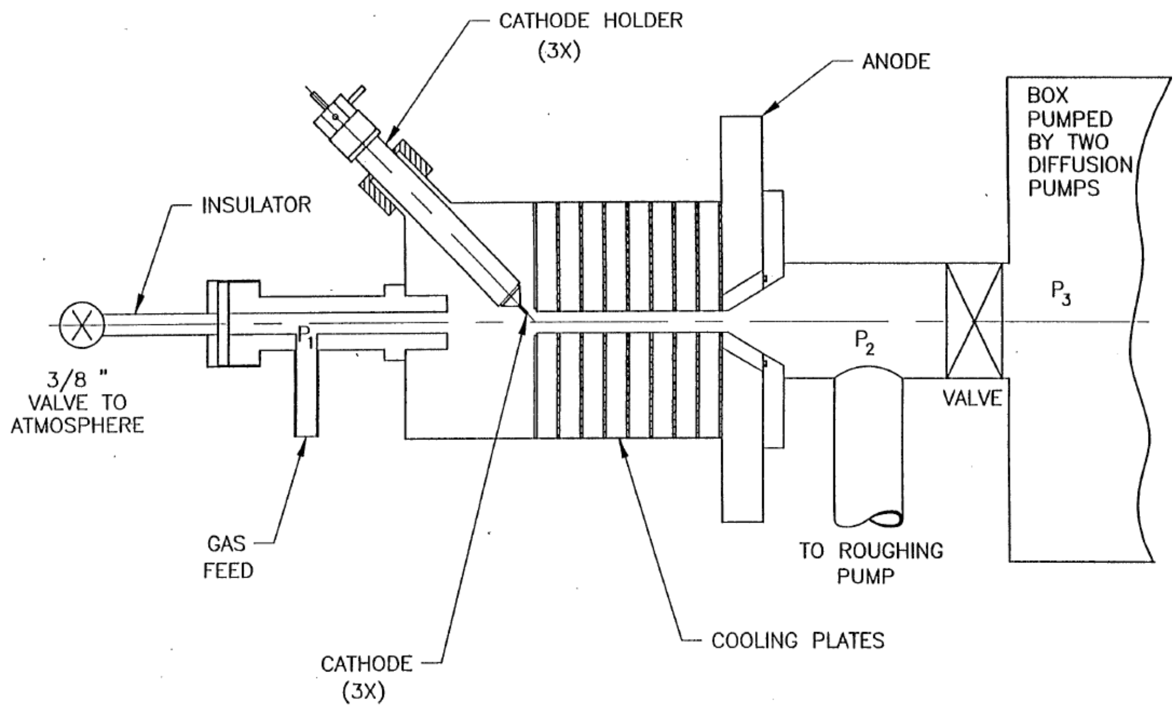
Nominal target region layout



- Windowless gas target
  - Defined as volume inside beampipe
  - 10^{19} atoms/cm^2 in 10 cm long target region (15–30 torr)
  - Two conductance-limiting tubes, upstream and downstream
    - 2 mm dia., 10 cm long
  - 20 mm diameter, 1 m long “exhaust pipe”
    - Downstream of W collimator
- W collimator design
  - To absorb beam halo
  - Recessed to absorb backscattered halo electrons
  - Limit Rutherford-scattered electrons entering the gas volume
- Differential pumping, 4 stages
  - FEL vacuum 10^{-8} torr
  - Pumping rate 15 torr-liter/sec
- Beampipe
  - Beryllium in 25°–165° angular lepton acceptance region
- Moller dump
  - Graphite to reduce showering
  - Shielded with lead on upstream side to reduce backscatter into tracker
- Challenges
  - Control power deposition
    - Beam core, halo, resistive wall heating
- Alternatives
  - Plasma windows
    - Under investigation
    - Reduces gas flow in apertures
  - Use heavier gas, e.g. xenon
    - Ionization loss and brem negligible for H_2 and Xe
    - Mott scattering similar for both Xe and H_2

Plasma windows

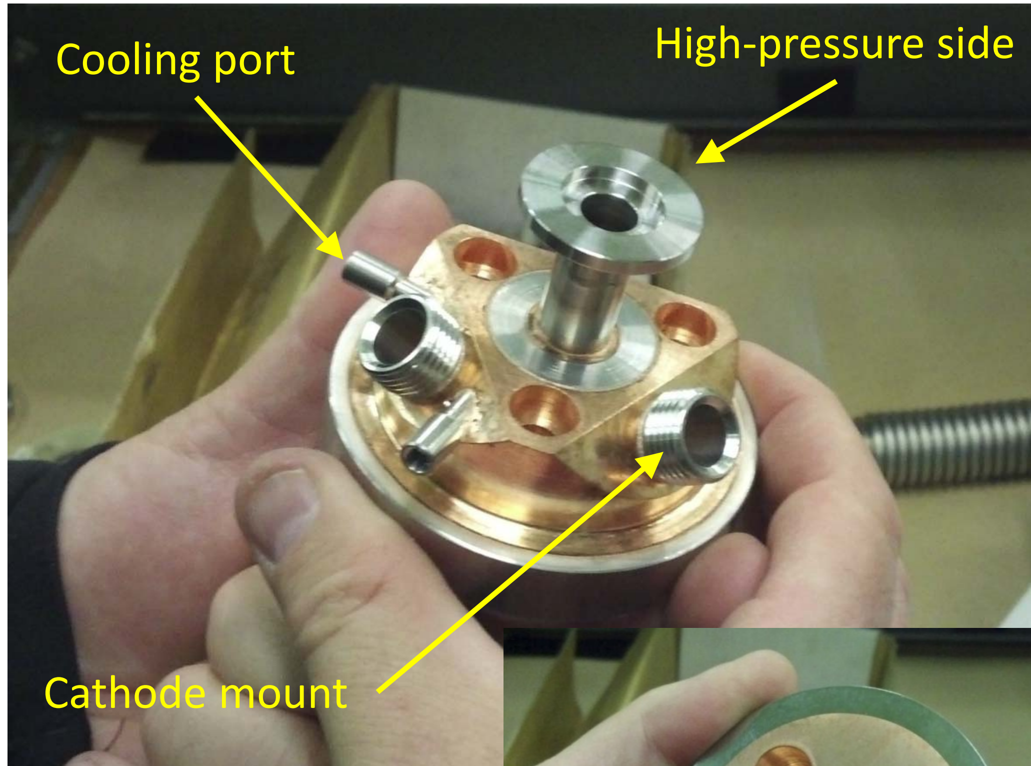
- Plasmas can serve as a barrier between two region of gas with different pressures
  - Low-to-high vacuum separation, vacuum—air separation
  - Proven examples: 1 atm–5 atm; 1 atm–1 torr
- Plasma has a higher viscosity, lower density than the same gas at STP
- Permits transmission of particle beams from one region to the other
  - Equivalent target thickness is typically O(10^{-4}) that of a few hundred μm of beryllium
  - No metallic barrier to damage
  - Have been used with 2 MeV protons, 200 keV electrons at 25 mA, X-rays, and other beams

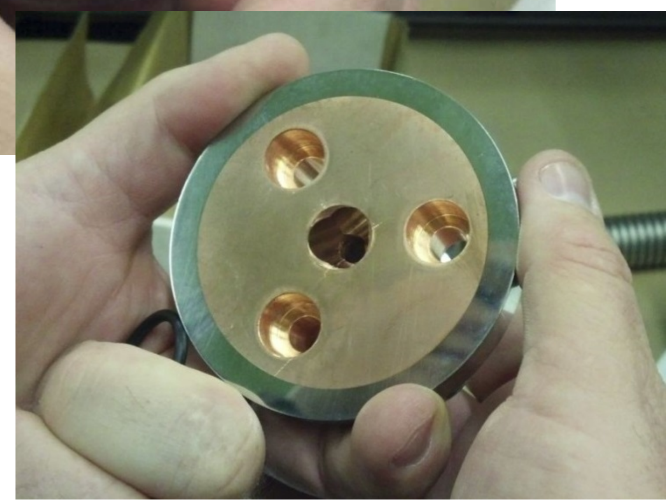


A. Hershcovitz, *A Plasma Window for Vacuum - Atmosphere Interface and Focusing Lens of Sources for Non-Vacuum Ion Material Modification*, BNL-64733 (1997).

Beam-plasma interactions

- The JLab FEL beam: 100 MeV electrons, 10 mA
- In principle will interact with electric and magnetic fields in the plasma
  - Magnetic field in plasma window
    - 0 on the axis, 20–30 gauss at maximum radius
    - Negligible compared to 0.5 T solenoidal field
  - Electric field in plasma window
    - Typically 100 V across the plasma, radially flat
    - Negligible effect
  - Collision losses and scattering
    - Has not been significant for 100-200 keV electron beams
    - Probably not here either
- Plasma-solenoidal field interactions
  - The 0.5 T solenoidal field may affect the plasma
  - Could require some engineering of window design and operating parameters



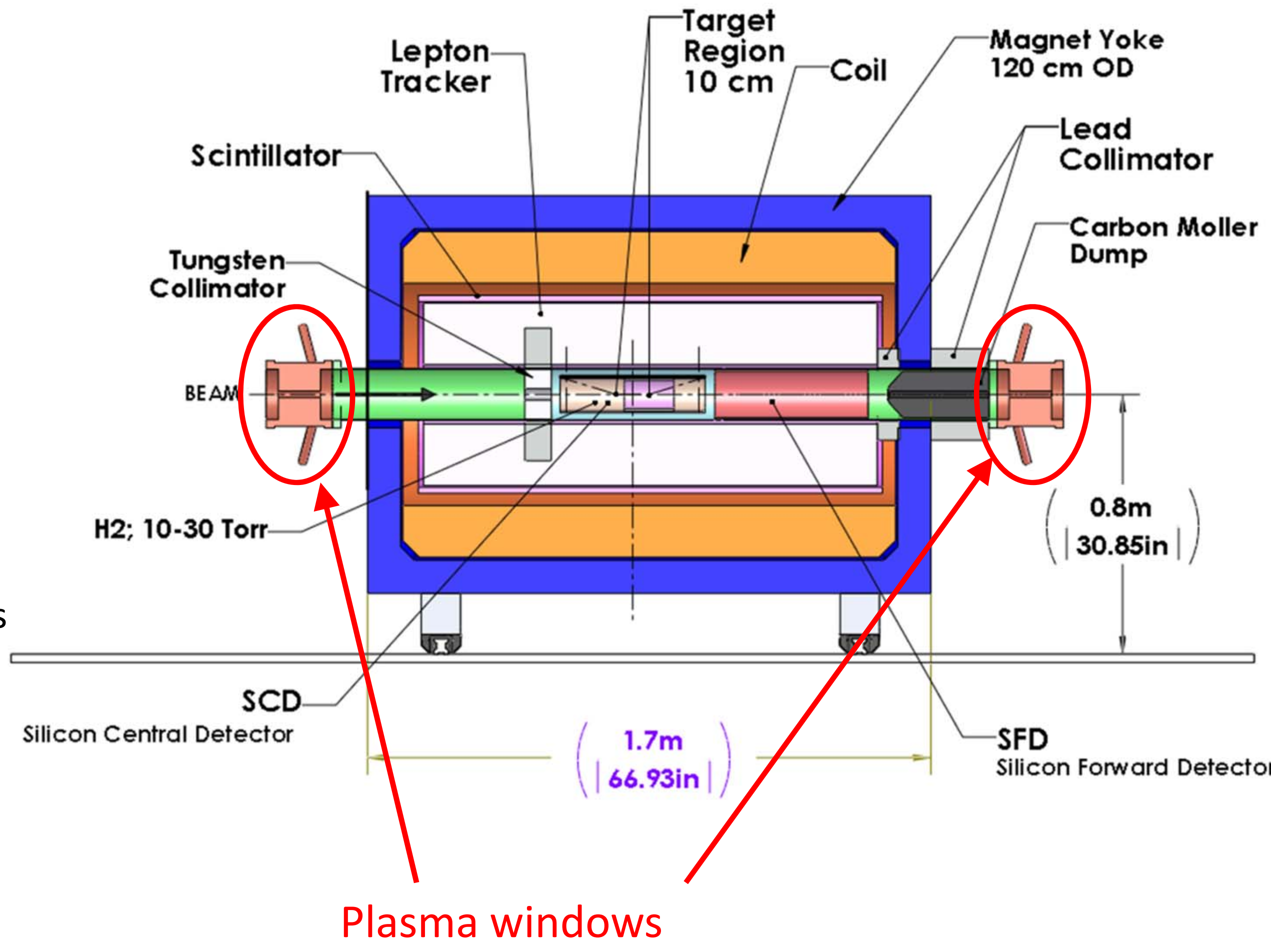


Cathode block:
Outside (upper),
Inside (lower)

Photos courtesy J. Bessuille (Bates, MIT), A. Hershcovitz (BNL)

Application to DarkLight

- Conventional design (no plasma windows)
  - Two conductance limiting apertures
    - 2 mm diameter, 10 cm length
  - Dense H_2 gas target
    - $10^{19}/cm^2$ thickness, 10–40 torr
- With plasma windows: expect 6 mm aperture feasible for DarkLight
  - And at higher target pressures, if desirable
  - Fewer stages of differential pumping needed
  - Reduces tight constraints on beam optics
- A previous plasma window experiment
  - Confined 280 mbar deuterium gas using a 5 mm aperture



Search for an invisibly decaying A'

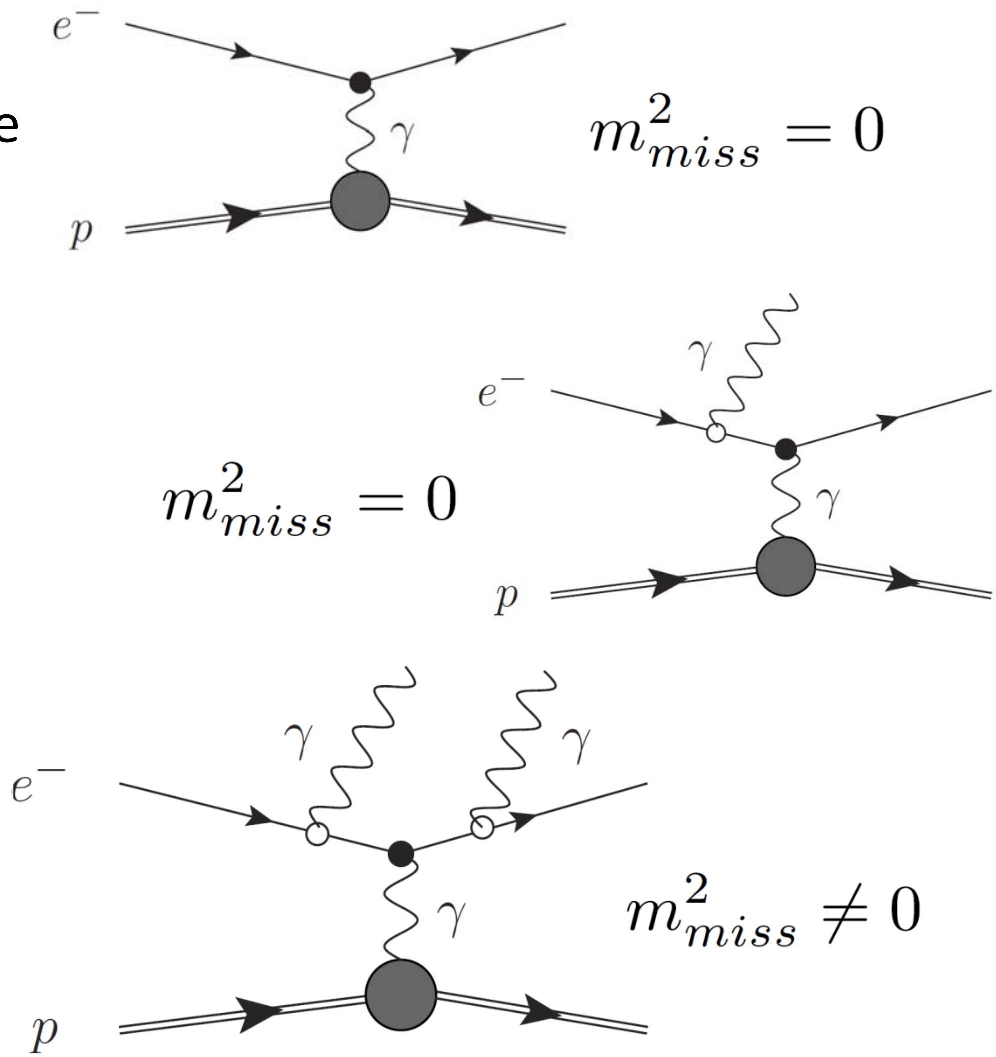
- If the A' decays into dark matter or some other invisible state

  $e^- + p \rightarrow e^- + p + A'$, $A' \rightarrow$ invisible

- Can look for it via missing mass

  (missing mass)$^2 = (p_1 + p_2 - p_3 - p_4)^2$

- Main backgrounds are
  - $e^-p \rightarrow e^-p\gamma$
  - $e^-p \rightarrow e^-p\gamma\gamma$
  - $e^-p \rightarrow e^-p\nu\nu$ (negligible this far from the *Z* pole)
  - Pileup



See Kahn & Thaler, *Phys. Rev.* **D86**:115012 (2012) and Y. Kahn at *Physics of Electron Beams Workshop*, MIT, March 2013

Dealing with backgrounds

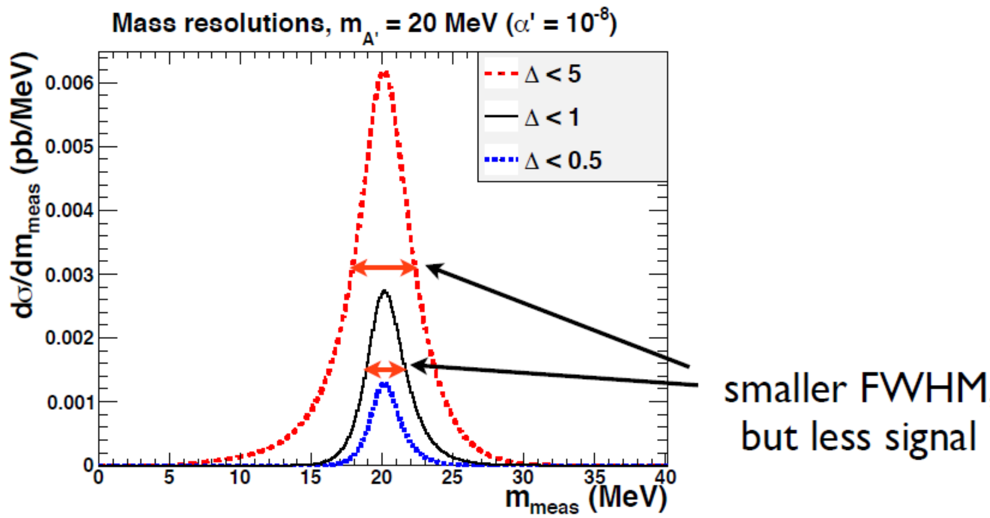
- Use event selection criteria to improve mass resolution
  - Cut on $E_{\mathrm{miss}}/m_{\mathrm{miss}}$
- Reject pileup using negative missing mass-squared cut
- Add photon detection (veto) to reject many QED backgrounds and to reduce data rate
  - Keep from saturating the event reconstruction rate with QED backgrounds
- These techniques are applicable to other experiments beside DarkLight

Dealing with mis-measurement: $E_{\text{miss}}/m_{\text{miss}}$ cut

- Mass resolution degrades with increasing *A'* energy
- So restrict missing energy based on missing mass

$$\sigma_m^2 = \left(\frac{E}{m}\right)^2 \sigma_E^2 \oplus \left(\frac{p}{m}\right)^2 \sigma_p^2$$

$$\frac{E}{m} \equiv 1 + \Delta$$

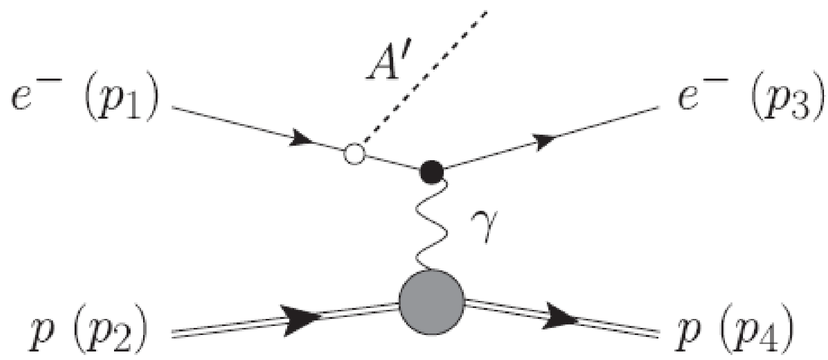


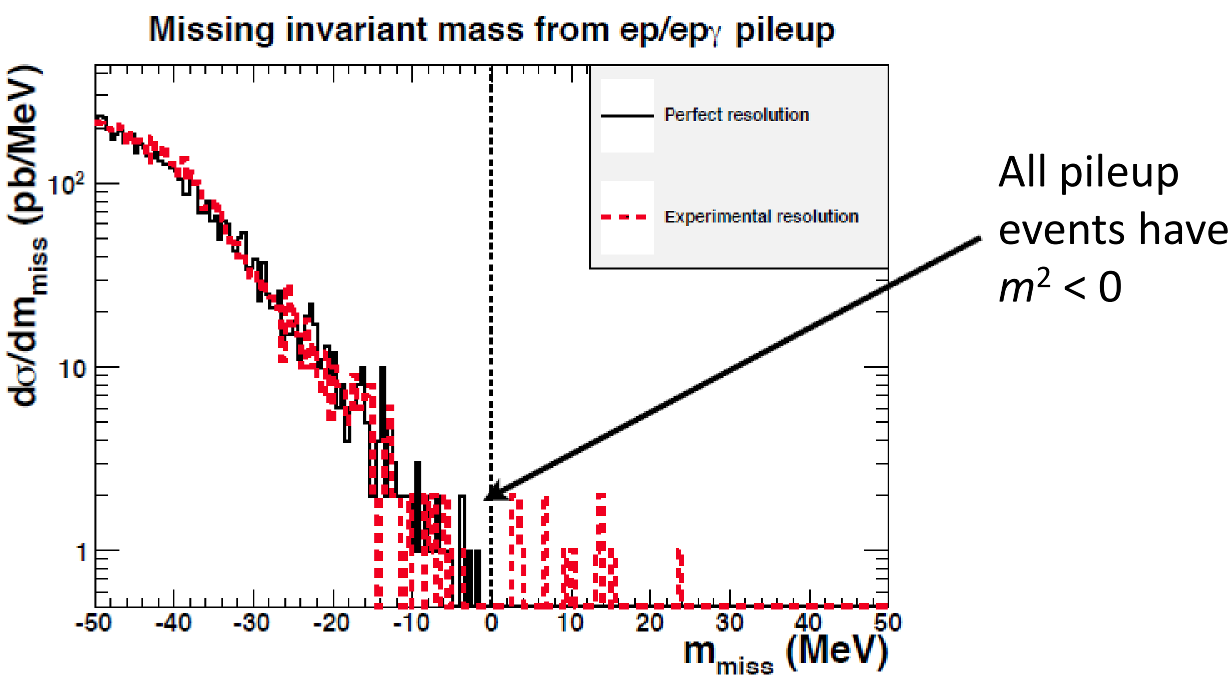
Pileup rate

- High rate of elastic scattering has big impact on triggering
  - Elastic rate x luminosity:
    - 1.1×10^{8} pb x 6×10^{35} cm^{-2} s^{-1} = 65 MHz elastic rate
  - TPC drift time 20 μs
    - 1300 events in pipeline (free-running trigger)
  - Each track timestamped to about 10 ns
  - In 10 ns window, overlap likely only for two scattering events

Pileup background

- Consider two events in the same time window
  - $p_1+p_2 \rightarrow p_3+p_4$
  - $p_1+p_2 \rightarrow p'_3+p'_4+q$
- Swap an electron
  - $m^2=(p_1+p_2-p'_3-p_4)^2$
  - $m^2=(p_3+p_4-p'_3-p_4)^2$
  - $m^2=(p_3-p'_3)^2$
  - $m^2 < 0$
- Same holds for swapping a proton or pileup with any elastic event

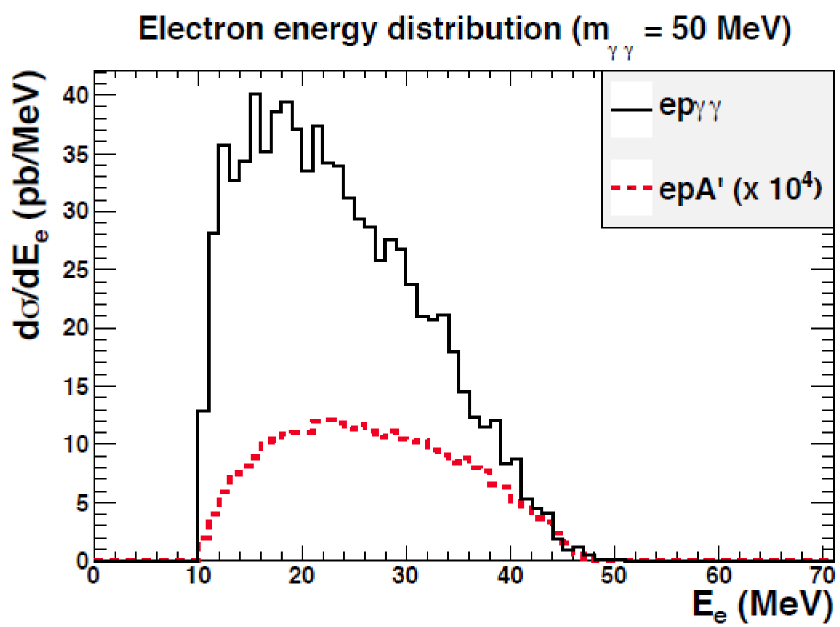


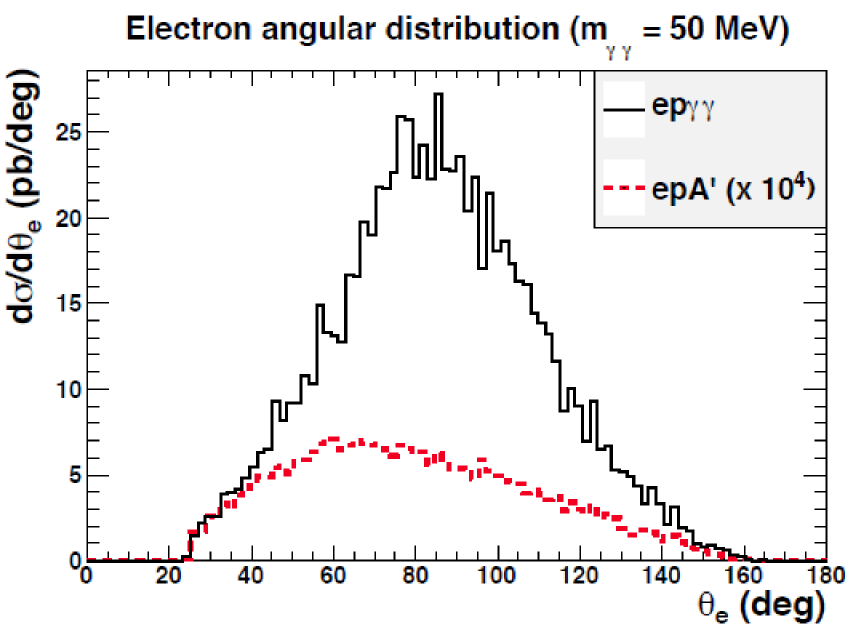


$m_{miss} \equiv \text{sign}(m^2) \times \sqrt{|m^2|}$

$e^-p \rightarrow e^-p\gamma\gamma$ background

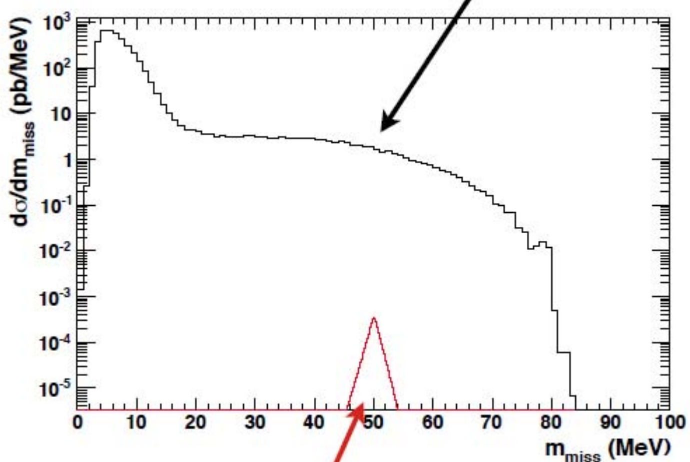
- Four bodies, same kinematics as signal
- Requires photon detection
  - Otherwise it is irreducible



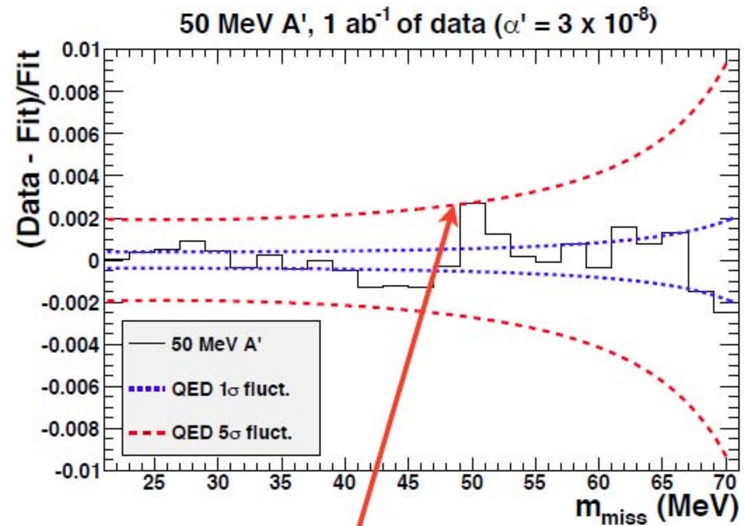


Observing a signal

photon background



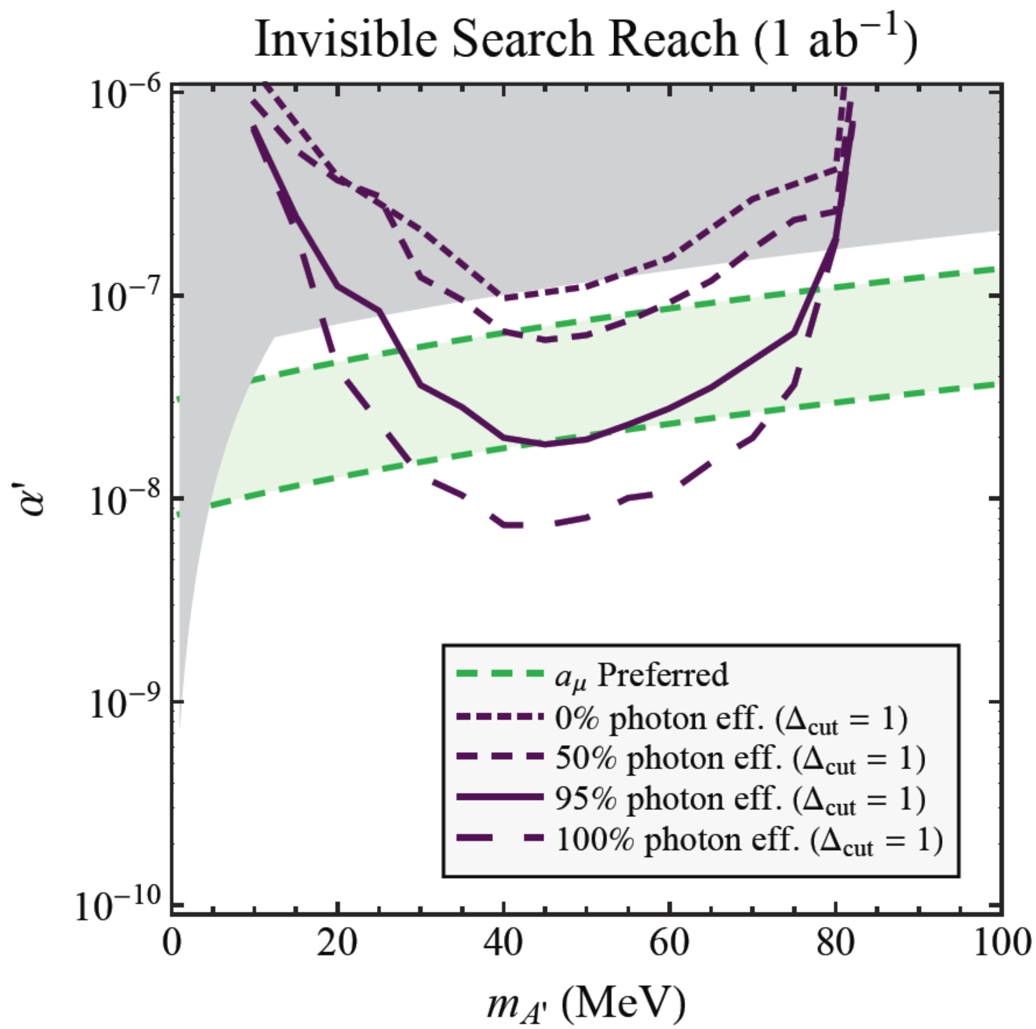
tiny signal



can actually see signal over enormous background, with enough statistics!

Invisible search reach

- Curves shown are for a 5σ signal-to-background signal
- For varying photon detection efficiencies
- Cannot detect if both photons go down the beampipe



Physics of Electron Beams workshop

- The first PEB workshop was held at MIT in March 2013
  - http://web.mit.edu/lns/PEB_Workshop/index.html
- Aim was to study what you can do with 0–300 MeV e^- beams
  - The physics (experiment and theory)
  - Accelerator technology
- There is a lot of interest in this energy range
- 100 participants
  - Almost 50% international participation
- Workshop was the first of a series
  - Mainz will host the next one

Workshop to Explore Physics Opportunities
with Intense, Polarized Electron
Beams up to 300 MeV

March 14-16, 2013
MIT, Cambridge, Massachusetts

Many topics relevant to NLWCP included

- Plenary talks
  - Maxim Pospelov: *Light and Dark: a Survey of New Physics Ideas in the 1-100 MeV Window*
  - Yury Kolomensky: *Parity Violation Physics*
  - Chris Carlson: *Precision Nucleon Structure*
  - Achim Schwenk: *Nuclear Astrophysics and Electron Beams*
  - Eugene Chudakov: *Precision Electron Polarimetry*
- Parallel Sessions
  - 1: Parity Violation
  - 2: Dark Photons
  - 3: Nucleon Structure
  - 4: Physics with Nuclear Targets
  - 5: Technology

Parallel Session 2: Dark photons
Location: Cosman Room CTP 6C-442

Co-Convenors: **Peter Fisher, MIT**
Achim Denig, U. Mainz
Maxim Pospelov, U. Victoria

PS2A: Dark photon searches (11:30 to 13:00)
Chair: Peter Fisher

11:30 Search for Dark Photons at MAMI **(Harald Merkel)**
11:55 Heavy Photon Search experiment at JLab **(Stepan Stepanyan)**
12:20 Searching for new gauge bosons in the A' Experiment (APEX) at Jefferson Laboratory **(Philip Schuster)**

PS2B: Dark photon searches (14:00 to 15:30)
Chair: Achim Denig

14:00 Experimental concept and design of DarkLight, a search for a heavy photons **(Ray Cowan)**
14:25 DarkLight beam background measurements **(Narbe Kalantarians)**
14:50 Detectors for dark photon search with MESA **(Matthias Molitor)**
15:15 Discussion

PS2C: Theory (16:00 to 18:30)
Chair: Maxim Pospelov

16:00 Theoretical Description of Light Dark Gauge Boson Searches in Electron Scattering Fixed Target Experiments **(Tobias Beranek)**
16:30 Searches at e+e- colliders **(Fabio Bossi)**
17:00 The TREK/E36 Experiment at J-PARC **(Michael Kohl)**
17:30 Hidden Photons in Beam Dump Experiments and in connection with Dark Matter **(Sarah Andreas)**
18:00 Searching for an invisible dark photon with DarkLight **(Yonatan Kahn)**

Summary

- Extending DarkLight's reach beyond its initial design is quite feasible
  - Nominal reach based on 1 month commissioning, one month of running
  - Plasma windows need some engineering development, but are promising
    - Especially on a two- to ten-year timescale
  - Additional ideas such as a search for invisibly decaying particles also extends the reach
- New ideas relevant to NLWCP were presented at the March 2013 Physics of Electron Beams workshop
    - From theory, experiment, and accelerator viewpoints
    - http://web.mit.edu/lns/PEB_Workshop/index.html

Backup Slides

DarkLight at a glance

- Luminosity 6 x 10^{35} cm^{-2} sec^{-1}
  - FEL beam produces 6 x 10^{16} electrons/sec
  - At 100 MeV onto $10^{19}/cm^2$ target
  - 10 mA beam current
- FEL beam traverses both field and target
- Gas jet target provides point-like electron-proton interaction
- Target and tracker components in 0.5 T solenoidal magnetic field
  - Recoil proton detector
  - Silicon strips in forward direction
  - Lepton tracker
  - Trigger scintillator
- Coincident detection of scattered electron and recoil proton along with the dilepton final state

- Performance goals
  - 1 MeV mass resolution
  - Tracking of e^+/e^- with K.E. > 5 MeV
  - Tracking of protons with K.E. > 0.5 MeV
- Typical signal and background rates
  - QED bkg ($\sigma \approx 10^4$ pb): 6 kHZ
  - For $m_{A'} = 50$ MeV/c^2 ($\sigma \approx 10^{-2}$ pb): 5200 counts/day
- Issues
  - Huge QED rate
  - Pileup
  - Beam halo/heating
  - Survivability in 1 MW beam
  - Multiple scattering, etc, at low momenta (10's of MeV/*c*)

The Jefferson Lab FEL

- Use the 1 MW, 100 MeV e⁻ beam at the JLab FEL
- Energy-recovery linac
  - SRF technology
  - High-power optics
  - Proven reliability over many years
  - Recovers about 75% of electron beam energy
- Originally built to provide IR & UV light
- Beam heating/halo/rad bkg tests last July
  - See Narbe's talk next
- Some upgrades needed for DarkLight
  - Lower emittance (smaller charge/bunch)
  - Higher rep rate: 75 MHz → 750 MHz