DARKLIGHT 1c

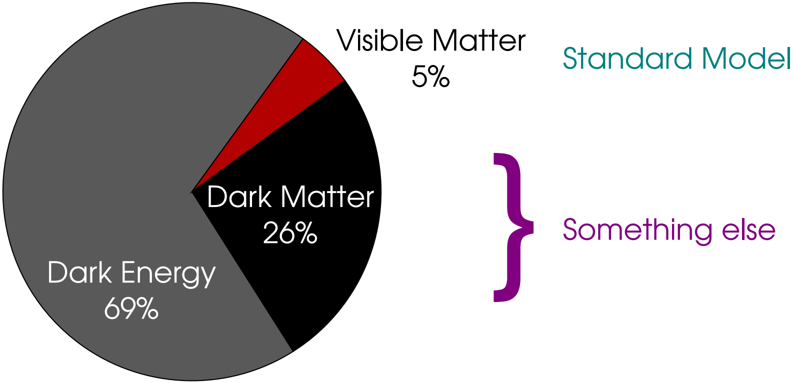
Search for New Physics in e+e- Final States Near an Invariant Mass of 17 MeV Using the CEBAF Injector

Jan C. Bernauer

JLAB PAC46 - July 2018

Massachusetts Institute of Technology

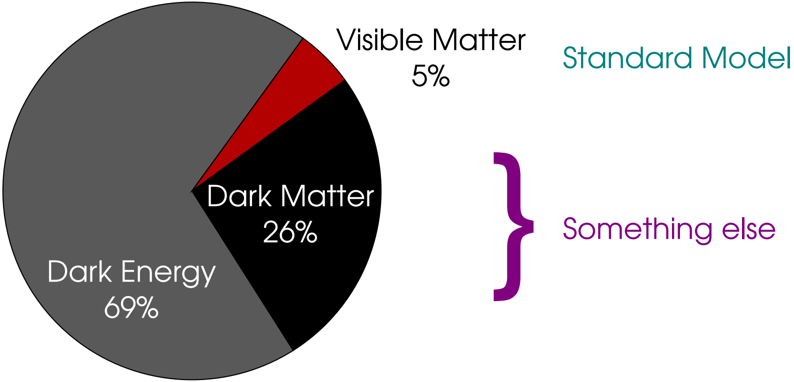
The search for Dark Matter



Evidence for dark matter force $\longrightarrow$ search for DM force carrier.

- Phase space large for simple, infinite for complex models

The search for Dark Matter



Evidence for dark matter force $\longrightarrow$ search for DM force carrier.

- Phase space large for simple, infinite for complex models
- Two approaches: Cover large area – or look at anomalies
  Beryllium anomaly, $g_\mu - 2$, proton charge radius

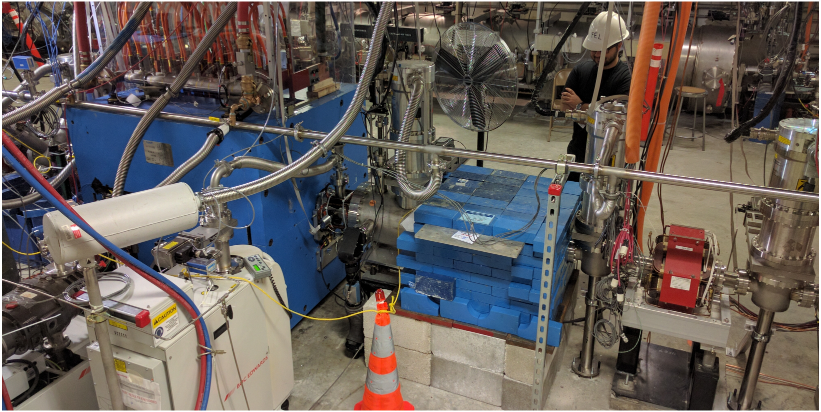
DARKLIGHT timeline (end of 2015)

Phase 1: R&D, funded

- Will run at Jefferson Lab's LERF (fka. FEL)
  - 1a: First internal target/solenoid in an ERL (2016)
  - 1b: First measurement of radiative Møllers at 100 MeV (2016)
  - 1c: Prototype with reduced acceptance (2017)

Phase 2: Full experiment

- Simulation / design work for full experiment still in progress.



- Search for A', via $e + p \to e' + p' + X$
  $X \to e^+e^-$ (visible) or $X \to (f^+f^-)||...$ (invisible)
- Record all outgoing visible momenta $\to$ thin target

DARKLIGHT timeline (mid 2018)

Phase 1: R&D, funded

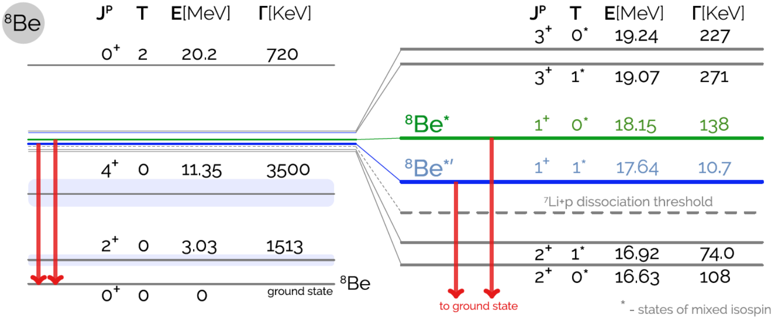
- Is run at Jefferson Lab's injector, LERF and MIT's HVRL
  - 1a: First internal target/solenoid in an ERL (2016)
  - 1b: First measurement of radiative Møllers at 2.5 MeV (2018)
  - 1c: Test of 17 MeV fifth force (2019)

Phase 2: Full experiment

- Simulation / design work for full experiment still in progress.

Many images from arXiv:1707.09749

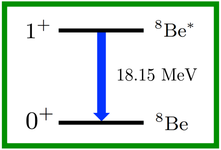
^{8}Be is special: two narrow, highly energetic states which can decay to ground state via E/M

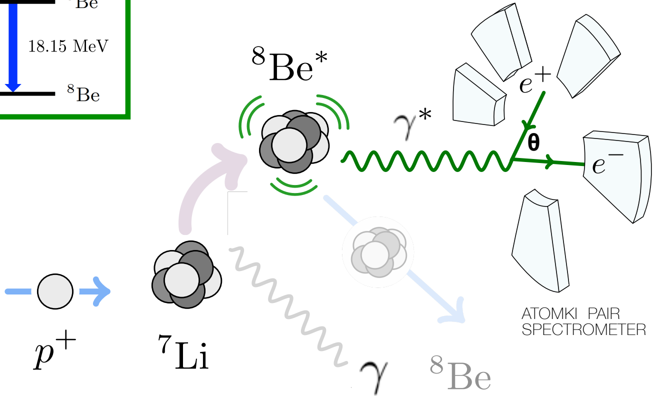


Decay modes of $^{8}Be(18.15)$

Hadronic, electromagnetic and through internal pair conversion

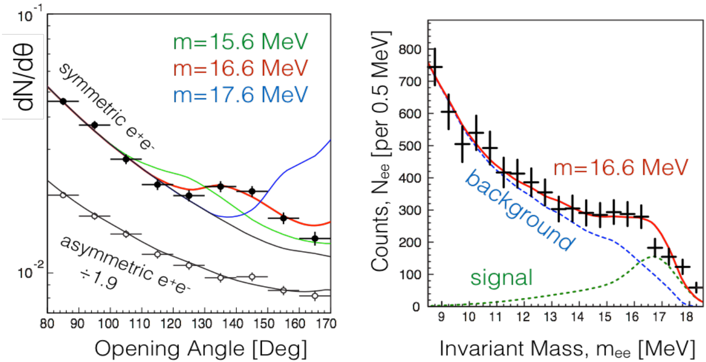
The Atomki experiment





1.04 MeV proton beam on ^7Li to $^8Be(18.15) + \gamma$. Followed by decay. Looked at $e^{\pm}$ pairs from internal conversion.

The Beryllium anomaly



(from: arXiv:1707.09749v1, modified from PRL 116 042501 (2016))

- Feng et al. (PRL 117, 071803 (2016)): Proto-phobic force to evade current limits

Why believe it?

- This model has $\chi^2/d.o.f.$ of 1.07, significance of 6.8σ
- Bump, not last bin effect
- Rises/falls when scanning through proton energies around resonance
- Excess only happens for symmetric-energy pairs
- Preliminary reports of same excess in $^8Be(17.6)$ (same group)

Why not believe it?

- The detector acceptance has a minimum at 140°
- DM boson interpretation is proto-phobic to evade NA48/2 limits
  - Actually: $\frac{\epsilon_p}{\epsilon_n}$ coupling below $\pm 8\%$. Z^0 is $\sim 7\%$

How can we measure it at JLab?

- This particle can be produced via Bremsstrahlung, predominantly ISR off the electron.
- Measure

$$e^- Ta \to e^- Ta\, X, \text{ followed by } X \to (e^- e^+)$$

- Irreducible background:

$$e^- Ta \to e^- Ta\, \gamma^\star \to e^- Ta\, e^+ e^-$$

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- 4π detection $\longrightarrow$ two spectrometers, measure only e^+ and e^- in coincidence
- Best kinematics:
  - highest production rate if X takes all electron energy. CS rise beats all.
  - with limited and same out-of-plane acceptance, symmetric angle optimal.

Background

- Main background is NOT the irreducible one. Random coincidences between
  - radiative elastic electrons
  - positrons from (virtual) photon pair-production where e^- is missed
- Can optimize by moving electron arm backward.

Proposed setup

- 45 MeV beam, 150 μA on 10 μm tantalum foil
  $\longrightarrow$about 0.3 inv. fb/s hydrogen equivalent
- Two spectrometers
  - $\pm 2^\circ$ in-plane, $\pm 5^\circ$ out-of-plane
  - Positron spectrometer at 16°, 28 MeV
  - Electron spectrometer at 33.5°, 15 MeV

Spectrometer design parameters

Kinematic var.	Acc.	Inv. mass res.	est. res. on focal plane	Error
in-plane angle	$\pm 2°$	$22\ \frac{keV}{mrad}$	5mm/7cm$\rightarrow$1.4 mrad	32 keV
out-of-plane angle	$\pm 5°$	$5\ \frac{keV}{mrad}$	1.5°	133 keV
momentum	$\pm 20\%$	$85\ \frac{keV}{\%}$	5mm/30cm$\rightarrow < 0.2\%$	17 keV

- Spectrometer can measure two quantities on first plane (position), but has additional multiple scattering for third quantity (angle)

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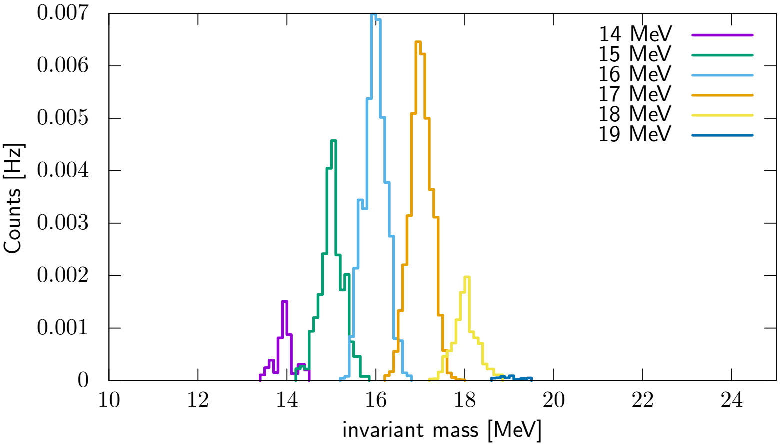
- Spectrometer can measure two quantities on first plane (position), but has additional multiple scattering for third quantity (angle)
- Simple dipole spectrometer, dispersive direction out-of-plane $\rightarrow$ out-of-plane angle is measured worst.
- Sum for two spectrometers: $194\ keV$, assumed $250\ keV$
- Have to do full simulation when realistic magnetic field is calculated.

Counting rates: X signal



Background rates

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... but 120 kHz e^+ singles

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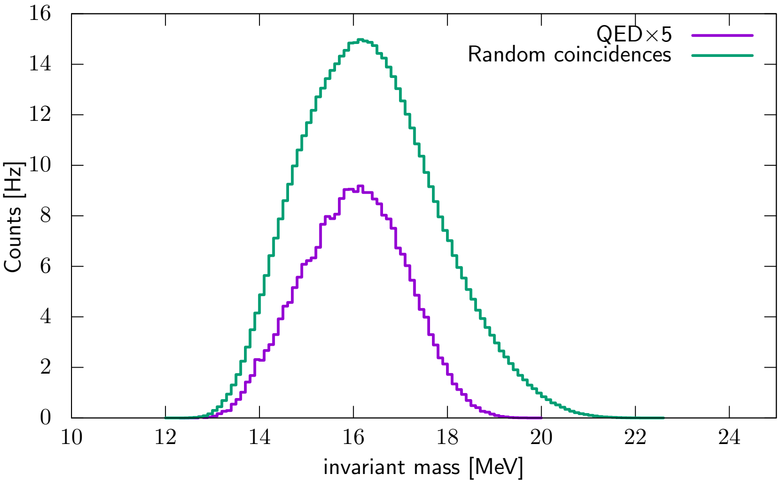
Elastic e^- + internal Bremsstrahlung: 6 MHz

$\longrightarrow$ Random coincidence rate 500 Hz

(at 1.5 GHz bunch rate)

This is the minimum trigger rate and sets the sensitivity.

Counting rates: Backgrounds



Dominated by accidental background

- Random coincidences dominate
- Scaling with instantaneous luminosity:
  - Signal S ~ $\mathcal{L}$
  - QED background Q ~ $\mathcal{L}$
  - Accidental background A ~ $\mathcal{L}^2$
  - Sensitivity $\frac{S}{\sqrt{Q+A}} \sim 1$

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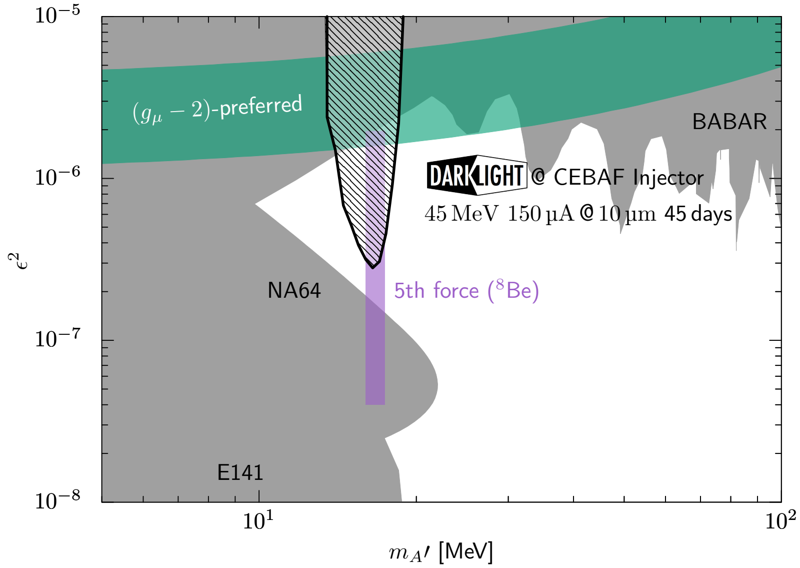
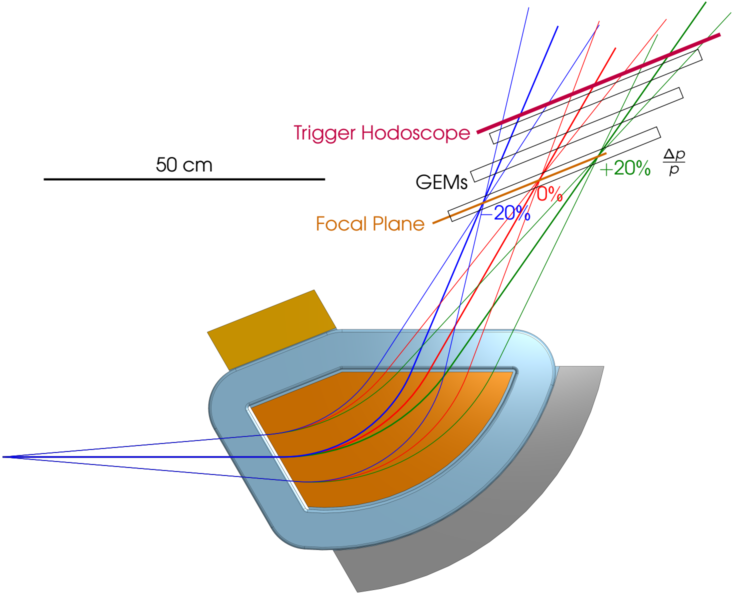
  - Sensitivity $\frac{S}{\sqrt{Q+A}} \sim 1$
- Sensitivity almost independent of luminosity. Scale is set by bunch-clock / time resolution

Reach

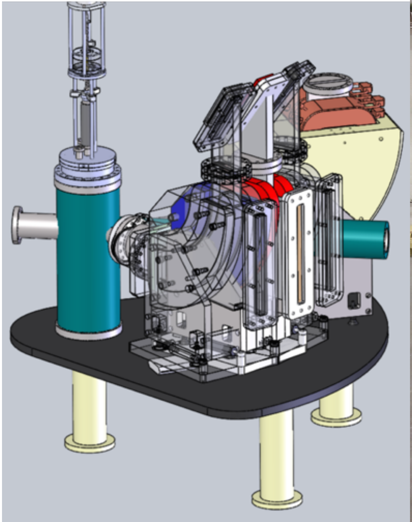


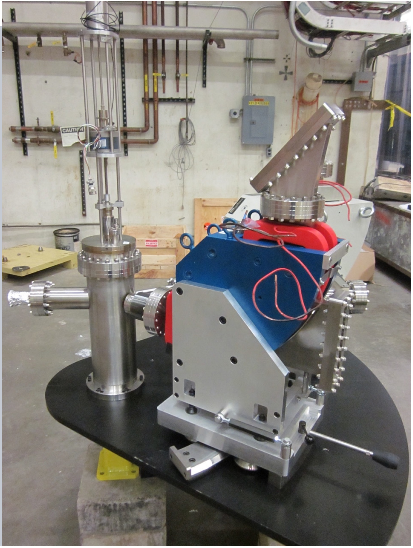
10^{-5}
10^{-6}
10^{-7}
10^{-8}
ϵ^2
$(g_\mu - 2)$-preferred
BABAR
DARKLIGHT @ CEBAF Injector
45 MeV 150 µA @ 10 µm 45 days
NA64
5th force (^{8}Be)
E141
10^1
10^2
$m_{A'}$ [MeV]

Spectrometers

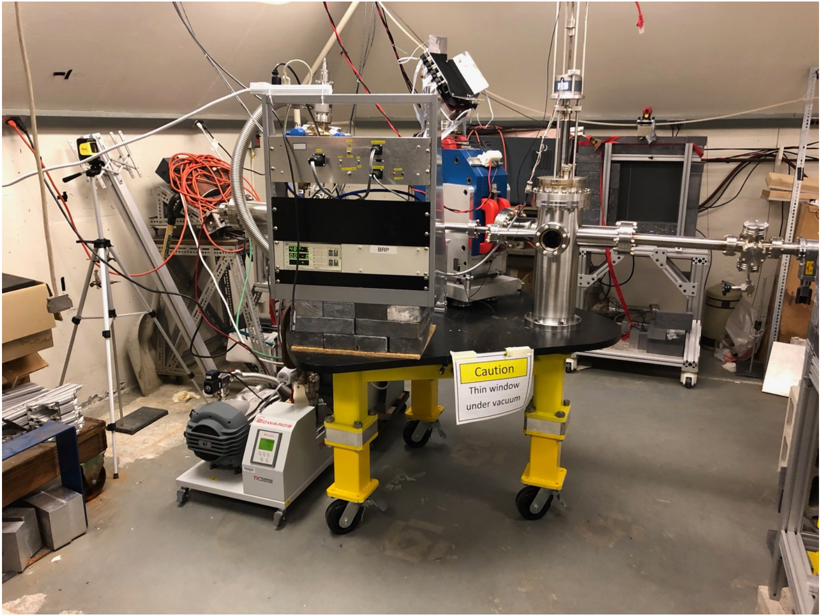


Experience: Møller at MIT HVRL

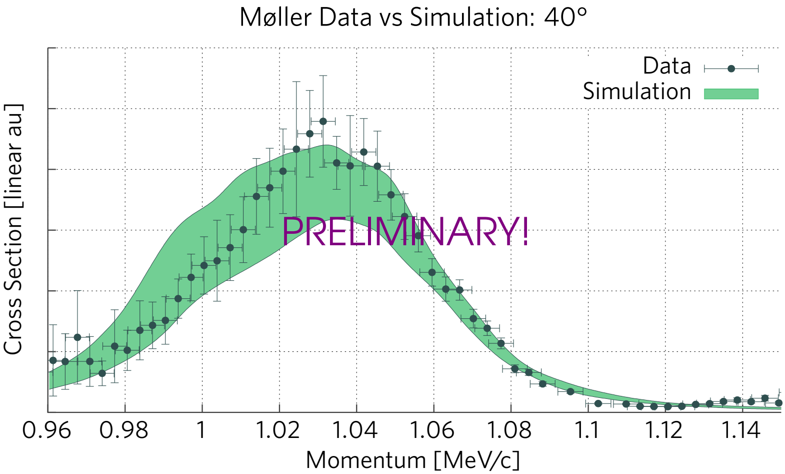




Møller experiment is running



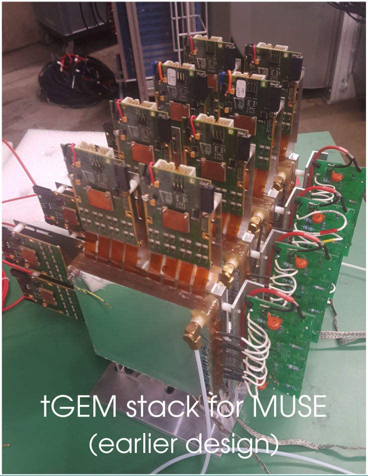
First data from Møller

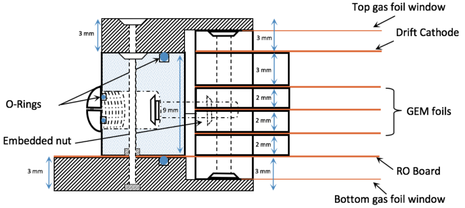


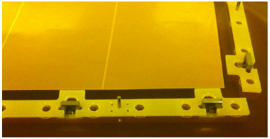
Plots and analysis provided by Charles Epstein

Tracking detectors

- Stack of three tGEMs, 25x40 cm, modified CERN design
- Readout via APVs and MPD4
- Hampton group is funded to and in progress to build these.
  (DL phase 1 MRI and 2018/19 JSA Graduate Fellowship award for Jesmin Neezer)


tGEM stack for MUSE
(earlier design)





Trigger detectors

- Scintillator Hodoscope, 10 segments/spectrometer
- Needs timing resolution of 500 ps
- MUSE beam hodoscope: 2 mm thick scintillator, SiPM readout: <100ps

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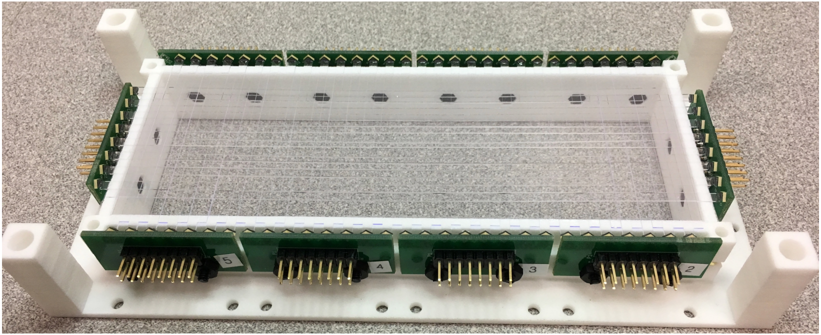
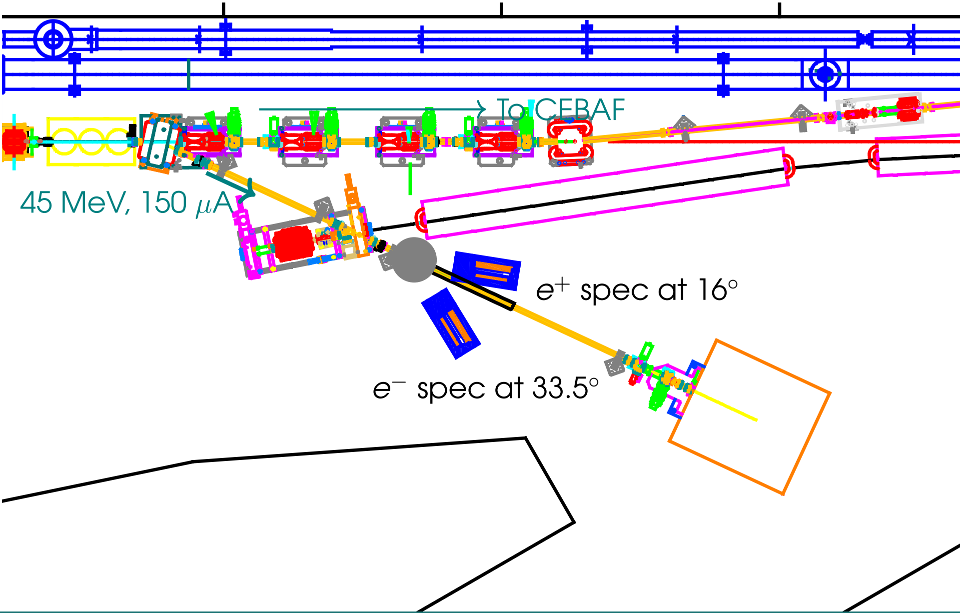
- Scintillator Hodoscope, 10 segments/spectrometer
- Needs timing resolution of 500 ps
- MUSE beam hodoscope: 2 mm thick scintillator, SiPM readout: <100ps
- Possibility: use fine-grained hodoscope as tracking detector
  - Streaming readout test platform



Space requirements



Modifications to beamline

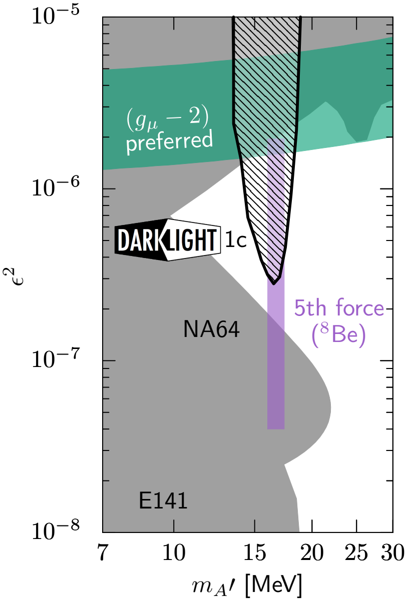
- Straight beam line segment replaced with target chamber + spool piece.
- Beam dump likely good enough, evaluating long term exposure.
- Normal operation and use of beamline for diagnostics possible with target in "out" position.

Could we run at LERF?

Yes, with these comments:

- Proposal was aimed at LERF, but we got guidance to look at injector, to facilitate a timely completion.
- Space should work out. Beam dump may be available.
- LERF needs laser upgrade or 2$\times$background.
- Experiment ideally run in several segments.

Summary



The **DARKLIGHT** *Collaboration*

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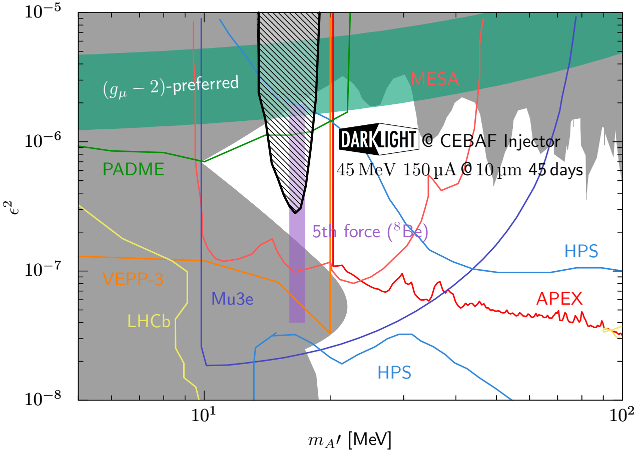
Backup slides

$\longrightarrow$backup slides$\longleftarrow$

Reach in comparison



- PADME: data taking planned for 2018 (6 month)
- Mu3e: Phase 1 planned for 2019-2021
- MESA: Did not include random coincidences, post 2021
- VEPP-3: Schedule not certain
- LHCb: Run 3, rejection for proto-phobic force not clear

Response to Review of Proposal PR12-18-006-PHY

The collaboration is appreciative of the strong endorsement of the scientific motivation for our proposed experiment, especially the importance of its timely completion. In addition, we found the technical issues raised in the review to be reasonable and constructive. Here, we provide a summary of our responses.

LERF running

August 2016 running established:

- Operating windowless hydrogen gas target
- Møller dump concept validated
- Effect of solenoid on LERF beam observed, explained and compensation scheme developed
- No showstoppers encountered

Papers are being written on

- The windowless hydrogen gas target
- The effect of the 0.5 Tesla solenoid on the LERF beam

Scintillator trigger

Several issues were raised:

- Thickness: Both considerations of timing resolution and background insensitivity push for a thinner scintillator. We have specified a thickness of 2 mm in the proposal.
- Timing resolution: A timing resolution of about 500 ps is adequate for the experiment.

We have experience with 2 mm thick, but less wide, scintillators used in the beam hodoscope for MUSE at PSI. They easily achieve sub 100 ps time resolution with SiPM readout.

Target cooling

- The beam deposits about 4 W in the target foil.
- Experience at Mainz with running small electrical motors in vacuum:
  Spinning the foil technically straightforward, eliminates the risk of accidental melting.
- Will consider the option to water cool the target and consult with the JLab target group.

Spectrometer design

- Conceptual design finished.
- Based on expertise building the radiative Møller experiment at MIT.
- Full magnetic field calculation is in progress.
- Once the experiment is approved, high priority to completely specify the spectrometer design.

Detector resolutions

- Geant4 simulations are in progress.
- In-plane angle and momentum is measured using the first layer of the GEM, minimizing the effect of multiple scattering.
- Out-of-plane angle measurement will be affected, being studied.
- To estimate the reach, we assumed resolutions easily achieved even with naive spectrometer designs and coarse detectors.

Backgrounds in detectors I

- Detailed Geant4 simulations must include the detailed mechanical design, background rates from e+/-, photons, neutrons etc.
- Experience of successfully simulating and measuring these backgrounds from the July 2012 test at the LERF.
  - For example, the giant dipole resonance is the main process for generating neutron backgrounds.
  - Extensive Geant4 simulations of the DarkLight-1a configuration that involved detailed tracking of low energy particles. This was essential to the design of the Møller dump that was successfully validated in August 2016 running.

Backgrounds in detectors II

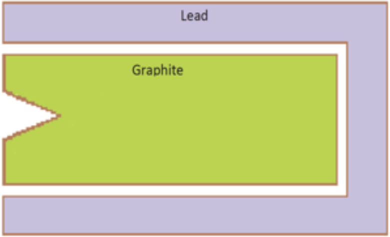
- Shielding to reject line-of-sight background trajectories from the target region to the detectors
- Collimator system to minimize particle trajectories hitting the magnets
- Minimized material thickness on the outside of the magnet bend so elastic scattered electrons can escape and are not rescattered.
- Photon background only affects the trigger rate, but not the background rate, because they will not produce tracks in the tracking detectors.

Beam dump

- The issue of a post-running radiation hazard due to activation of the beam dump during an extended running period will be looked into, in consultation with the JLab radiation control group.
- Initial findings indicate that it's likely that beam dump is useable.
- In case it's not, building of replacement beam dump is straight forward. See next slide.

6kW (40 MeV x 150 μA) beam dump

(Cite & Yilmaz, AIP Conf. Proc. 1722, 030001)



- Graphite core
  - low-cost
  - lower x-ray and neutron yield
  - $E_C = 110$ MeV for carbon
- Lead shielding
- Cone shaped entrance to redirect secondary electrons

- Fluka simulation yields:
  - few keV γs at edge of carbon, easily shielded by the lead
  - absorbed dose at the edge of carbon is low
- G. Fallon at MIT: estimate based on iron core, found a radiation level < 1mr/hr when shielded with 20 cm of lead. Dominant activation product: Mn-54.

Conclusion: Beam dump for DL-1c is technically straightforward.