Precision Measurements at Jefferson Lab

Testing the Standard Model and Exploring Beyond

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(College of William & Mary)

LNF Workshop on Jefferson Lab at 12 GeV
December 18, 2012

Outline

Standard Model and Beyond

Dark Heavy Photons
- APEX: A' Experiment
- HPS: Heavy Photon Search
- DarkLight

Parity-Violating Electron Scattering
- Qweak Experiment
- MOLLER Experiment
- SoLID Experiment (PV-DIS)

Precision Tests of the Standard Model

Contemporary view of the Standard Model

Standard Model is an effective low-energy theory of the more fundamental underlying physics.

Experimental approaches to uncover the underlying physics

- Energy frontier: direct searches for new particles
- Precision or intensity frontier: searches for indirect effects

Energy frontier

- Highest energies
- Few signature events
- Real particle creation
- *E.g.*: LHC, ILC

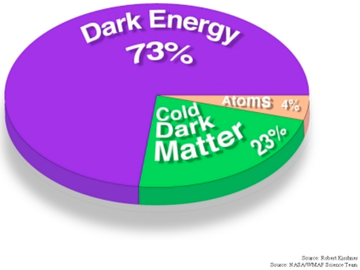
Precision or intensity frontier

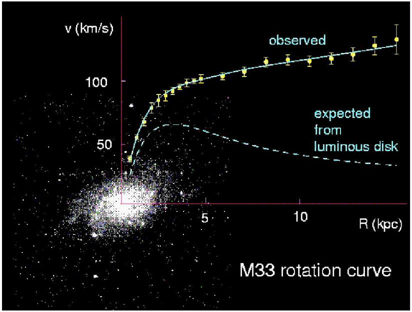
- Modest or low energies
- High statistical precision
- $g-2$, EDM, $\beta\beta$, rare decays
- Dark photons, parity-violation $\rightarrow$ Jefferson Lab 12 GeV

Precision Tests of the Standard Model

Challenges for the Standard Model

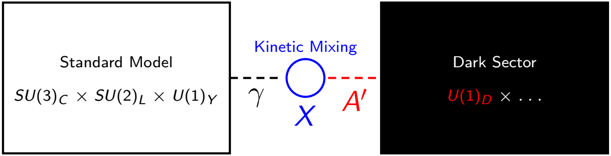
- Hierarchy problem: m_H much lower than naively expected
- Cold dark matter, dark energy: no observed explanations for 96% of the energy density of the universe





Dark Heavy Photons

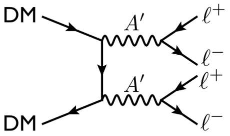
Dark gauge fields in addition to Standard Model



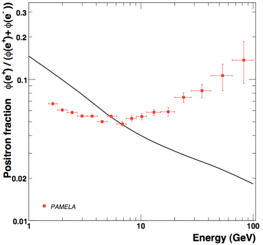
- Standard Model $SU(3) \times SU(2)_L \times U(1)_Y$ with extra $U(1)_D$
- New neutral vector boson: dark heavy photon A'
- No direct couplings between A' and Standard Model
- Kinetic mixing ϵ through X loops well above TeV
- Effective coupling strength to charged particles given by ϵq
- Region of interest is $m(A') \approx$ MeV–GeV with $\epsilon \approx 10^{-2}$–10^{-5}

Dark Heavy Photons: Candidates for Dark Matter

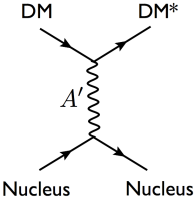
Dark matter annihilation



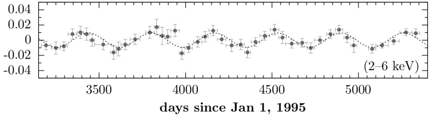
- PAMELA positron excess



Dark matter scattering



- DAMA/Libra seasonal variation

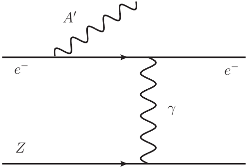


Dark Heavy Photons: Search Strategy

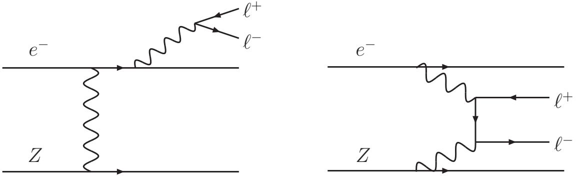
Search strategy at JLab

- Search for an e^+e^- resonance associated with A' decay (Bjorken, Essig, Schuster, Toro, Phys. Rev. D80, 2009)
- For heavy photon decay to lepton pair with coupling α' small, then lifetime large and vertex displaced
- Minimize hadronic processes (Z^2/A) with heavy targets

Signal

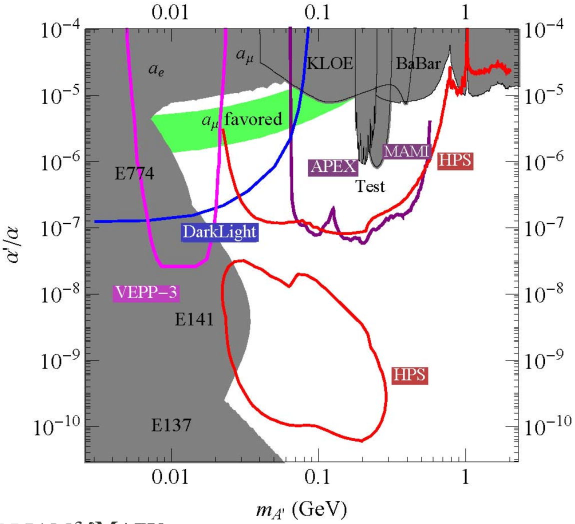


Bremsstrahlung and Bethe-Heitler (QED)



(a) (b)

Dark Heavy Photons: Planned Experiments



Parameters

- Mass $m(A')$
- Coupling ϵ with $\epsilon^2 = \alpha'/\alpha$

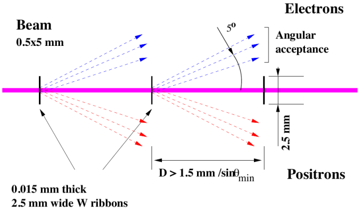
Experiments

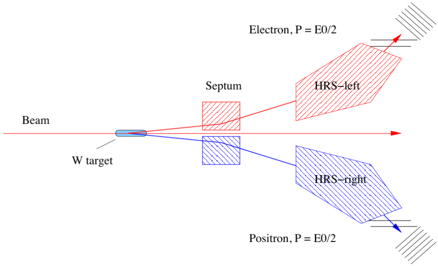
- APEX
- HPS
- DarkLight
- MAMI
- VEPP-3

APEX: The A' Experiment

Narrow Resonance Search

- Hall A High Resolution Spectrometers (HRS)
- Tungsten target ribbons

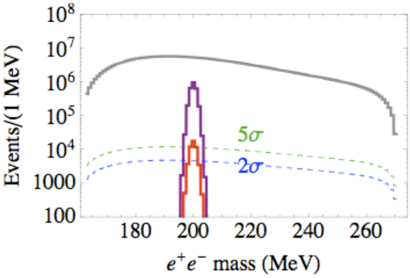


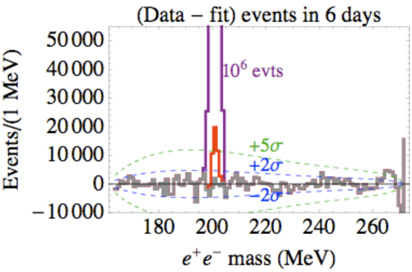


APEX: The A' Experiment

Narrow Resonance Search

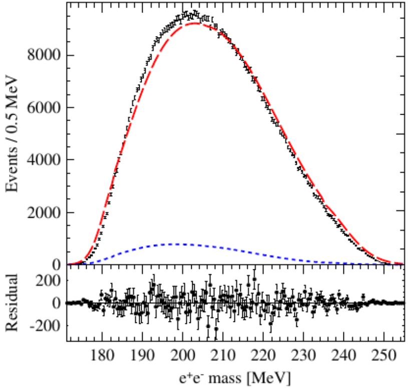
- Hall A High Resolution Spectrometers (HRS)
- Tungsten target ribbons
- Invariant mass distributions (with injected signal)





APEX: The A' Experiment

Published Results of Test Run



- Demonstration of feasibility (high read-out rates)
- 6 days of data: quick analysis and publication

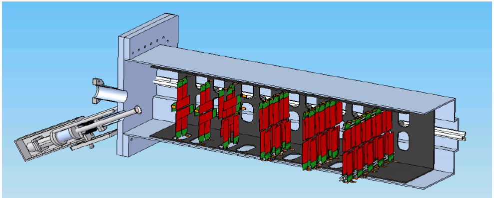
HPS: Heavy Photon Search

Forward Compact Spectrometer

- Spectrometer 20 m downstream of CLAS spectrometer in magnetic chicane (horizontal 'sheet of flame')
- 2.2 and 6.6 GeV electron beam (450 μA) on W foil targets
- Fast trigger and particle identification in calorimeter (ECal)
- Muon system with four hodoscope layers between iron absorbers
- Two modes of operation:
  - Narrow resonance search
  - Displaced vertex search

HPS: Heavy Photon Search

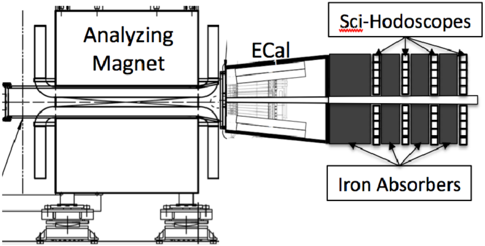
Target and Silicon Vertex Tracker



- Rotating target foil to achieve cooling
- SVT with 60 μm strip pitch

HPS: Heavy Photon Search

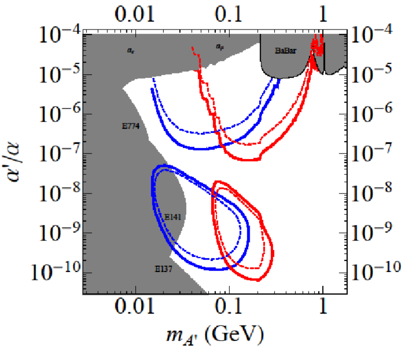
Analyzing Magnet, ECal, Muon System



- SVT inside 1 T magnetic field of analyzing dipole
- Calorimeter: inner modules $PbWO_4$, outer modules lead-glass
- Muon system

HPS: Heavy Photon Search

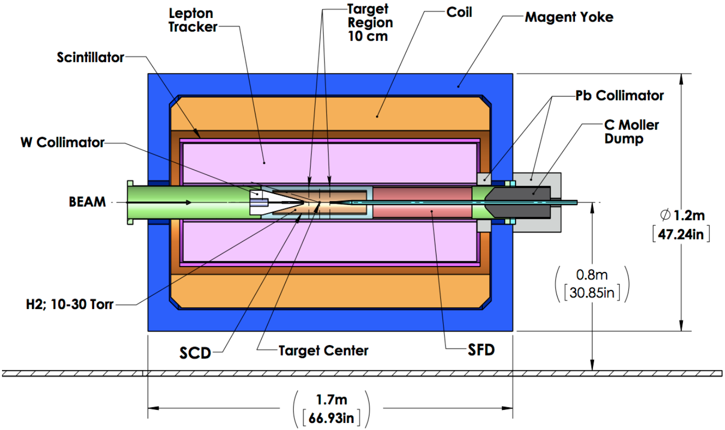
Parameter Space



- Two different beam energies: 2.2 GeV and 6.6 GeV
- Resonance search (large α') and displaced vertices (small α')

DarkLight

A' production on protons



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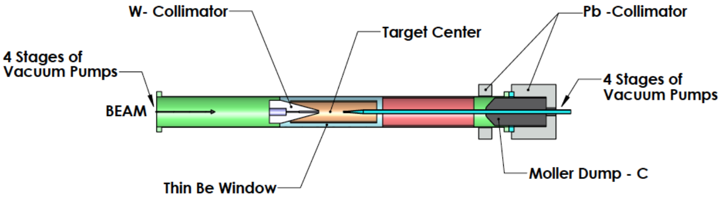
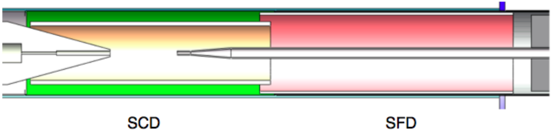


Internal H_2 gas target

- Small apertures confine gas, plasma windows considered
- Multiple differential pumping stages and target ends

DarkLight

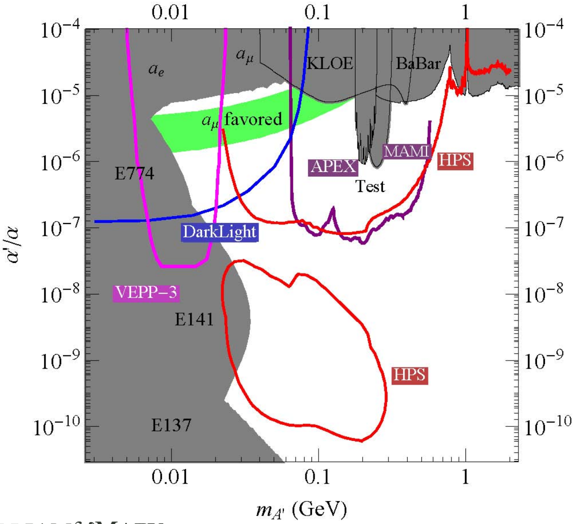
A' production on protons



Detector technologies

- 0.5 T toroidal magnet system
- Central and forward silicon trackers
- Drift chambers with 100 μm resolution
- Lead/scintillator sandwich calorimeter as trigger

Dark Heavy Photons: Planned Experiments



Parameters

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Experiments

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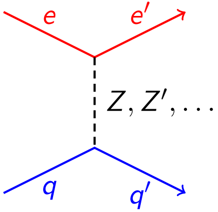
Electroweak Interaction

Glashow–Weinberg–Salam theory of weak interaction

- Left-handed leptons in doublets, right-handed in singlets
- Gauge symmetry $SU(2)_L \times U(1)_Y$ with couplings g, g'
- Parity-violation is used to measure electroweak parameters

Parity-violation neutral current (quarks)

$$\begin{aligned}\mathcal{L}_{PV}^{EW} &= -\frac{G_F}{\sqrt{2}} \left[g_A^e \left(\bar{e}\gamma_\mu\gamma_5 e\right) \cdot \sum_q g_V^q \left(\bar{q}\gamma^\mu q\right) \right. \\ &\quad + \left. g_V^e \left(\bar{e}\gamma_\mu e\right) \cdot \sum_q g_A^q \left(\bar{q}\gamma^\mu\gamma_5 q\right) \right] \\ &= -\frac{G_F}{2\sqrt{2}} \left[\sum_q \mathbf{C_{1q}} \left(\bar{e}\gamma_\mu\gamma_5 e\right) \cdot \left(\bar{q}\gamma^\mu q\right) \right. \\ &\quad + \left. \sum_q \mathbf{C_{2q}} \left(\bar{e}\gamma_\mu e\right) \cdot \left(\bar{q}\gamma^\mu\gamma_5 q\right) \right]\end{aligned}$$



Electroweak Interaction

Parity-violating electron scattering couplings

- Weak vector coupling: $\mathbf{C_{1q}} = 2g_A^e g_V^q$
- Weak axial coupling: $\mathbf{C_{2q}} = 2g_V^e g_A^q$
- Electron coupling: $\mathbf{C_{ee}} = 2g_V^e g_A^e$

Particle	Electric charge	Weak vector charge ($\sin^2\theta_W \approx 1/4$)
u	$+2/3$	$-2C_{1u} = +1 - 8/3 \cdot \sin^2\theta_W \approx +1/3$
d	$-1/3$	$-2C_{1d} = -1 + 4/3 \cdot \sin^2\theta_W \approx -2/3$
n(udd)	0	$Q_W^n = -1$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$
e	-1	$Q_W^e = -1 + 4\sin^2\theta_W \approx 0$

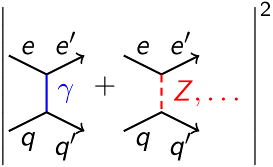
Electron and proton weak charge Q_W^e and Q_W^p

Suppression of weak charges $\rightarrow$ *sensitive to new physics*

Parity-Violating Electron Scattering

Interference of photon and weak boson exchange

$\sigma =$



Asymmetry between left and right helicity

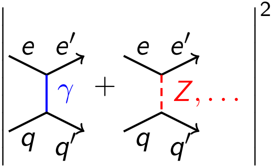
$$\mathcal{M}^{EM} \propto \frac{1}{Q^2} \qquad \mathcal{M}^{NC}_{PV} \propto \frac{1}{M_Z^2 + Q^2}$$

$$A_{PV}(p) = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\mathcal{M}^{NC}_{PV}}{\mathcal{M}^{EM}} \propto \frac{Q^2}{M_Z^2} \quad \text{when } Q^2 \ll M_Z^2$$

Parity-Violating Electron Scattering

Interference of photon and weak boson exchange

$\sigma =$



Asymmetry between left and right helicity in protons

$$A_{PV}(p) = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[\frac{\epsilon G_E G_E^Z + \tau G_M G_M^Z - (1 - 4\sin^2\theta_W)\epsilon' G_M G_A^Z}{\epsilon (G_E)^2 + \tau (G_M)^2} \right]$$

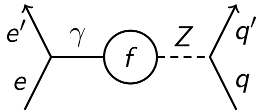
In the forward elastic limit $Q^2 \to 0$, $\theta \to 0$ (plane wave)

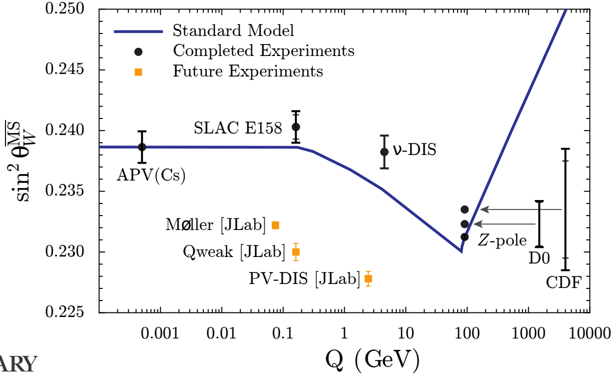
$$A_{PV} \xrightarrow{Q^2 \to 0} \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p + Q^2 \cdot B(Q^2) \right] \sim Q_W^p$$

Parity-Violating Electron Scattering

$Q_W^{e,p} \sim 1 - 4\sin^2\theta_W$

- Precision measurement $\sin^2\theta_W$
- Running due to loop diagrams
- Effects from TeV-scale physics





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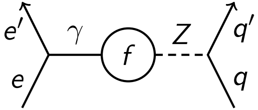
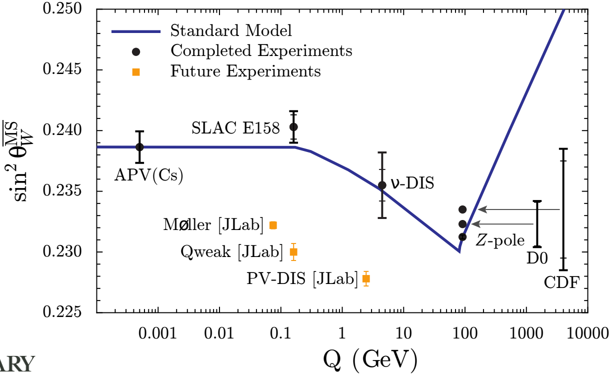




Parity-Violating Electron Scattering at Jefferson Lab

Q_{Weak} Experiment

- Measurement of Q_p^W in $\vec{e}p \to e'p$ on protons in hydrogen
- Completed, preliminary results released in fall 2012

MOLLER Experiment

- Measurement of Q_e^W in $\vec{e}e \to e'e$ on electrons in hydrogen
- Planned for running at Jefferson Lab 12 GeV

SoLID Experiment (PV-DIS)

- Measurement of $C_{1,2q}$ in $\vec{e}p \to e'p$ on hydrogen, deuterium
- Planned for running at Jefferson Lab 12 GeV

The Q_{Weak} Experiment

- Precision measurement of a quantity suppressed by fundamental symmetries ($Q_W^p \approx 0$, asymmetry of 230 ppb)
- Elastic scattering of electron beam on proton target to measure the proton weak charge Q_W^p to a precision of 4%

Pushing the envelope of intensity (more events)

- Higher beam current (180 μA versus usually $< 100\,\mu$A)
- Longer cryo-target (35 cm versus 20 cm, < 40 ppb 'boiling')
- Higher event rates up to 800 MHz (integration)

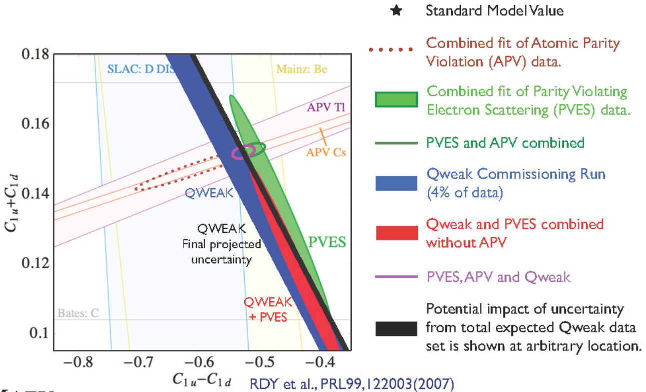
Pushing the envelope of precision

- Electron beam polarization precision of 1% at 1 GeV
- Helicity-correlated asymmetries controlled at ppb level

The Q_{Weak} Experiment

Preliminary Result

- For 4% of total data: $Q_W^p = 0.0945 \pm 0.020$ ($\delta Q_W^p = \pm 21\%$)
- Full data set: $\delta Q_W^p = \pm 4\%$ and $\delta \sin^2 \theta_W = \pm 0.3\%$



RDY et al., PRL99,122003(2007)

The MOLLER Experiment

Measurement **o**f **L**epton **L**epton **E**lastic **R**eaction

- Elastic scattering of electrons on electrons in hydrogen
- Precision measurement of the weak charge of the electron $Q_W^e \approx 0$ at 11 GeV
  - Asymmetry $A_{PV} \approx 35.6\,\text{ppb}$, with precision $\delta A_{PV} = \pm 0.7\,\text{ppb}$
  - Precision $\delta Q_W^e \approx \pm 2.1\%$, $\delta \sin^2\theta_W = \pm 0.1\%$

Pushing the envelope of intensity (more events)

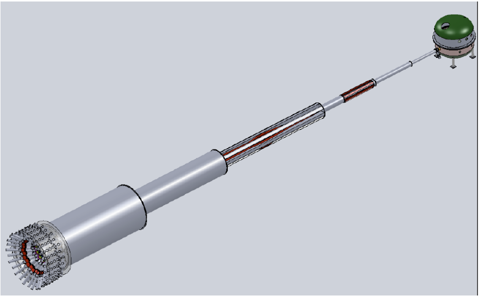
- Even higher luminosity: $85\,\mu\text{A}$ on 1.5 m long cryo-target
- Event rates up to 150 GHz

Pushing the envelope of precision

- Electron beam polarization precision of 0.4% at 11 GeV

The MOLLER Experiment

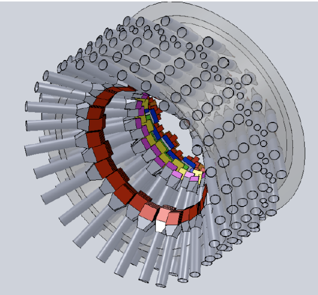
Experimental Layout



- Long, narrow hybrid toroidal spectrometer system
- Focusing of *ee* and *ep* on segmented quartz detector rings

The MOLLER Experiment

Experimental Layout



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The MOLLER Experiment

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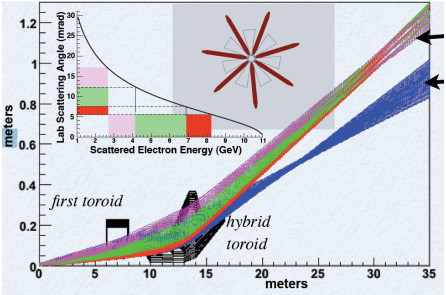

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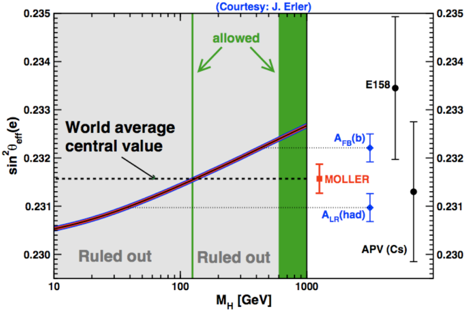
The MOLLER Experiment

Projected precision on $\sin^2\theta_W$



Future experiments

- Better precision will only be reached at linear collider, neutrino factory, or muon collider

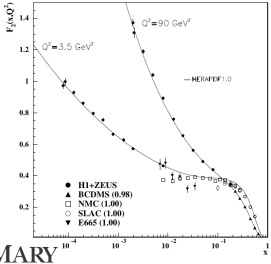
The SoLID Experiment

Deep Inelastic Scattering: longitudinal nucleon structure

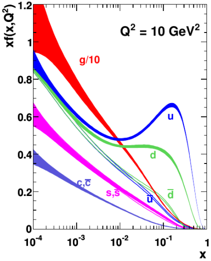
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\left(\frac{2}{M}F_1(x)\sin^2\frac{\theta}{2} + \frac{1}{\nu}F_2(x)\cos^2\frac{\theta}{2}\right)$$

Quark structure through **DIS**

- $F_2(x) = x\sum_q e_q^2(q+\bar{q}) \approx 2xF_1(x)$ (Callan-Gross)



$$F_2(x) \Rightarrow q(x)$$



The SoLID Experiment

Deep Inelastic Scattering: longitudinal nucleon structure

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Quark structure through **PV-DIS**: interference of γZ

- $F_2^{\gamma Z}(x) = x \sum_q e_q g_q^V (q + \bar{q}) \to a_1(x) \sim \sum_q e_q C_{1q} (q + \bar{q})$
- $F_3^{\gamma Z}(x) = x \sum_q e_q g_q^A (q - \bar{q}) \to a_3(x) \sim \sum_q e_q C_{2q} (q - \bar{q})$

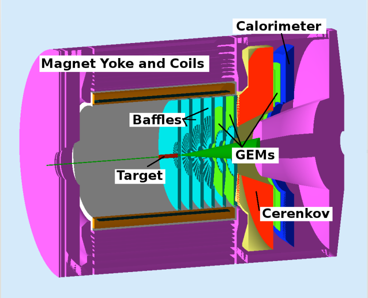
Parity-violating asymmetry (with kinematic factors Y_1, Y_3)

$$A_{PV} \approx \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left(Y_1 a_1(x) + Y_3 a_3(x) \right)$$

The SoLID Experiment

Solenoidal **L**arge **I**ntensity **D**evice

- $2\,\mathrm{GeV} < p < 8\,\mathrm{GeV}$
- $2\,\mathrm{GeV}^2 < Q^2 < 10\,\mathrm{GeV}^2$
- $0.2 < x < 1$
- 40% azimuthal acceptance
- $\mathcal{L} \approx 5 \cdot 10^{35}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$

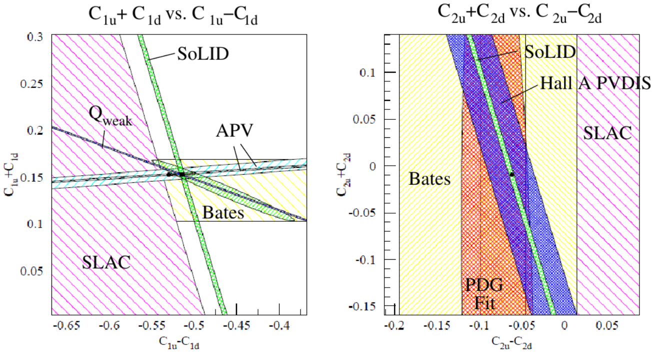


Experimental design

- Counting mode at rate $> 200\,\mathrm{kHz}$, 30 independent sectors
- Baffles filter low energy and neutral particles (no line of sight)
- Light gas Čerenkov for 1000–200 : 1 rejection of low-E π^-
- Electromagnetic calorimeter (shashlyk) for 50 : 1 π^- rejection

The SoLID Experiment: Weak Axial Couplings

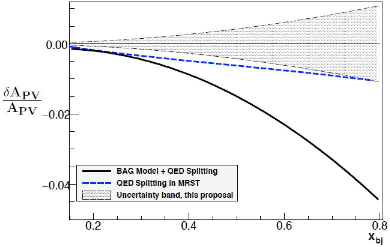
Projected Precision on C_{1q} and C_{2q} Couplings



The SoLID Experiment: Other Measurements

Charge Symmetry Violation

- CSV due to EM effects and quark mass difference
- PV-DIS will measure at valence parton level
- Might impact NuTeV



Direct Access to d/u on p

- $a_1^p(x) \approx \frac{1 - 0.912\frac{d}{u}}{1 + 0.25\frac{d}{u}}$
- Three experiments at JLab

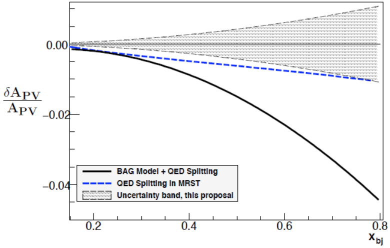
Non-PV Experiments

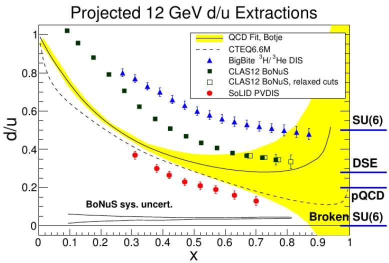
- J/ψ, SIDIS on $\vec{H}$ & $\vec{He}$

The SoLID Experiment: Other Measurements

Charge Symmetry Violation

- CSV due to EM effects and quark mass difference
- PV-DIS will measure at valence parton level
- Might impact NuTeV





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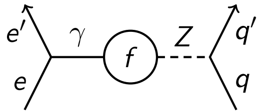
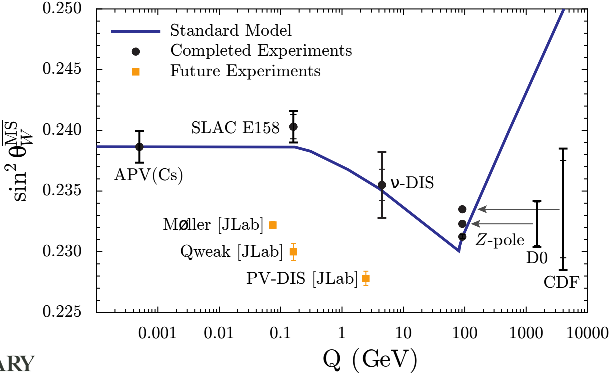
Parity-Violating Electron Scattering

$Q_W^{e,p} \sim 1 - 4\sin^2\theta_W$

- Precision measurement $\sin^2\theta_W$
- Running due to loop diagrams
- Effects from TeV-scale physics





Summary: Precision Measurements at JLab 12 GeV

Dark Photon Searches

- New opportunities since 2007, excellent fit to JLab's capabilities, test runs completed.
- A' Experiment (APEX): 11 GeV e^- on W, Hall A standard spectrometers
- Heavy Photon Search (HPS): 2.2–6.6 GeV e^- on W, forward spectrometer
- DarkLight: JLab FEL 100 MeV e^- on internal H_2 gas target
- Complimentary regions in mass $m_{A'}$ and coupling α'/α

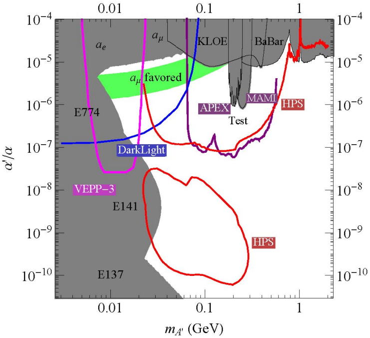
Summary: Precision Measurements at JLab 12 GeV

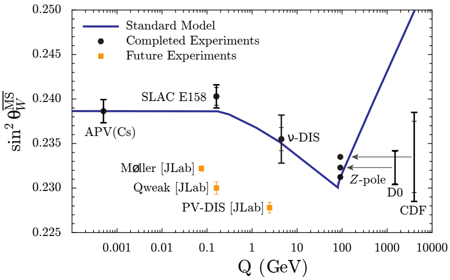
Parity-Violating Electron Scattering

- Excellent control of electron beam, experience with techniques
- Unique access to weak couplings probes TeV-scale processes
- MOLLER: precision measurement of weak mixing angle $\sin^2\theta_W$
- SoLID: access to weak vector and axial quark couplings $C_{1,2q}$
- Complimentary to direct 'beyond Standard Model' searches

Summary: Precision Measurements at JLab 12 GeV

- International collaborations with opportunities for involvement
- Promising program of precision measurements in near future





Additional Material

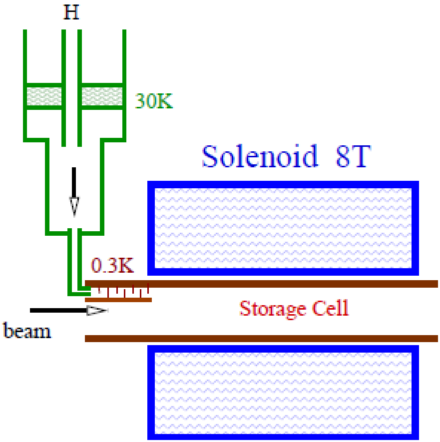
Atomic Hydrogen Polarimetry

Møller polarimetry

- 300 mK cold atomic H
- 8 T solenoid trap
- $3 \cdot 10^{16}$ atoms/cm^2
- $3 \cdot 10^{15-17}$ atoms/cm^3
- 100% polarization of e in the atomic hydrogen

Advantages

- High beam currents
- No Levchuk effect
- Non-invasive, continuous



Reference: E. Chudakov, V. Luppov, IEEE Trans. on Nucl. Sc. 51, 1533 (2004).

Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge *uud*

$Q_W^p = -2(2C_{1u} + C_{1d})$

Early experiments

- SLAC and APV

Electron scattering

- HAPPEx, G0
- PVA4/Mainz
- SAMPLE/Bates

Q_{Weak} experiment

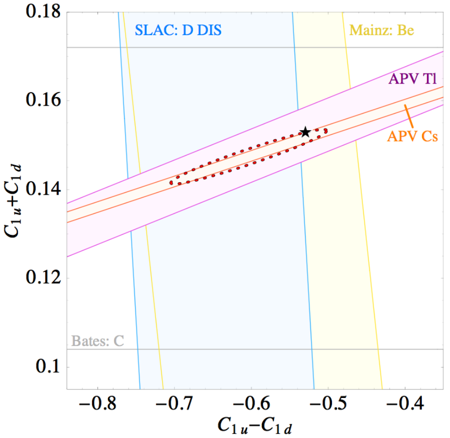


Figure: Young, Carlini, Thomas, Roche

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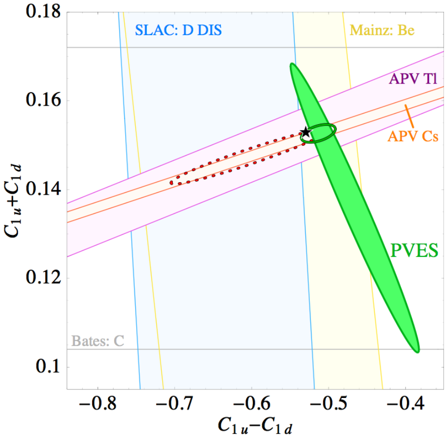

Figure: Young, Carlini, Thomas, Roche

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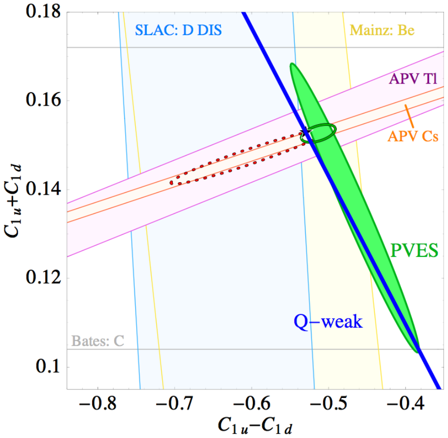


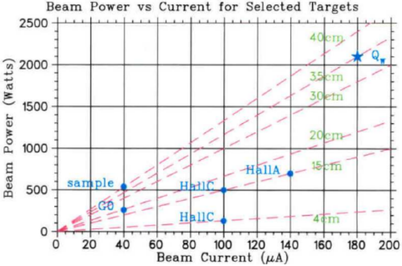
Figure: Young, Carlini, Thomas, Roche

The Q_{Weak} Experiment: High Power Cryotarget

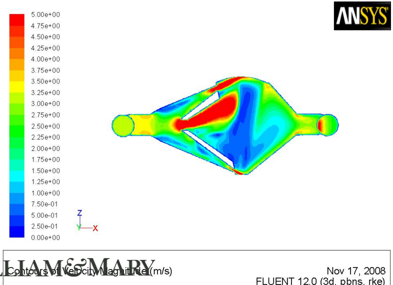
Operational Parameters

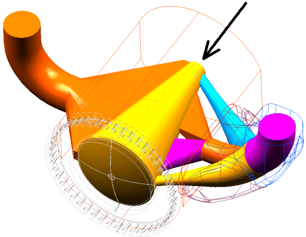
- Transverse flow: 2.8 m/s
- Target length: 35 cm
- Beam current: 150 μA
- Heating power: 2.5 kW

Power for other cryotargets



Design using CFD

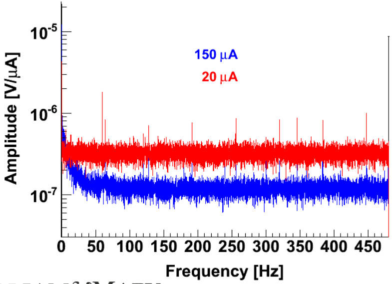




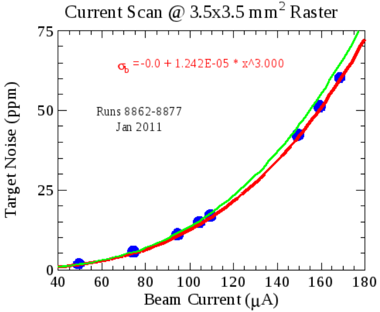
The Q_{Weak} Experiment: High Power Cryotarget

Low-frequency ‘boiling’ noise

- Helicity flip rate 960 Hz → 240 Hz (quartet cycles)
- Target density fluctuations at low frequencies occur
- Power spectrum of signal



Current dependence

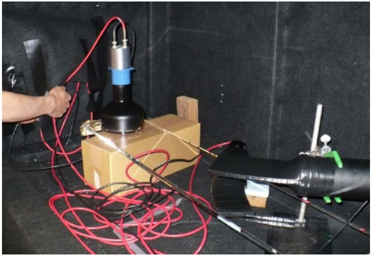


- Additional noise smaller than statistical width
- Consistent for different current and beam rasters
- Current to 180 μA

The Q_{Weak} Experiment: Main Detector

Preradiated Čerenkov detector bars

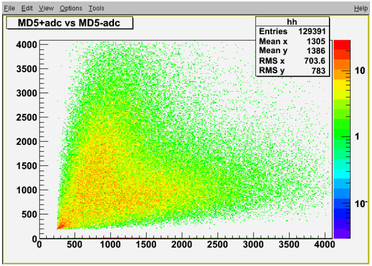
- 8 fused silica radiators, 2 m long $\times$ 18 cm $\times$ 1.25 cm
- Pb preradiator tiles to reduce low-energy tracks (neutrals)
- Light collection: total internal reflection
- 5 inch PMTs with gain of 2000, low dark current
- 800 MHz electron rate per bar, defines counting noise



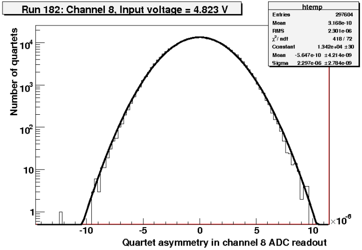
The Q_{Weak} Experiment: Main Detector

Event mode characterization

- Larger signal in + or - end depending on proximity
- Number of photo-electrons $\approx$ 85 per track



Integrating data chain noise



- Current source (9V battery)
- Collect integrating data
- Width ($\approx$ 230 ppm) is consistent with expectations
- Two orders of magnitude better resolution than in counting mode

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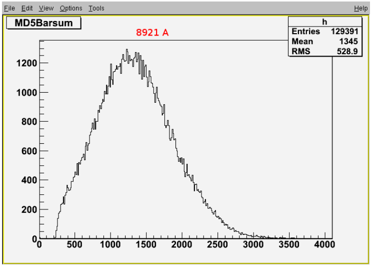

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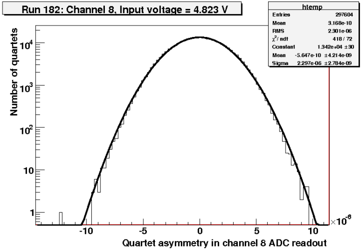

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The Q_{Weak} Experiment: Systematic Uncertainties

Largest projected uncertainties on Q_W^p

- Total uncertainty on Q_W^p: 4.1%
- Statistical uncertainty: 3.2%
- Hadronic structure: 1.5%
- Beam polarimetry: 1.5%
- Measurement of Q^2: 1.0%
- Background events: 0.7%
- Helicity-correlated beam properties: 0.7%

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The Q_{Weak} Experiment: Tracking Mode

Reasons for a tracking system?

- Determine Q^2, note: $A_{meas} \propto Q^2 \cdot \left(Q_W^p + Q^2 \cdot B(Q^2)\right)$
- Quartz detector light output versus position
- Contributions from inelastic background events

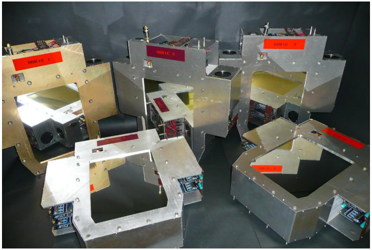
Instrumentation of two octants

- Horizontal drift chambers (HDC) for front region
- Vertical drift chambers (VDC) for back region
- Rotation allows measurements in all 8 octants

The Q_{Weak} Experiment: Tracking Mode

Horizontal drift chambers

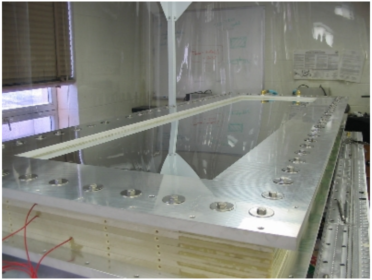
- 12 planes per octant
- Constructed at Va Tech



- Read-out using JLab F1 TDCs

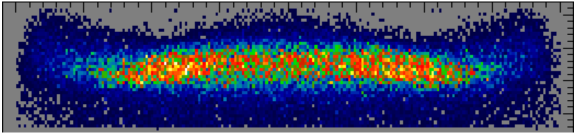
Vertical drift chambers

- 181 wires in 2 m long multiplexed planes
- 4 planes per octant
- Constructed at W&M

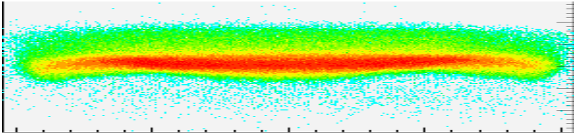


The Q_{Weak} Experiment: Tracking Mode

Simulation of electrons on detector bar (flipped)



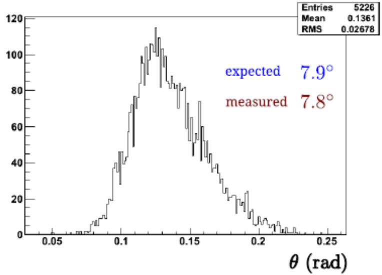
Projection of reconstructed tracks to detector bar



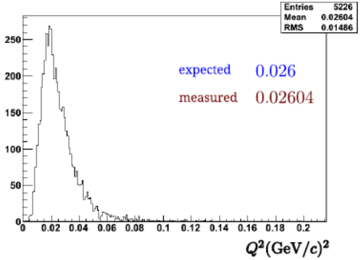
- Periodic tracking runs at 50 pA (HDC/VDC) to few nA (VDC)
- Excellent performance of HDC and VDC drift chambers
- VDC track resolution of 250 μm meets design goal
- HDC track resolution of 350 μm (software work ongoing)

The Q_{Weak} Experiment: Tracking Mode

Reconstruction of angle θ (preliminary)



Reconstruction of momentum transfer Q^2 (preliminary)



- Excellent agreement with expected kinematics
- Required precision on Q^2 seems not a problem

The Q_{Weak} Experiment: Beam Polarimetry

Requirements on beam polarimetry

- Statistical precision of 1% after one hour
- Systematic uncertainty of 1% (on absolute measurements)

Upgrade existing Møller polarimeter ($\vec{e} + \vec{e} \rightarrow e + e$)

- Scattering off atomic electrons in magnetized iron foil
- Operation limited to dedicated low current runs ($I < 8\,\mu$A)

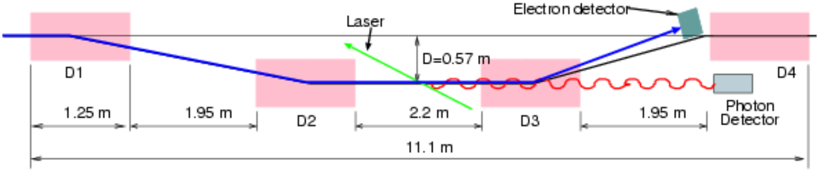
Construction new Compton polarimeter ($\vec{e} + \vec{\gamma} \rightarrow e + \gamma$)

- Compton scattering of electrons on polarized laser beam
- Continuous, non-destructive, high precision measurements
- Systematic uncertainty of 1% (for absolute measurements)

The Q_{Weak} Experiment: Beam Polarimetry

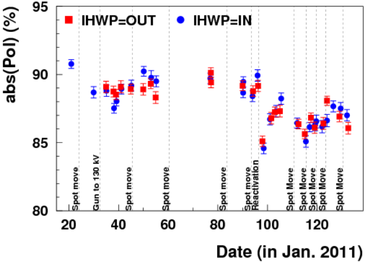
Compton polarimeter

- Beam: 150 μA at 1.165 GeV
- Chicane: interaction region 57 cm below straight beam line
- Laser system: 532 nm green laser
  - 10 W CW laser with low-gain cavity
- Photons: $PbWO_4$ scintillator in integrating mode
- Electrons: Diamond strips with 200 μm pitch



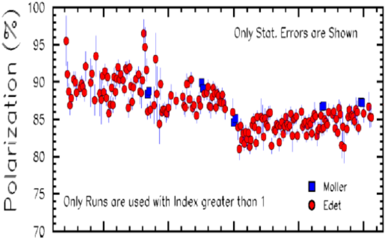
The Q_{Weak} Experiment: Beam Polarimetry

Møller polarimetry (preliminary)



- New beamline, refurbished
- Invasive measurements
- Polarization larger than anticipated: 86% to 88%

Compton polarimetry (preliminary)



- Excellent performance
- Continuous measurements
- Operates at full 180 μA
- Phosphorescence in CsI $\rightarrow$ $PbWO_4$