Sub-percent Møller Polarimetery in Jefferson Lab Experimental Hall C

Josh Magee

Sept. 11^{th},2013

- Basic principles of Møller polarimetry
- Hall C Møller Design
- Sub-percent Møller precision
    - An example: Q-weak

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Hall C Polarimetry

Møller Polarimetery Basic Principles

Møller scattering: elastic $\vec{e} \cdot \vec{e}$ scattering.

Since this is pure QED, the scattering cross section is well understood and easily calculable to high order.

For free electron:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma_0}{d\Omega}\right)\left[1 + A_{zz}(\theta)P_b^{||}P_t^{||}\right]$$

$$\left(\frac{d\sigma_0}{d\Omega}\right) = \left(\frac{\alpha(4 - \sin^2\theta)}{2m_e\gamma\sin^2\theta}\right)^2$$

Unpolarized cross section

Helicity dependence

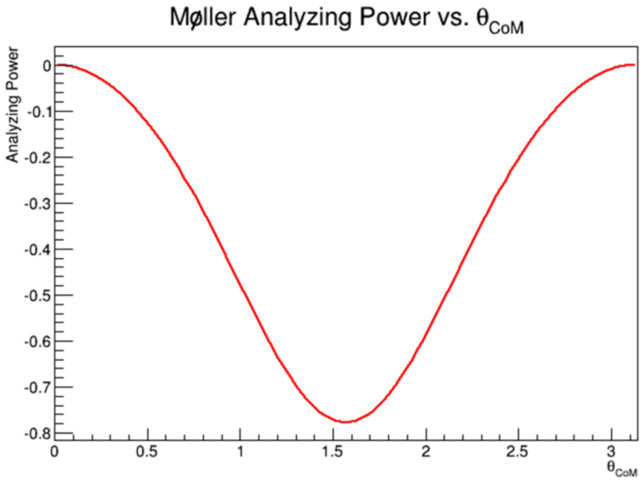
Analyzing power: $A_{zz}(\theta)$

Beam polarization: $P_b^{||}$

Target polarization: $P_t^{||}$

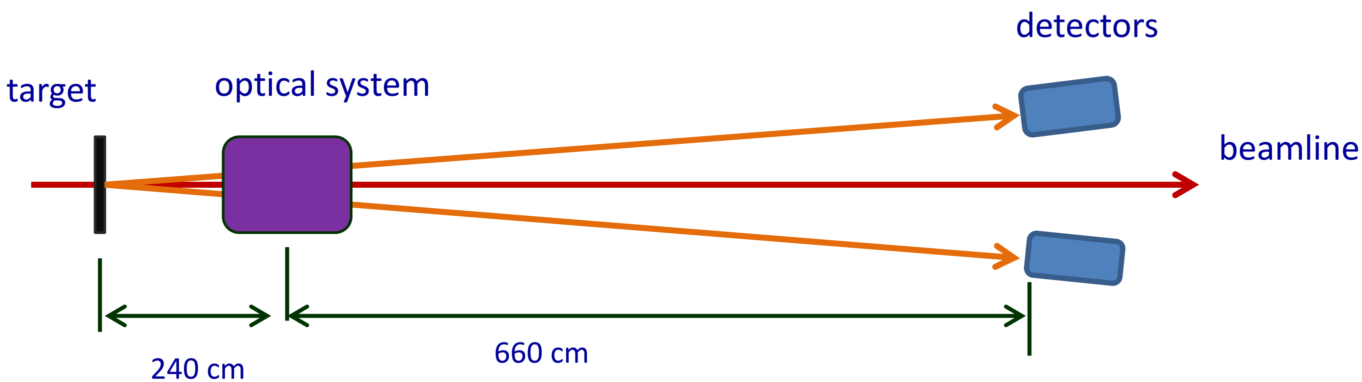
In the center-of-mass frame, where $\theta_{scatter} = 90°$, $A_{zz}(\theta)$ is maximal (-7/9)(slope=0):

$$A_{zz}(\theta) = -\sin^2\theta\,\frac{(8 - \sin^2\theta)}{(4 - \sin^2\theta)^2}$$



Møller Polarimetery Basic Principles

A typical setup consists of the following optical elements:



- Magnetized Fe-*alloy* foil provides target electrons
- Low-B field polarizes target in plane
- Foil is rotated ~20° relative to beam
- Requires quadrupole or septum magnet to separate scattered beams
- ~~Single~~ Coincidence detection

Year	Facility	Max. E_{beam} (GeV)	Limitation	detectors: Single	detectors: Coinc.	Uncert. $\Delta P/P$	Ref.
1975	SLAC	19.4	foil/stat/bck	√		4%	[Co75]
1976	SLAC-E80	12.9	foil/stat/bck	√		12%	[Al76]
1978	SLAC-E122	22.2	foil/stat/bck	√		5.5%	[Pr78]
1982	SLAC-E130	22.7	foil/stat		√	4%	[Ba83]
1984	Bonn	2.0	stat		√	12%	[Br85]
1986	Mainz	$0.071 \rightarrow 0.35$	foil/stat		√	4%	[Wa90]
1990	MAMI	$0.185 \rightarrow 0.84$	foil/bck		√	4%	[Wa90]
1992	Bates	0.574	stat/bck	√		12%	[Ar92]
1992	SLAC-linac	46.6	foil/bck	√		4.2%	[Sw95]
1993	SLAC-E142	26	foil/bck	√		4%	[An93]
1995	Bates	0.868	stat/bck		√	5%	[Be95]
1995	SLAC-E143	29	foil		√	2%	[Fe97]

(circa 1995)

Møller Polarimetery Basic Principles

Advantages include:

- Simplicity
- Large analyzing power (-7/9)
- Large cross section = short measuring times

Disadvantages include:

- Only 2/26 electrons polarized (effective target polarization is ~8%)
- Need precise knowledge of target magnetization
- Atomic motion of inner shell electrons (Levchuk effect)

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Previous challenge: Iron-alloys. They saturate (in-plane) at low B-fields (~100s Gauss).
Implications:

- Bulk magnetic properties may be "nonlinear", and calculating these difficult
- Need absolute in-situ measurements to determine magnetization M
- Need to compare M_{center} to M_{edge}
- Sensitivity to foil inhomogeneities
- Sensitivity to annealing

State-of-the-art: 1.5% uncertainty of M (dominate systematic)

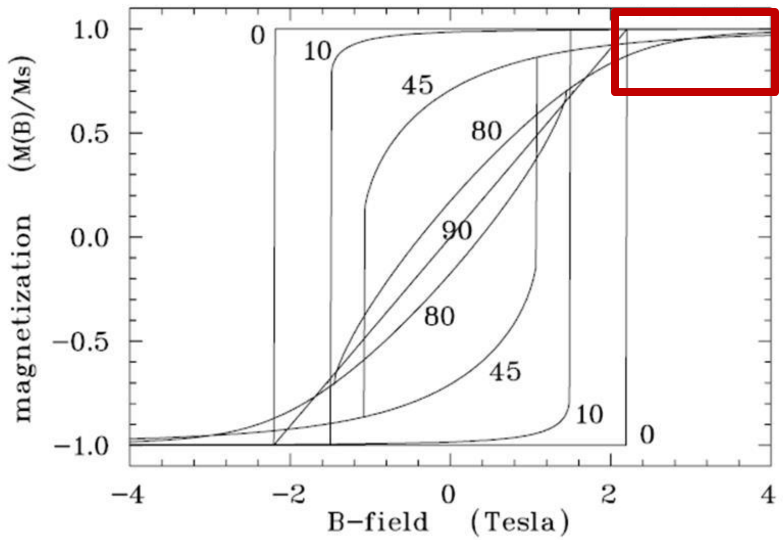
Møller Polarimetery Iron Target Properties

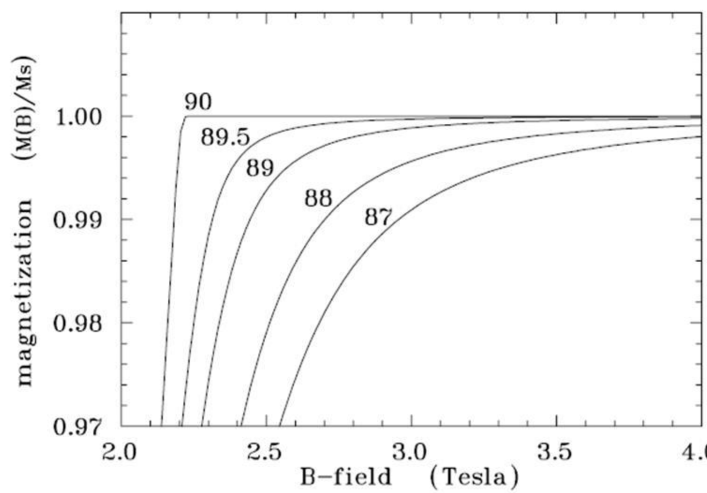
OR: use *pure* iron and brute-force magnetically saturate it *out-of-plane* with high (3-4T) field.

(iron saturates at 2.2 Tesla)

By brute-forcing the foil to saturation, several advantages are clear:

- Magnetic properties of iron known to high-precision
- Foil properties uniformly saturated
- We don’t really need to measure the target polarization





The numbers (10,45,80,90…) respond to the foil tilt in-plane (90° = perpendicular out-of-plane).

Taken from: L.V. de Bever et al. NIM A400 (1997)

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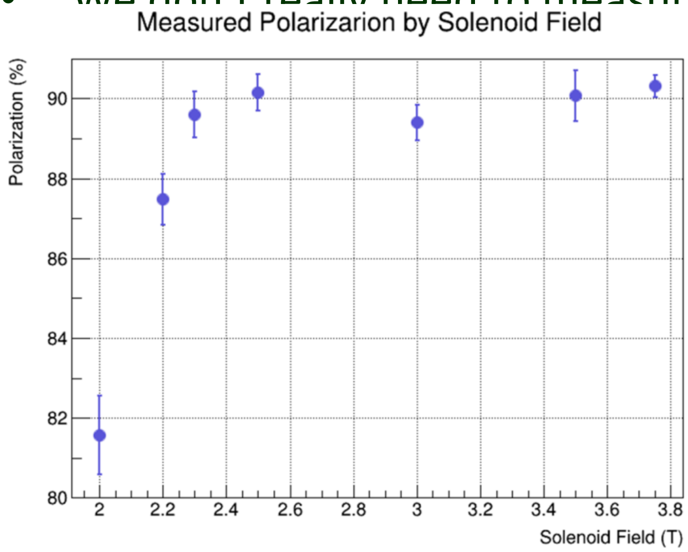
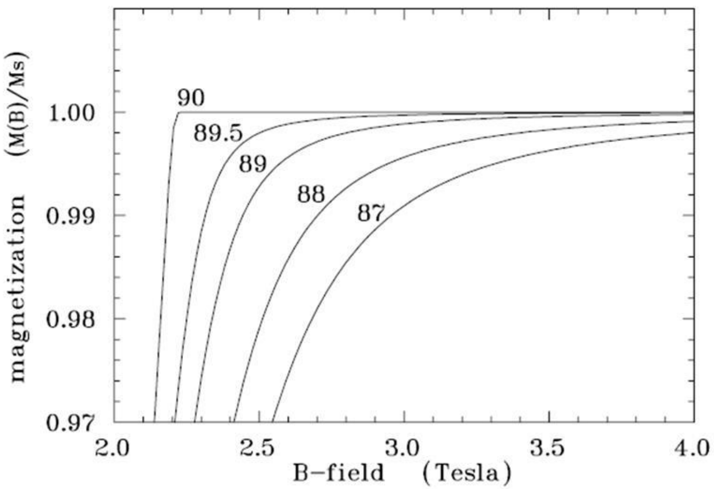




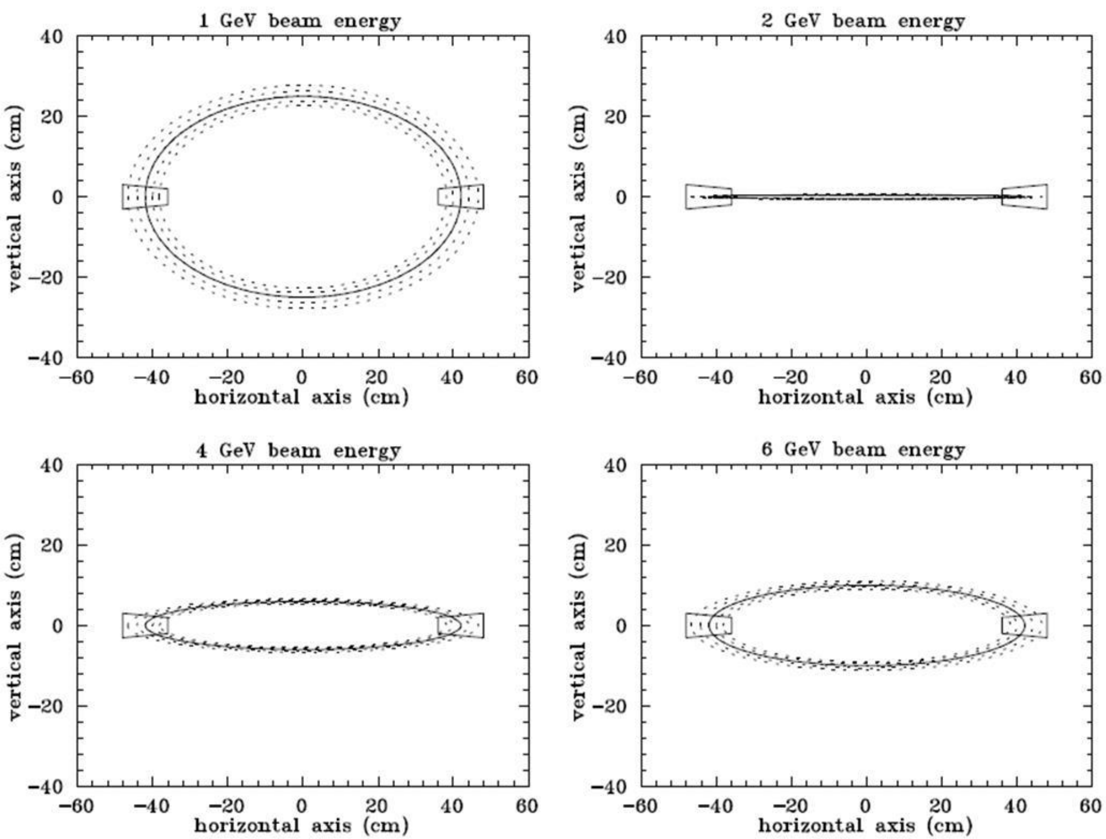
Measurements taken in Hall C, 2010.

Taken from: L.V. de Bever et al. *Nucl. Instr. Meth.* A, 400 (1997)

Møller Polarimeter Design

Two particular goals for Jlab were to measure polarization over a wide energy range (1-6 GeV) and current range (10 nA – 50μA).

If we simply keep the "traditional" optical set-up, we see the $\theta_{CM} = 90°$ cone has an undesirable energy dependence.



When boosted, the cone should form an ellipse on the detector array. When the ellipses "collapses", two problems arise:

1. Analyzing power is diluted by non $\theta_{CoM} = 90°$ scatters
2. We loose position information, which is an important diagnostic

M. Loppacher. *Thesis, University of* Basel, 1996.

Møller Polarimeter Design

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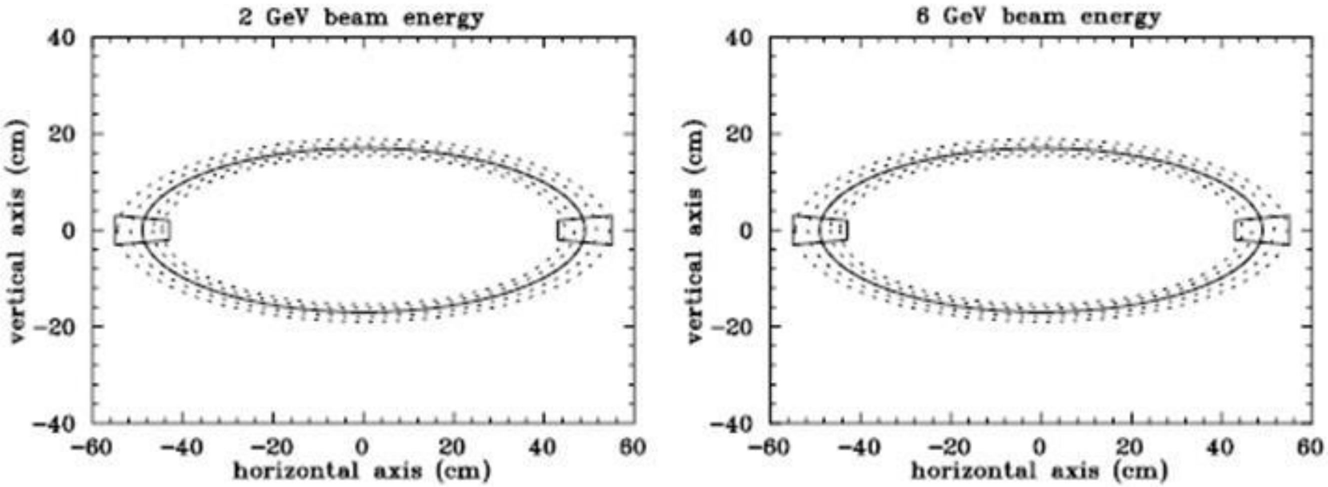
However, a 2-quadrupole setup eliminates this problem, and essentially removes the energy dependence from 1-6 GeV. One can tune each quad individually to select the optimal magnet tune.



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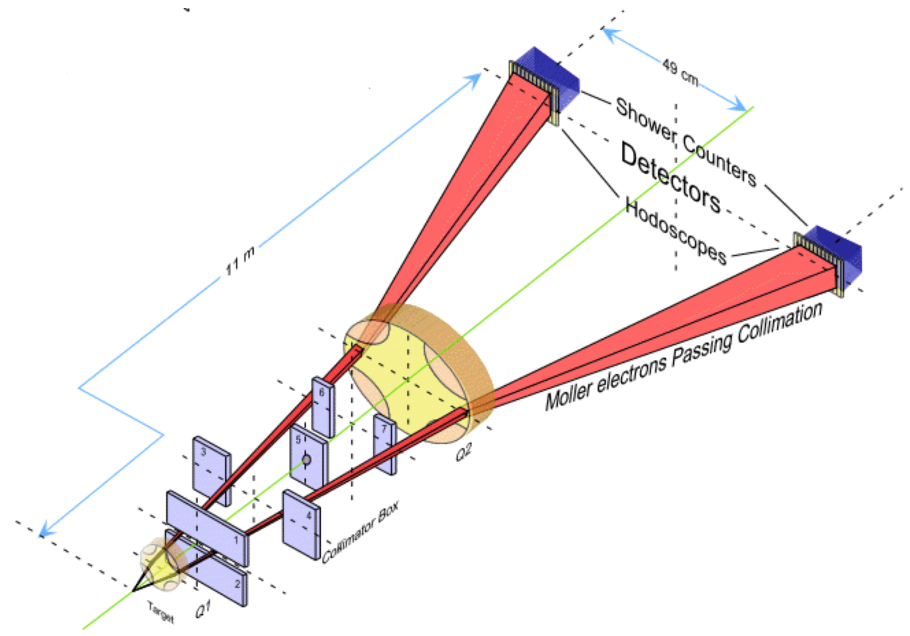
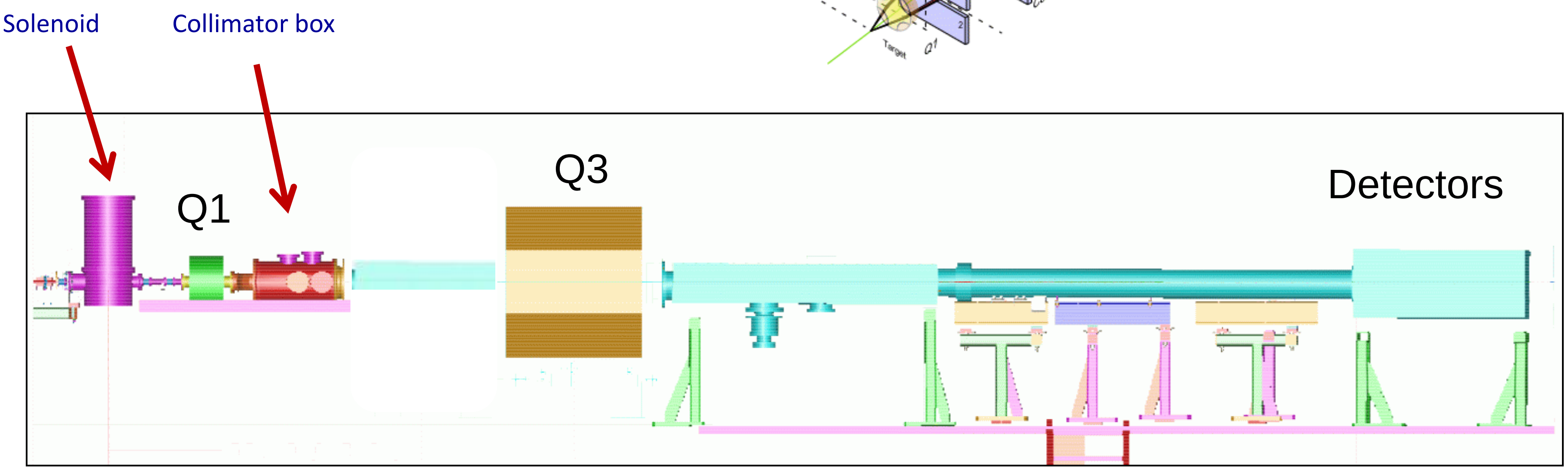
Hall C Møller Set-up

Our design looks like this

- Superconducting solenoid
- Pure iron foil (thin)
- 2 quads (~optical lens)
- Moveable collimator box
- Two detectors in coincidence

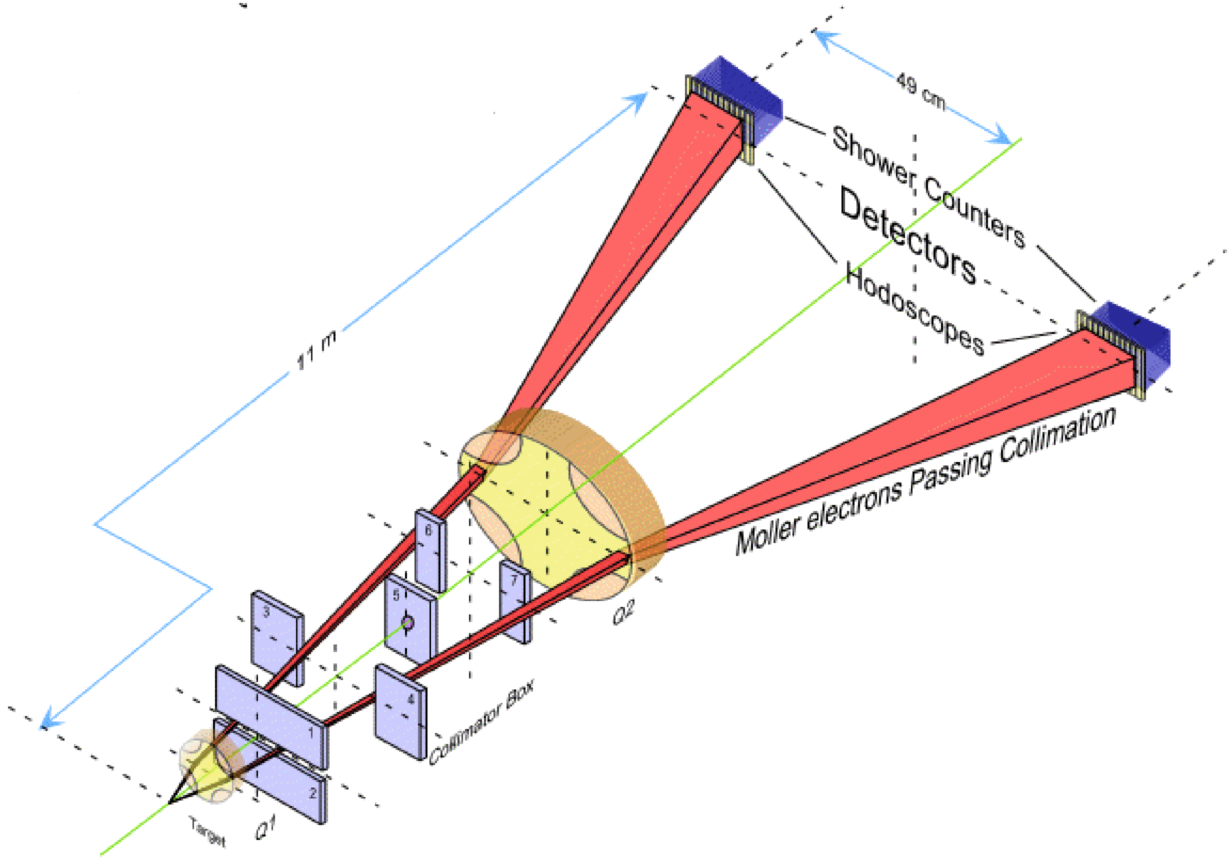




Hall C Møller Set-up

6 moveable collimators

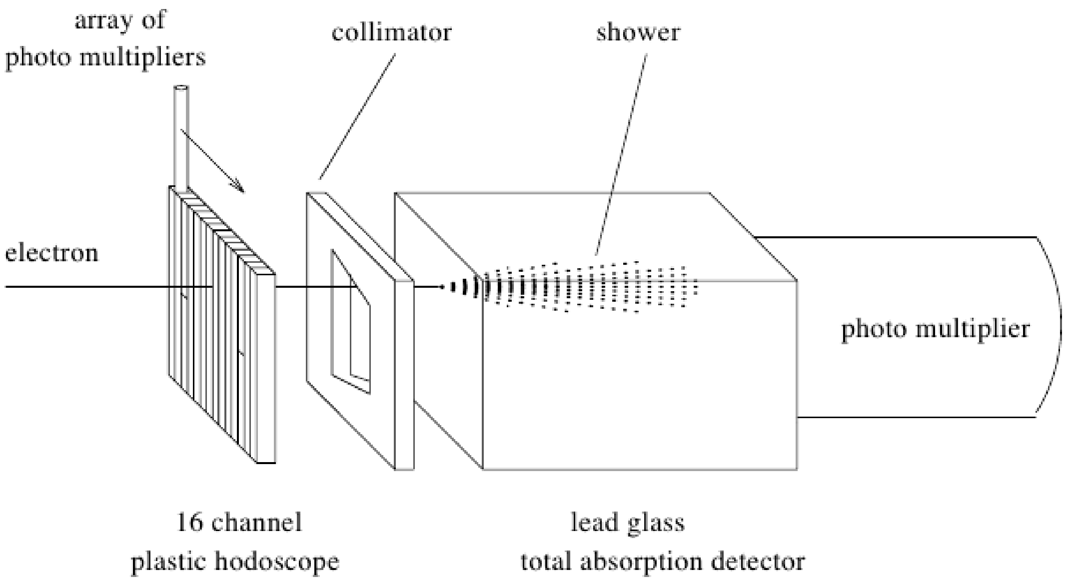
- Only for background reduction only (does not define acceptance)
- Reduces Mott background (dominant background)
- Densimet construction – 8cm//22 rad. Lengths



Detector Specs

Detector equipment

- Lead glass total absorption detector (20x14x23 cm^3)
- 5 ns coincidence gate narrow gate eliminates predominate (Mott) background
- Fixed collimator defines acceptance
- Hodoscope not used during measurement (only for tuning)



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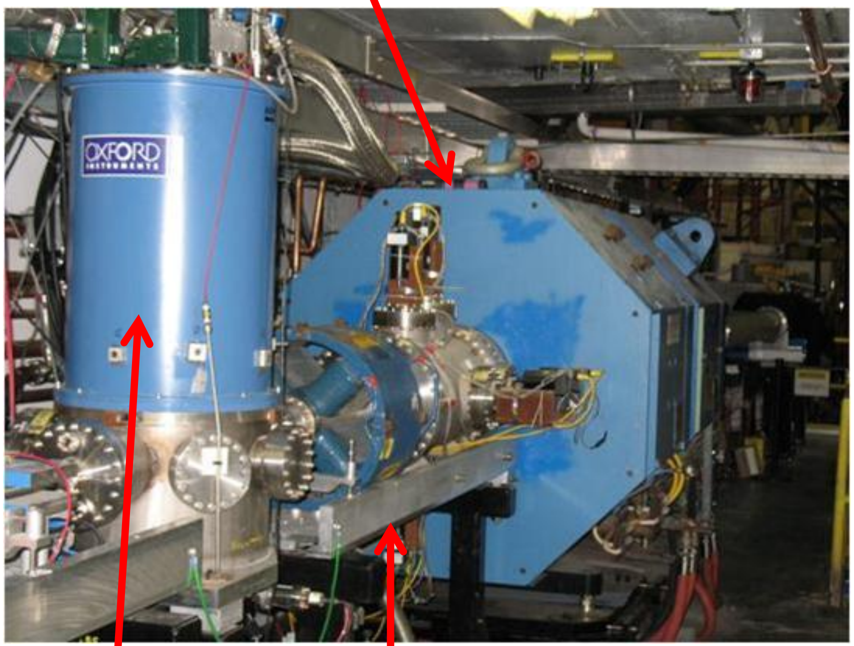
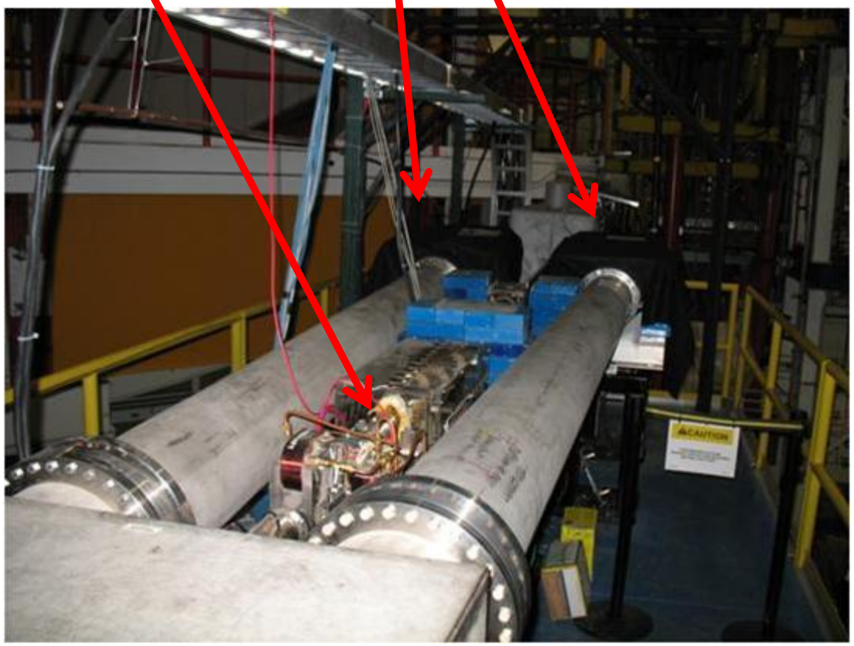
Hardware As Installed

Big quads

Beam pipe

Detectors





Solenoid (target)

Small quad

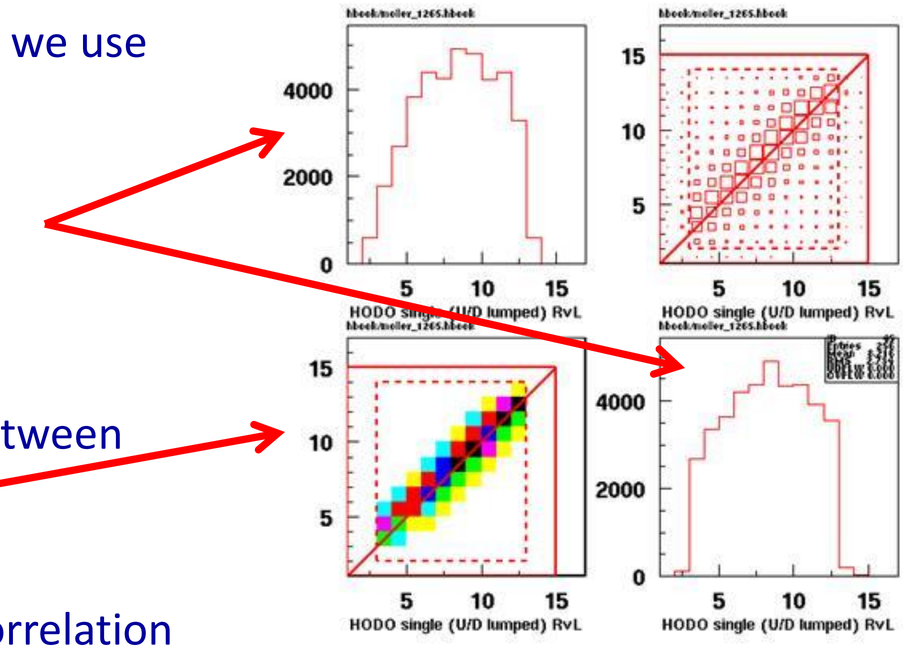
Hall C Møller

Lastly, one important diagnostic tool we use is a "tune plot."

At left, one can see the left and right hodoscope signals.

The colored plot is the correlation between both detector arms.

If the optics weren't balanced, the correlation would shift up or down (examples to follow).



Nominal tune

Hall C Møller

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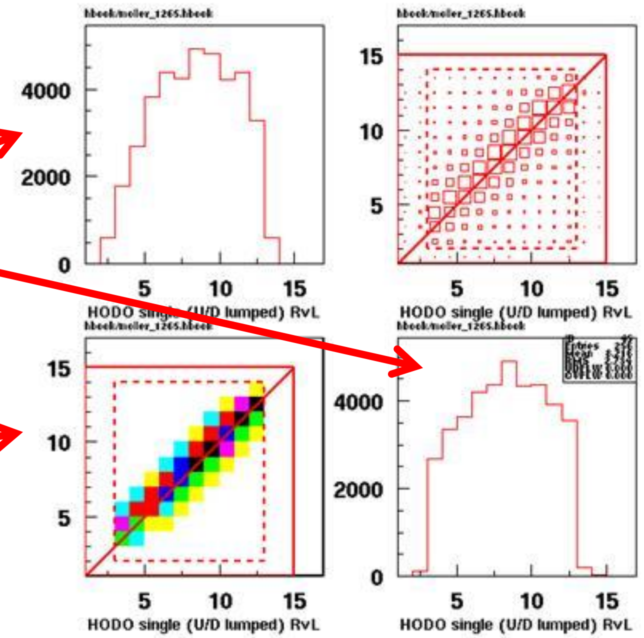

Nominal tune

Design summary:, the Hall C Møller device design was unique:

– Hall C Møller device was unique – *pure* iron foil polarized *out-of-plane*
– Beam currents 1-10 μA
– Beam energies 1-6 GeV
– Fe foils 4-10 μm thick

0.5% statistical measurement of P_{beam} in ~5 minutes

Sub-percent Measurements

Until recently, many experiments were adequate with %-level beam polarization knowledge (ex. G0/SANE). Recently, the Q-weak experiment required a polarization uncertainty <1%.

Q-weak's goal: a high-precision measurement of the proton's weak charge. The experiment measured the parity-violating asymmetry in $\vec{e}\cdot p$ scattering in Jefferson Lab Hall C. Eventually this will be the most precise (relative and absolute) PVES measurement to date.

$$A_{exp} = \frac{A_{measured}}{P}$$

Error source	Contribution to $\Delta A_{phys}/A_{phys}$ (%)	Contribution to $\Delta Q^p_W/Q^p_W$ (%)
Counting statistics	2.1	3.2
Hadronic structure	-	1.5
Beam polarimetry	1.0	1.5
Absolute Q^2	0.5	1.0
Backgrounds	0.7	1.0
Helicity-correlated beam properties	0.5	1.0
Total	2.5	4.2

Møller uncertainty budget

Source	Uncertainty	dA/A (%)
Beam pos x	0.2 mm bpm + calculation	0.17
Beam pos y	0.2 mm bpm + calculation	0.28
Beam direction x	0.2 mm bpm + calculation	0.1
Beam direction y	0.2 mm bpm + calculation	0.1
Q1 current	2%	0.07
Q3 current	1%	0.05
Q3 position	1 mm	0.10
Multiple scattering	10%	0.01
Levchuk effect	10 %	0.33
Collimator positions	0.5 mm	0.03
Target temp. rise	100%	0.14
B-field direction	2°	0.14
B-field strength	5%	0.03
Spin polarization in Fe		0.25
Electronic D.T.	100%	0.045
Solenoid focusing	100%	0.21
Solenoid position (x,y)	0.5 mm	0.23
High-current extrapolation	----	0.50
Monte Carlo statistics	----	0.14
Total		0.85

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We can measure position sensitivity and compare to simulation

Measure+simulate magnet strengths.

Can simulate quadrupole position

Detailed calculations and simulations

Previous experiments could have achieved this, but it's a lot of work, and they didn't require it.

Many of these systematic uncertainties shrink at higher beam energy.

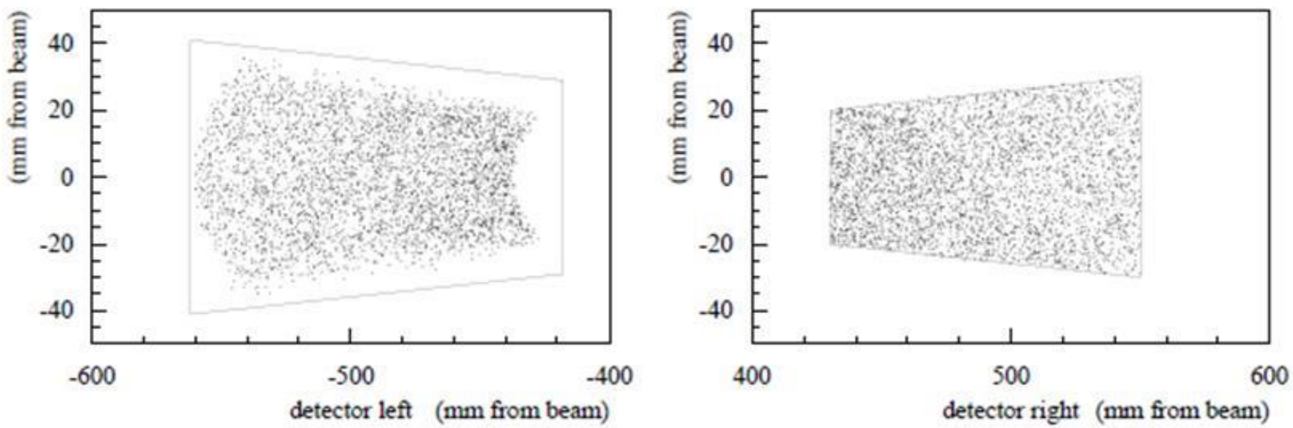
Mitigating the Levchuk Effect

Since our effective analyzing power is ~8%, it is possible to scatter off of the inner shell, unpolarized electrons.

- Inner shells have greater binding energies, and greater momenta,
- These directly affect the scattering kinematics.
- Broaden our signal

We have two basic choices:

- Enlarge our detectors to essentially integrate over it
- Let one fixed collimator define the acceptance



M. Loppacher. *Thesis, University of* Basel, 1996.

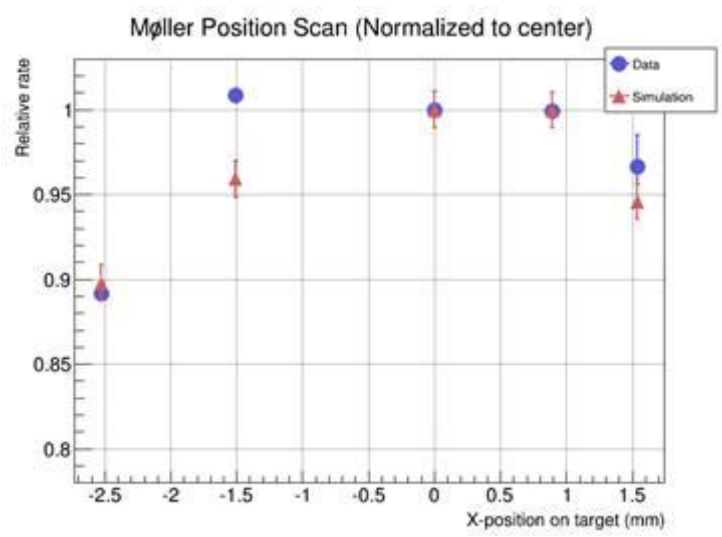
Simulations and Position scans

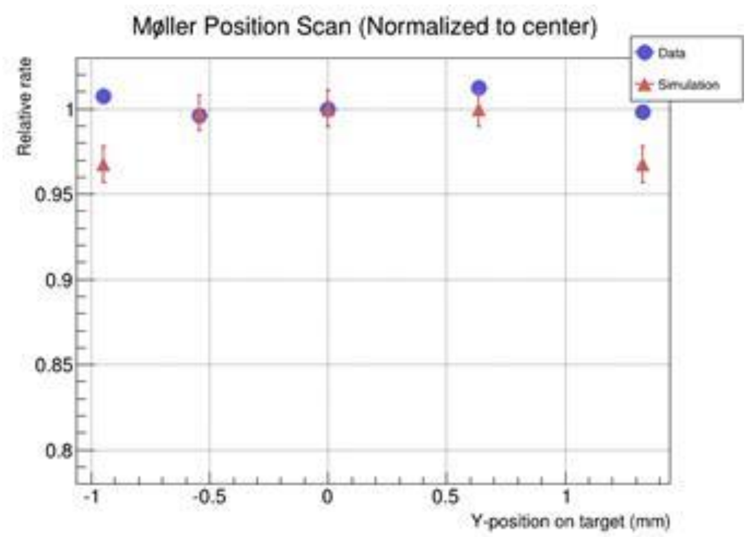
We use a monte carlo calculation to calculate our analyzing power. One "benchmark" we use is comparing the relative/absolute rates measured to simulation.

For Q-weak we completely re-vamped our simulation optics to improve agreement

- Introduced corrections for beam transport through a *split* solenoid
- Improved quad-transport routines (2^{nd} order calculation)

Position/angle on target is our dominant systematic.





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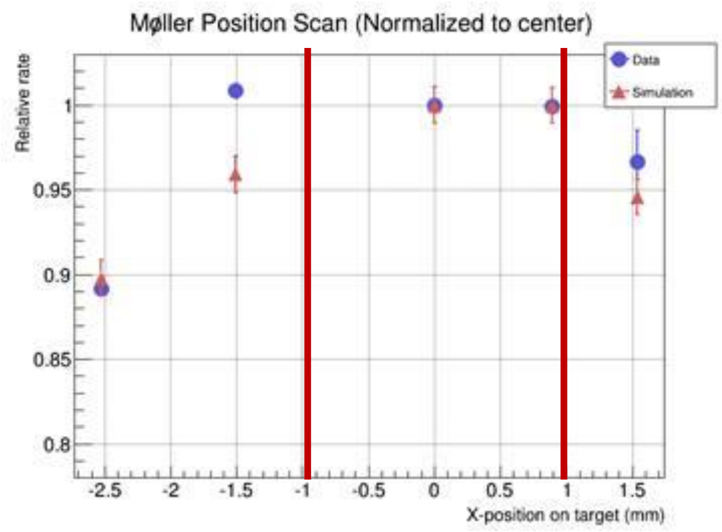
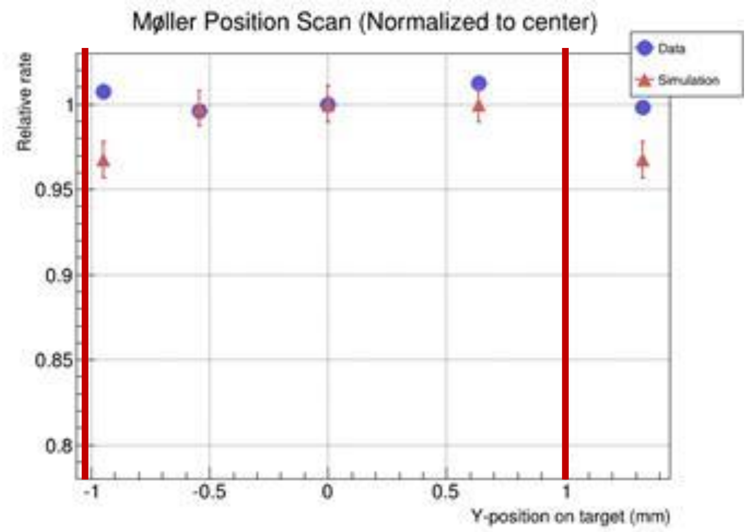




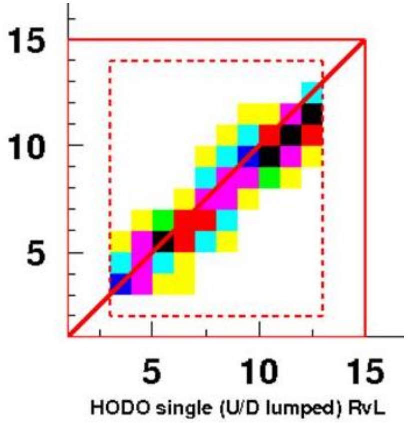
Note great agreement out to 1mm in x/y. We never took production data beyond these limits!

Møller Optics uncertainty

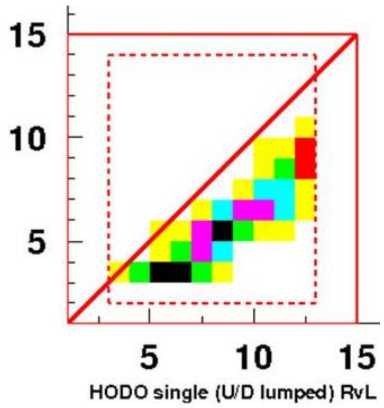
The quadrupole currents, and therefore fields, are highly *correlated*.

Source	Uncertainty	dAsy/Asy (%)
Q1 current	2%	0.07
Q3 current	1%	0.05
Q3 position	1 mm	0.10

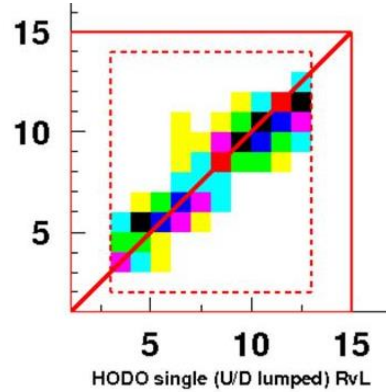
Using the quad1/3 correlation plots, we can correct a small %-level offset in one quad by adjusting the other. The tunes below are from an actual study – the measured polarization didn't change.



Nominal tune



Quad 3 lowered
129 →124 Amps



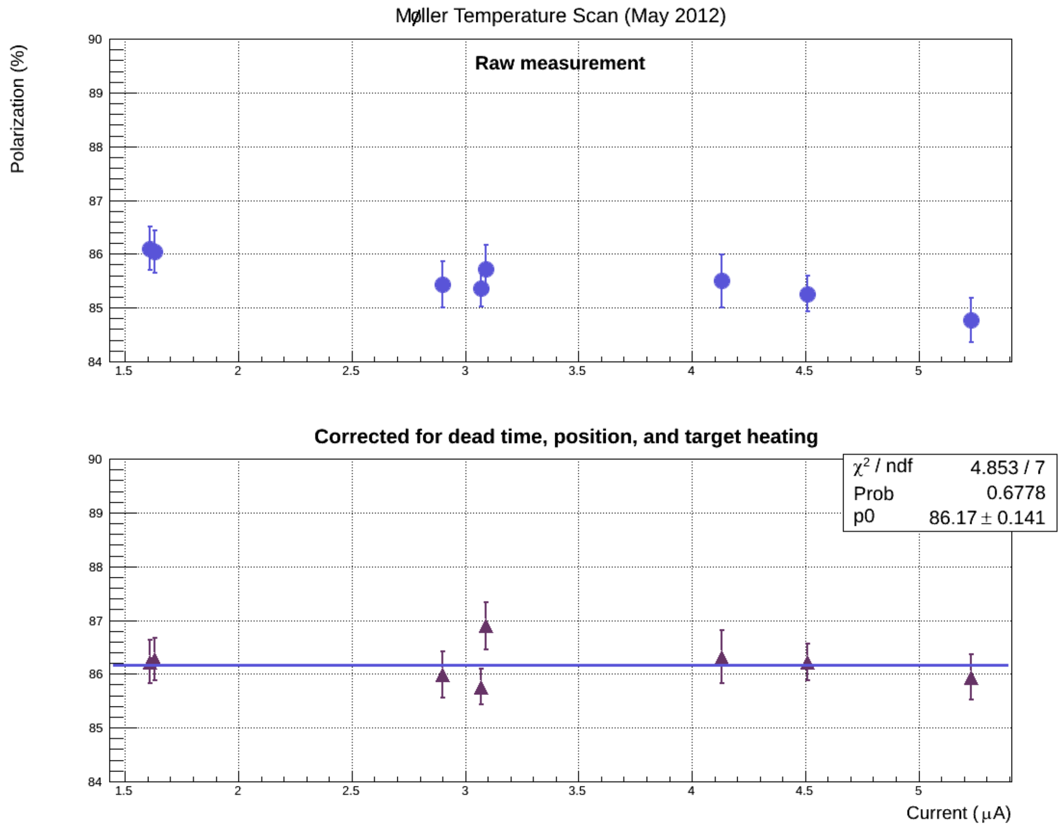
Q3 lowered+Q1 raised
93.7 → 95.7 Amps

Target Temperature Dependence

For the Møller-Compton cross-calibration, we wanted to understand the temperature dependence on our measured polarization. This procedure had two parts:

- Calculating the temperature rise of the target
- Determining the actual depolarization

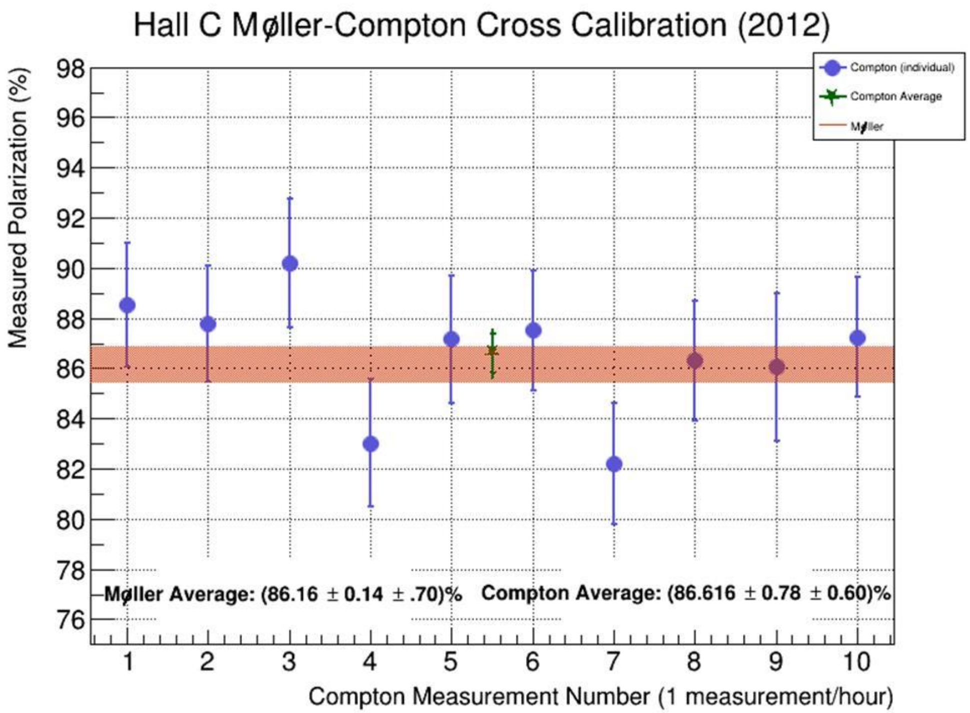
The temperature rise was numerically calculated, while the depolarization was determined from two independent fits to published data.



Møller-Compton-Møller

During Q-weak's installation, Hall C also installed a new Compton polarimeter (electron and photon detectors). The original goal was to use the Compton as a continuous relative polarization monitor, with the Møller performing periodic absolute measurements.

During the 2nd half of Q-weak running, we did perform a device cross calibration.



Note the systematic uncertainty *does not* include any high-current effects, as the study was conducted at 4.5 μA.

Summary

Josh Magee

Sept. 11th,2013

Hall C Møller Design

- The Hall C design was unique by using a *pure* iron foil, that is forced into magnetic saturation out-of-plane by large superconducting fields. This eliminates large systematic uncertainties from previous designs.
- Large analyzing power/cross section enable fast + accurate measurements
- Careful optical design enables measurements taken at wide energy range

- Sub-percent Møller precision
  - Recent studies brought the total systematic uncertainty of the Hall C Møller to 0.85%.
  - Previous experiments could have achieved this, but unnecessary.

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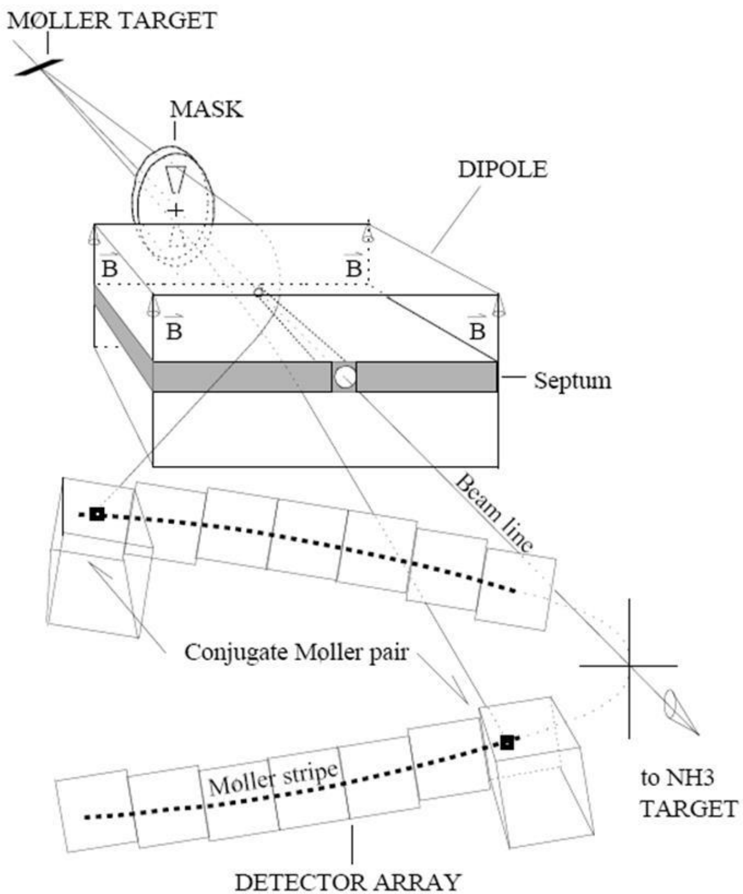
Hall C Polarimetry

Møller Polarimetery Basic Principles

Example from SLAC 143.



Taken from I. Sick, 2003 pstp talk.

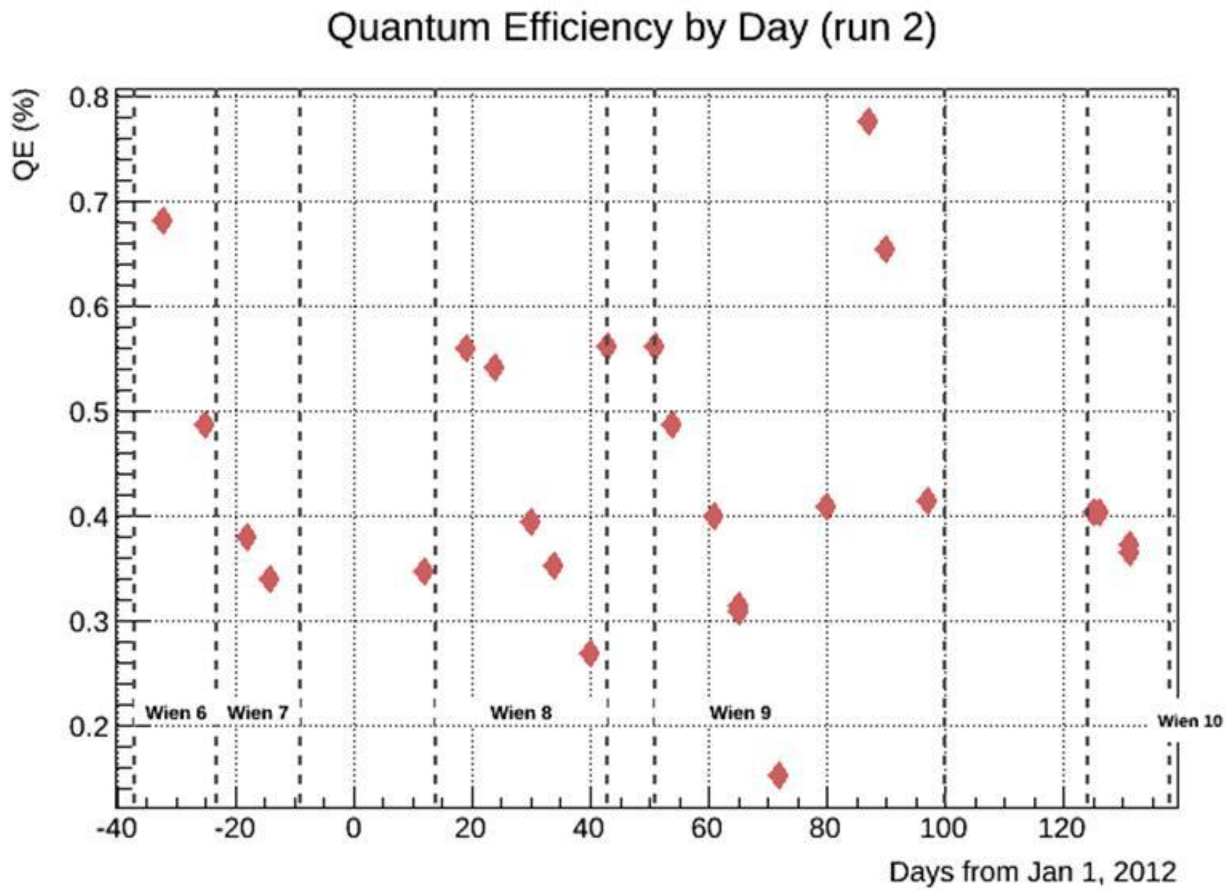
High Current Extrapolation

Some Jefferson Lab experiments, such as Qweak, run at 180 µA, while the Møller measures at 1 µA. Some have suggested that the polarization changes as a function of current, and therefore not appropriate at higher currents. We included this uncertainty to be conservative – there is little evidence to suggest this.

A few thoughts:

1. Qweak ran at 1-pass with the energy lock on. Our energy lock is good enough that any procession of the beam is negligible.
2. Several previous studies have shown polarization independent of current up ("kicker" and "beat-frequency" studies).
3. We have seen the polarization change as a function of quantum efficiency (QE). As we increase the laser power for high current, the QE changes more quickly. However, when we did a Pol/QE study at low QE, we saw no effect.
4. After the Møller-Compton cross calibration, we saw no change from 4.5 µA to 180 µA.

Run 2 Outlook

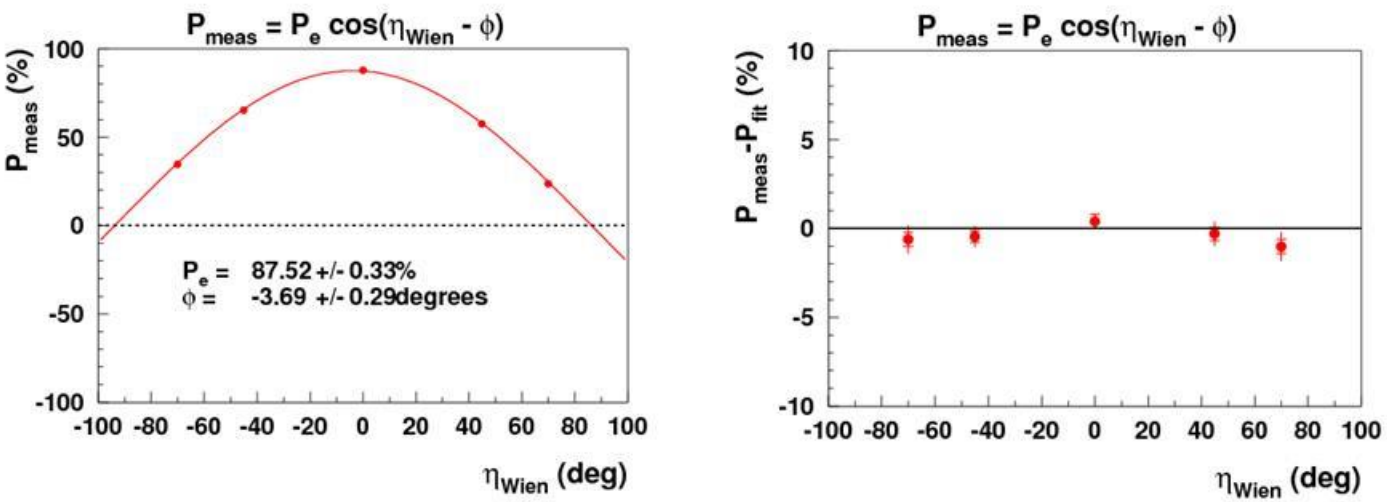


We have noticed a dependence on the polarization based on the QE. The QE was high for most of the run period, except around day 70, where we purposely continued running to study the effects of low QE.

Møller Spin Dances

For our parity-violating program, we performed periodic “slow reversals” to look at possible systematic effects. For example:

- Inserting/removed a half wave plate every 8 hours.
- Flipping our Wien filter settings (flip “right”, flip “left”). To determine the optimal Wien settings, we performed a “spin dance.”

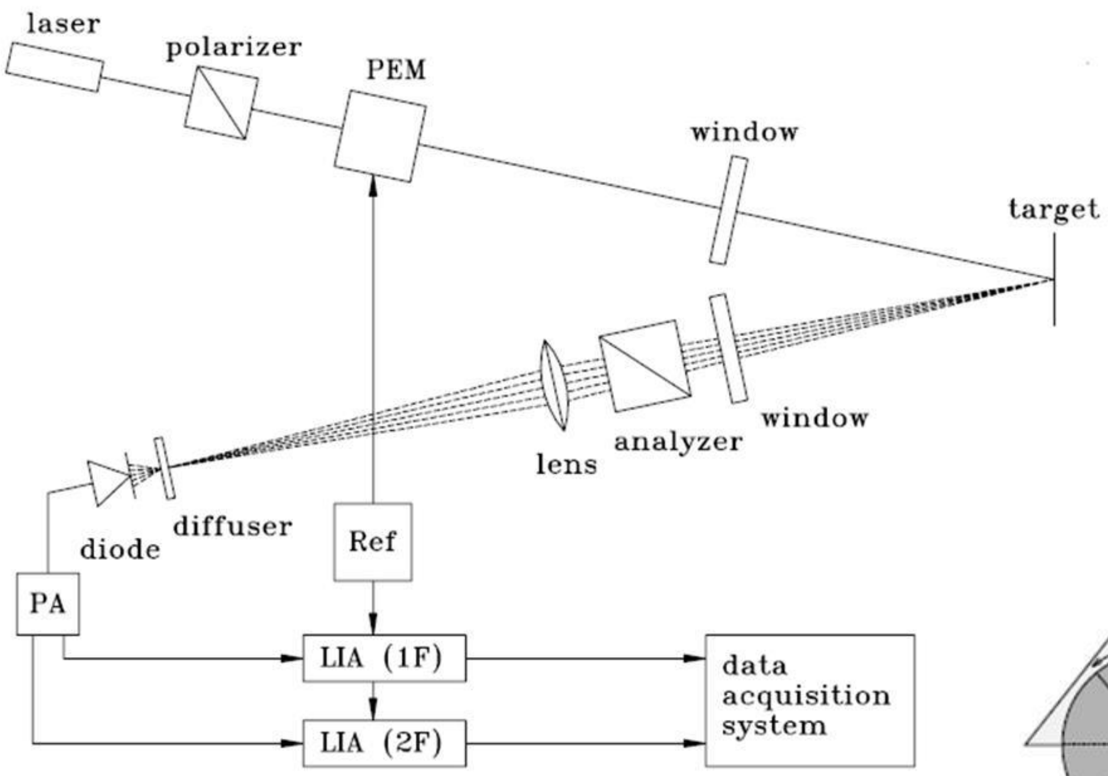


Spin dance: taking data at multiple Wien settings to determine those that provided optimal polarization.

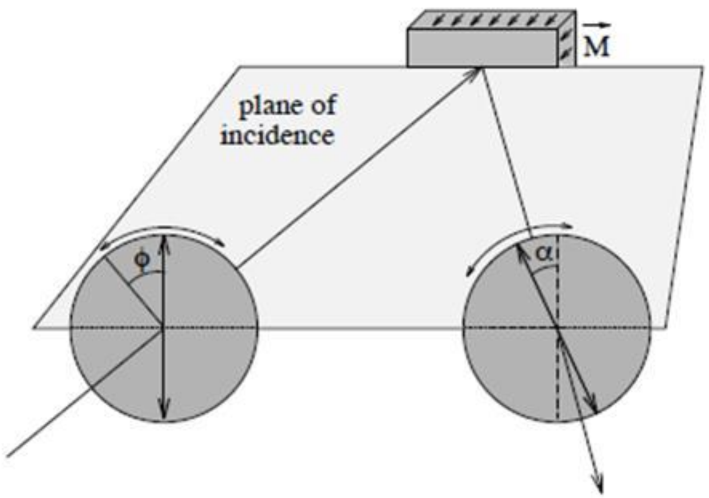
Determining Target Magnetization

Target *magnetization* can be measured in-situ using a Kerr apparatus.

Magnetization is linearly related to target polarization.



Idea is to send vertically polarized light to the Møller target and then measure the change in angular polarization vector.



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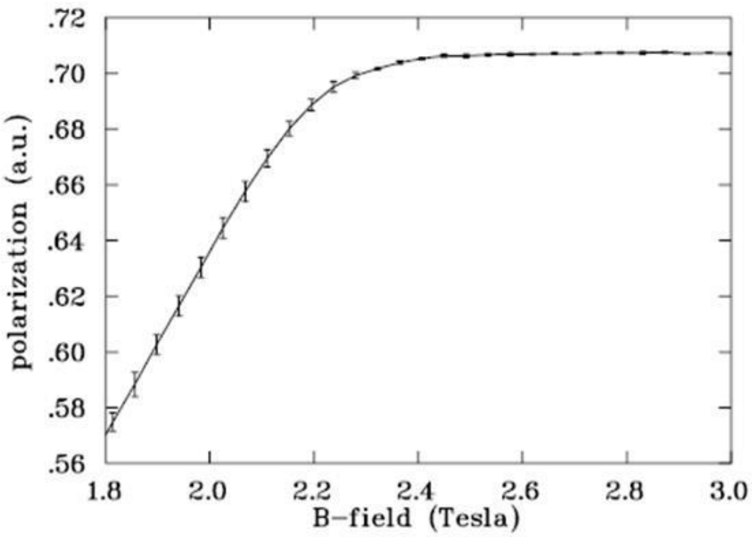
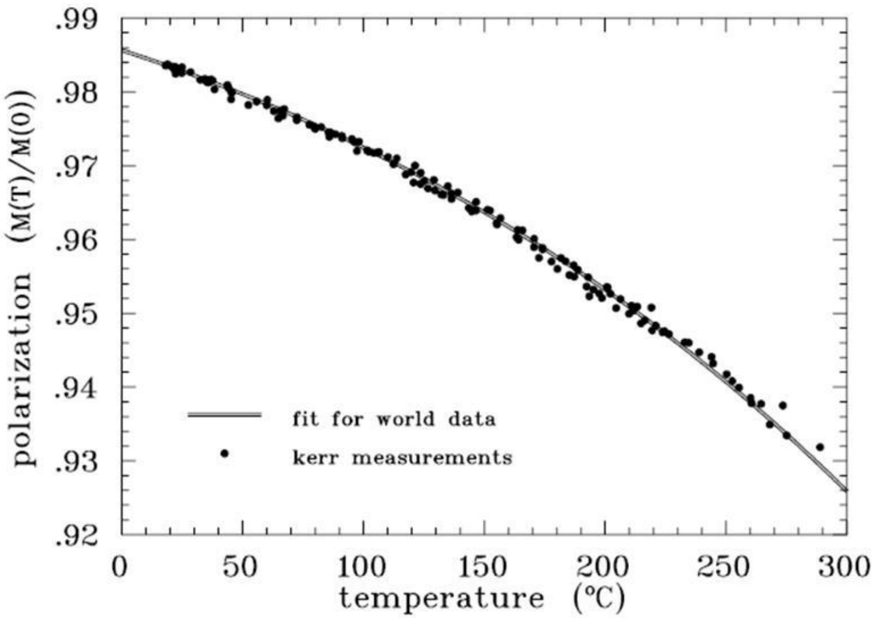
Target *magnetization* can be measured in-situ using a Kerr apparatus.

Magnetization is linearly related to target polarization.

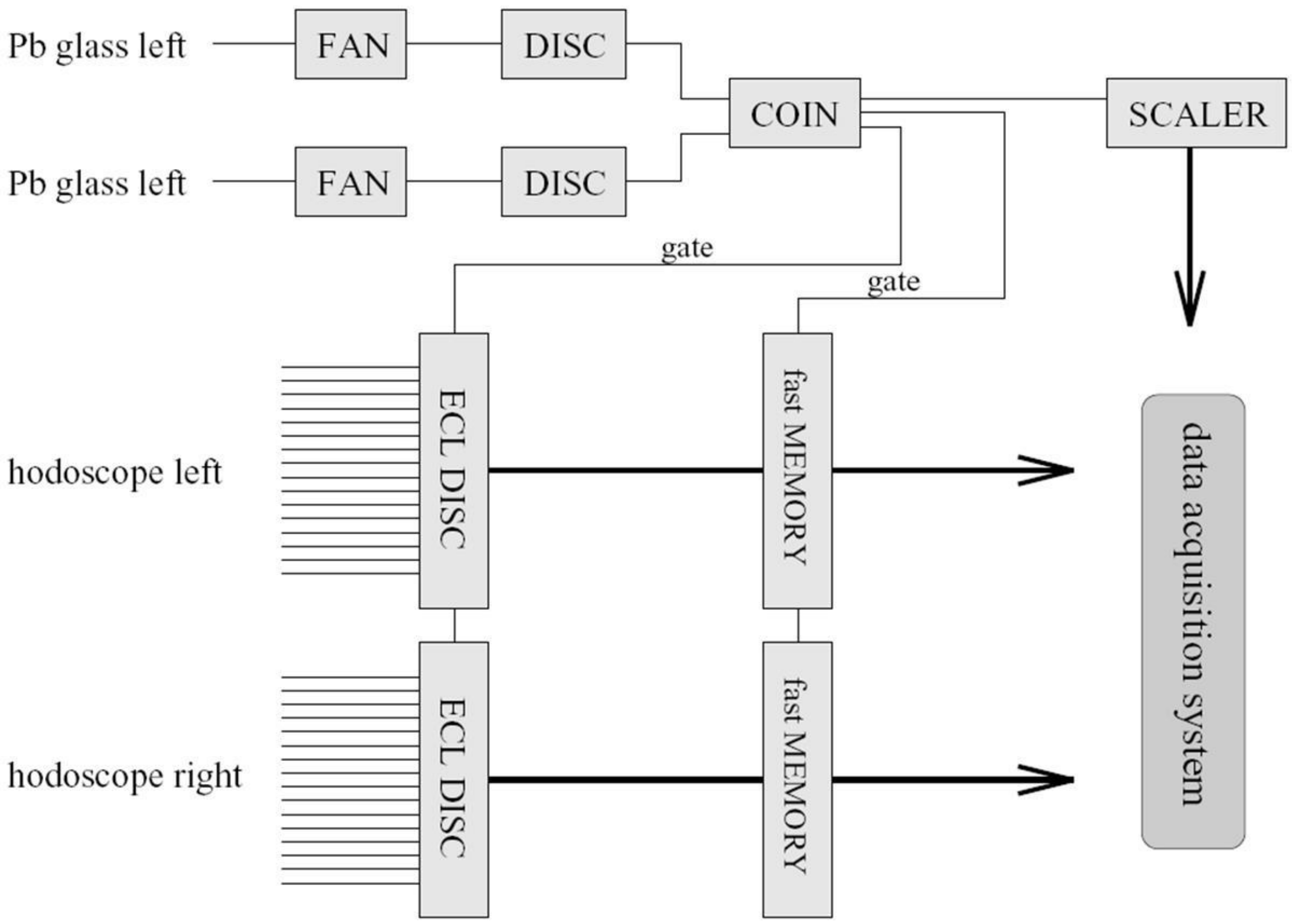




Emphasize: the "polarization" determination is really relative, not absolute.

M. Loppacher. *Thesis, University of* Basel, 1996.

Electronics chain



M. Loppacher, 1996 thesis.

Møller Polarimetery Examples

Year	Facility	Max. E_{beam} (GeV)	Limitation	detectors Single	Coinc.	Uncert. $\Delta P/P$	Ref.
1975	SLAC	19.4	foil/stat/bck	$\surd$		4%	[Co75]
1976	SLAC-E80	12.9	foil/stat/bck	$\surd$		12%	[Al76]
1978	SLAC-E122	22.2	foil/stat/bck	$\surd$		5.5%	[Pr78]
1982	SLAC-E130	22.7	foil/stat		$\surd$	4%	[Ba83]
1984	Bonn	2.0	stat		$\surd$	12%	[Br85]
1986	Mainz	$0.071 \rightarrow 0.35$	foil/stat		$\surd$	4%	[Wa90]
1990	MAMI	$0.185 \rightarrow 0.84$	foil/bck		$\surd$	4%	[Wa90]
1992	Bates	0.574	stat/bck	$\surd$		12%	[Ar92]
1992	SLAC-linac	46.6	foil/bck	$\surd$		4.2%	[Sw95]
1993	SLAC-E142	26	foil/bck	$\surd$		4%	[An93]
1995	Bates	0.868	stat/bck		$\surd$	5%	[Be95]
1995	SLAC-E143	29	foil		$\surd$	2%	[Fe97]

Taken from M. Loppacher, 1996 thesis

Møller Polarimetery Iron Target Properties

Effect	$M_s[\mu_B]$	error
saturation magnetization (T→0k,B→0k)	2.2160	±0.0008
saturation magnetization (T=294K, B=1T)	2.177	±0.002
corrections for B=1→4T	0.0059	±0.0002
Total magnetization	2.183	±0.002
Orbital motion contribution	0.0918	±0.0033
Remaining magnetization from spin	2.0911	±0.004
Target electron polarization (T=294k, B=4T)	0.08043	±0.00015

Information taken from M. Loppacher, 1996 thesis.

Møller position uncertainty

Let's focus on a few of the larger uncertainties and understand exactly how we calculated them.

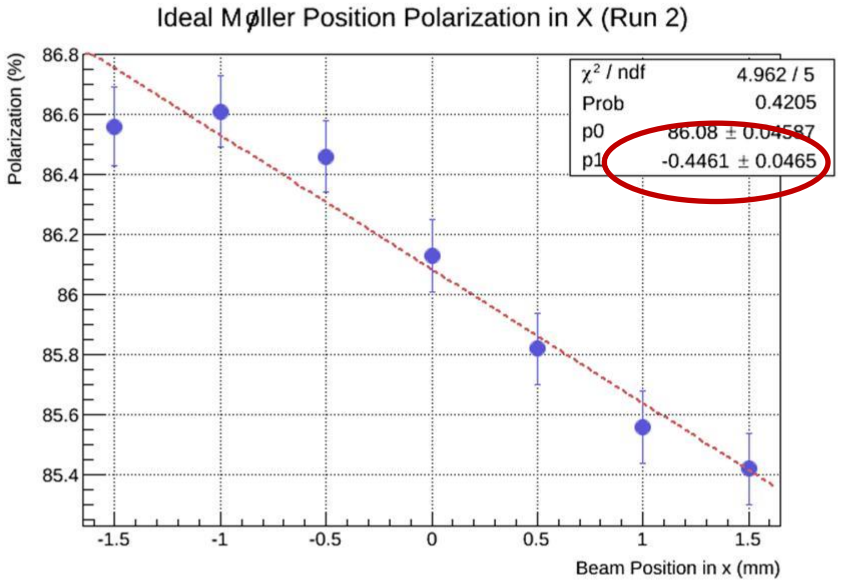
Beam position

The beam position is our largest experimental uncertainty, and our largest correction.

Three major factors contribute to the uncertainty of beam position:

- The dependence of the measured polarization from beam position ($\frac{\partial P}{\partial x}$)
- Uncertainty in projecting from the bpms to the target ($\delta\omega_{calculation}$)
- Instrumental uncertainty in bpm3c20 and 3c21 absolute position ($\delta\omega_{instrument}$)

We can determine $^{\partial P}/_{\partial x}$ directly from simulation.



Møller position uncertainty

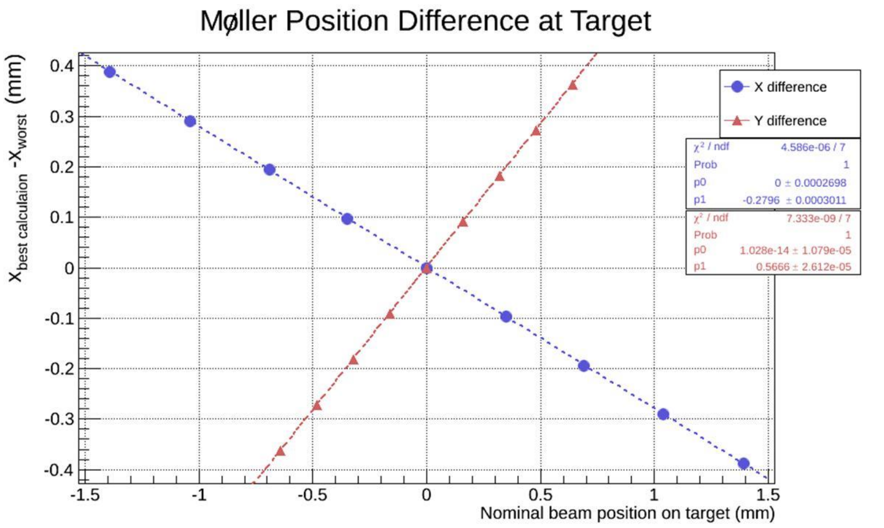
Beam position

- The dependence of the measured polarization from beam position ($\frac{\partial P}{\partial x}$)
- Uncertainty in projecting from the bpms to the target ($\delta\omega_{calculation}$)
- Instrumental uncertainty in bpm3c20 and 3c21 absolute position ($\delta\omega_{instrument}$)

The projection from the bpm's to the target is non-trivial, hence $\delta\omega_{calc}$. For instance, there are quadrupoles between the bpms and the target, and also the solenoid field.

To estimate the uncertainty we compare our "best" projection to target with the "worst possible" case.
The best projection uses the spilt solenoid transport equation discussed previously.
The worst assumes a straight projection from the bpms-->target.

$$\delta x_{calc} = (\Delta x) \cdot \left(\frac{\partial P}{\partial x}\right)$$



Møller position uncertainty

Beam position

- The dependence of the measured polarization from beam position $(\frac{\partial P}{\partial x})$
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Finally, our knowledge of absolute bpm position is good to about ~.1mm. To be conservative, I assumed they were good to 0.2mm. I moved bpm3c20 and 3c21 individually to see their individual effects.

Assuming .2mm offset in bpm3c20 or 3c21 yields about $(\Delta x)\sim.08mm$

In all, we have:

$$\delta x_{model} = .17\%$$
$$\delta x_{instr} = .036\%$$

$$(\delta x) = \sqrt{(\delta x_{model})^2 + (\delta x_{instr})^2} \approx .17\%$$

Playing the same game with y, and x-angle and y-angle yields:

$$(\delta y) \approx .28\%$$

$$(\delta xp) \approx .06\%$$

$$(\delta yp) \approx .04\%$$

We rounded both these up to .1%, but makes no difference in quadrature.

The weak charges

What exactly is the proton's weak charge (Q_W^p)?

- Neutral-weak analog of the proton's electric charge
- Dirac form factor of the neutral-weak interaction

The Standard Model makes a firm prediction of Q_W^p

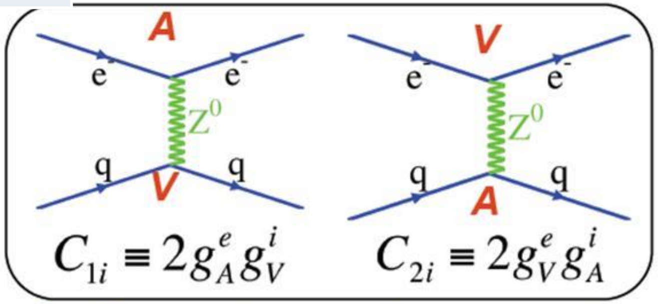
	EM Charge	Weak Charge
u	2/3	$1-\frac{8}{3}sin^2(\theta_w) \approx 0.38$
d	-1/3	$-1+\frac{4}{3}sin^2(\theta_w) \approx -0.69$
P (uud)	+1	$1-4\,sin^2(\theta_w) \approx 0.07$
N (udd)	0	-1

"Accidental suppression"
→sensitivity to new physics

Note: $Q_W^n = -1$

Q-weak is particularly sensitive to the quark *vector* couplings (C_{1u} and C_{1d}) .

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



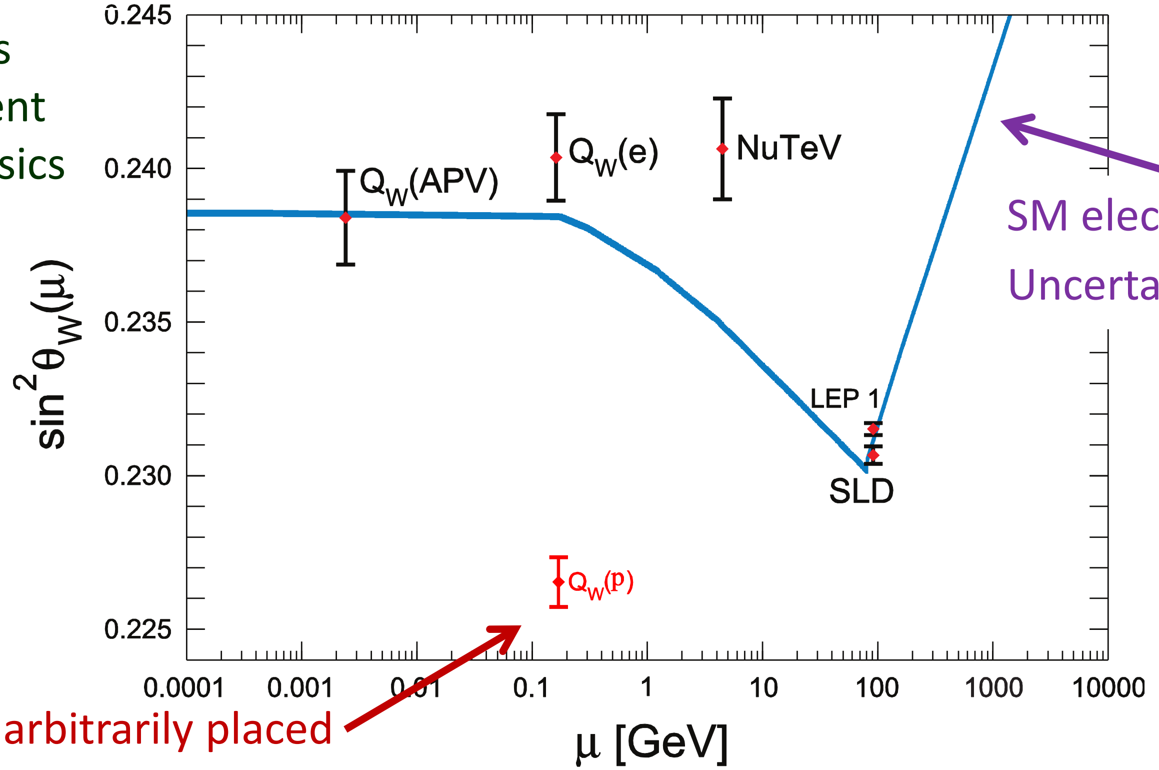
Small scattering angles

Large scattering angles

The Running of the Weak Mixing Angle

The measurements at the Z-pole pin down the scale; they don't describe the evolution in the low Q^2 regime.

Each experiment is sensitive to different potential new physics



SM electroweak fit.

Uncertainty is line width.

Vertical position arbitrarily placed

Error bar is proposed goal

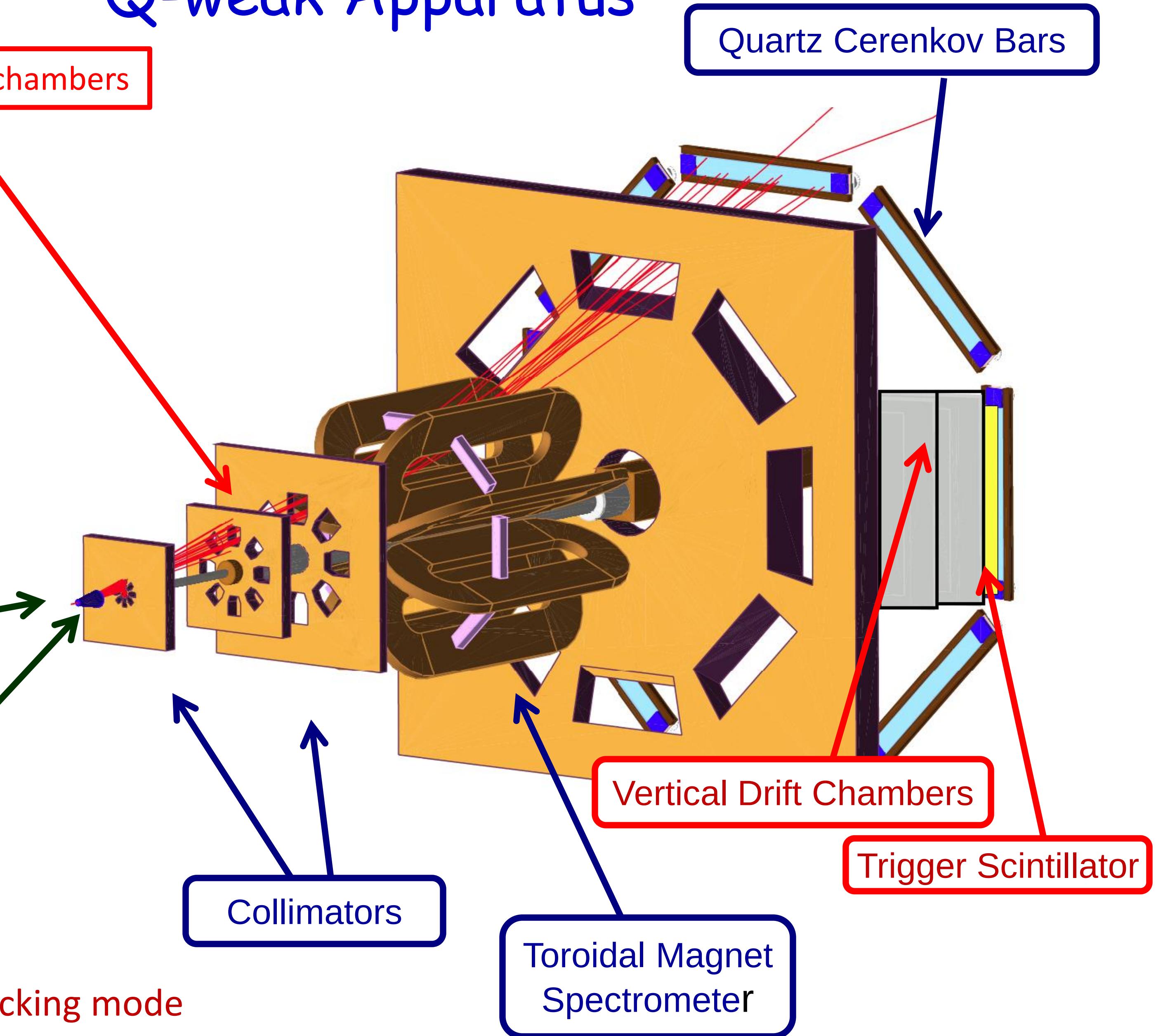
Q-weak will make the most precise measurement of $\sin^2(\theta_W)$ at low-Q^2

$$\delta(\sin^2\theta_W) \approx \pm 0.3\%$$

Beringer et al, (PDG), Phys. Rev D86, 010001 (2012)

Q-weak Apparatus

E_{beam} = 1.165 GeV
Q^2~0.025 GeV^2
θ ~ 7-11°
Current = 180 μA
Polarization = 85%
Target = 35 cm LH2
Cryopower = 2.5 kW



Red = low-current tracking mode
Blue = production ("integrating") mode

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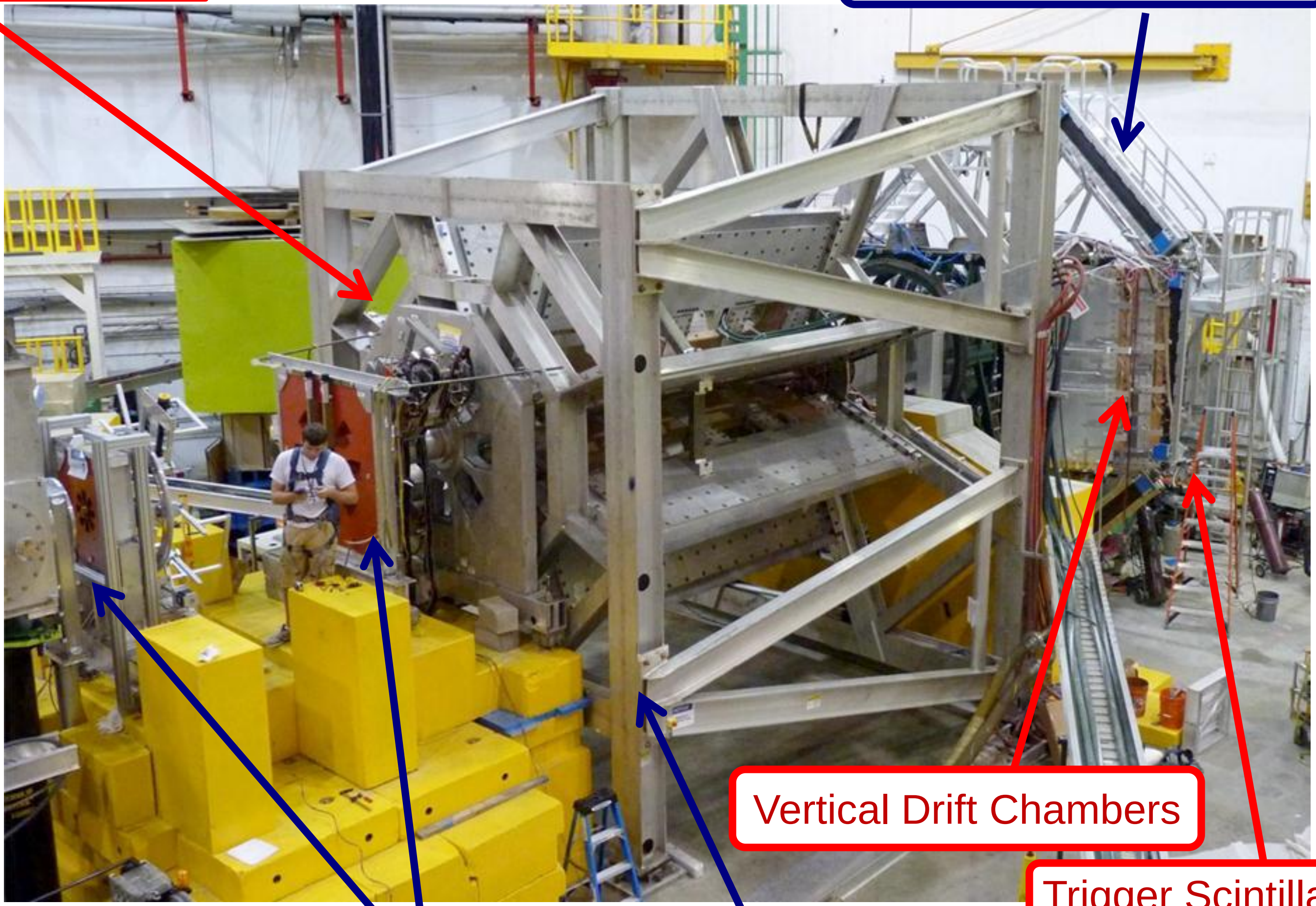

Red = low-current tracking mode

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Probing the Weak Charge

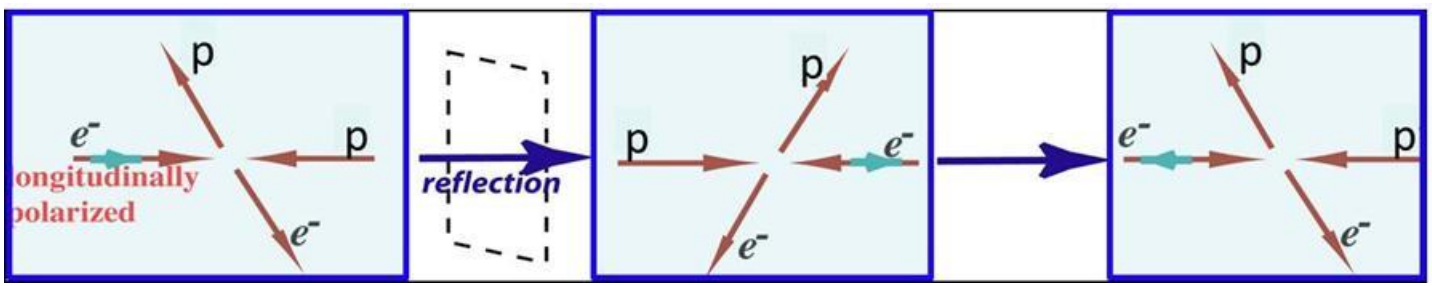
The weak force is *unique*: it violates parity

To extract Q_W^p: measure the parity violating asymmetry in electron-proton scattering

$$\vec{e} + p \rightarrow e + p$$

35 cm LH2 target

Beam helicity change is equivalent to parity transformation



Rapid helicity reversal pattern (960 Hz) "quartets"

+ − − +   − + + −