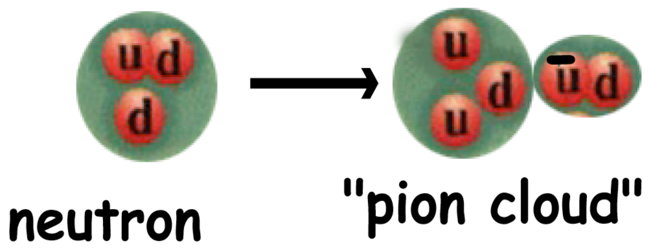
Measurement of Nucleon Strange Form Factors at High Q^2

Rupesh Silwal

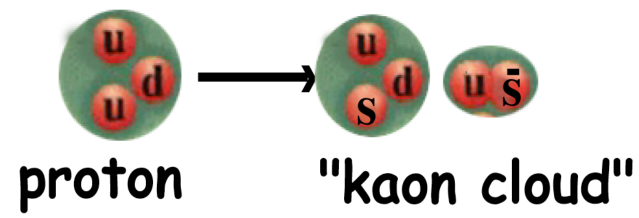
30 March 2010

At very low Q2, GsE/M relates to the strange matrix elements of the nucleon (strange radius ρs and strange magnetic moment μs)

neutron charge distribution



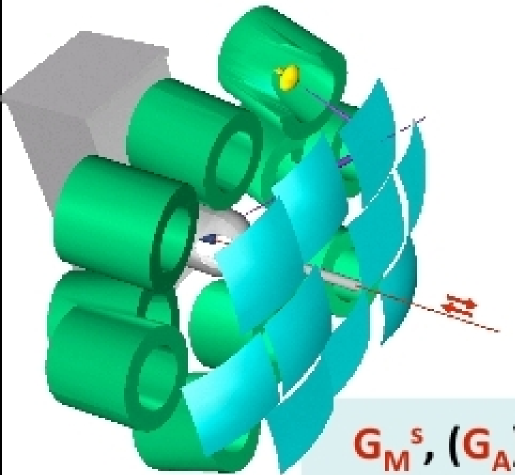
proton flavor distribution



The bare mass of the three quarks only makes up ~ 1% of the proton mass, the rest is a sea of gluons, quarks and anti-quarks, which is dominated by the up, down and strange quarks.

Do the strange quarks contribute to the electric and magnetic structure of the proton?

World Data

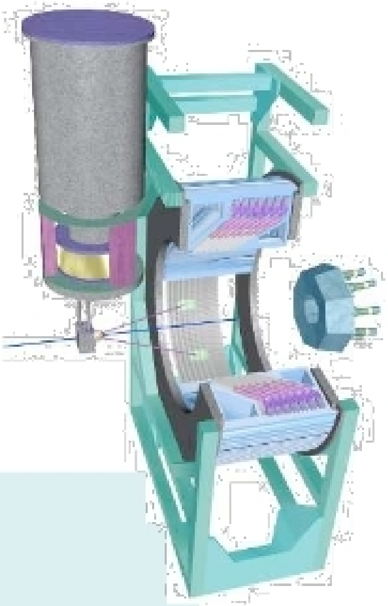


SAMPLE

open geometry, integrating

G_M^s, (G_A) at $Q^2 = 0.1$ GeV^2

A4



Open geometry

Fast counting calorimeter for background rejection

$G_E^s + 0.23\, G_M^s$ at $Q^2 = 0.23$ GeV^2

$G_E^s + 0.10\, G_M^s$ at $Q^2 = 0.1$ GeV^2

G_M^s, G_A^e at $Q^2 = 0.23$ GeV^2

HAPPEX

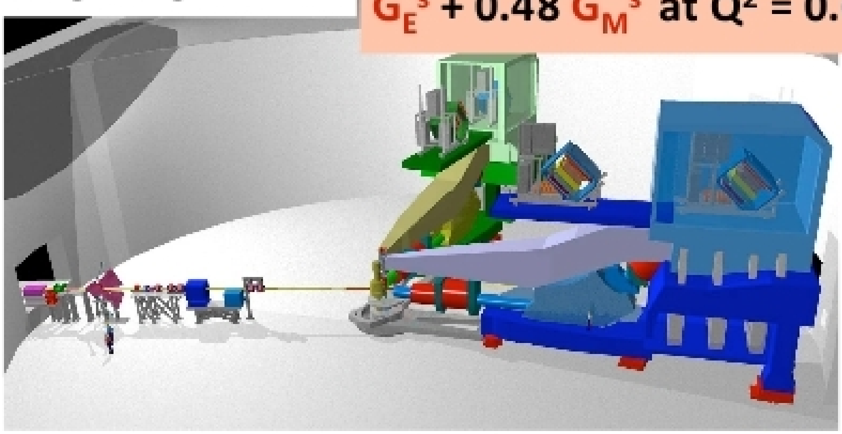
Precision spectrometer, integrating

$G_E^s + 0.39\, G_M^s$ at $Q^2 = 0.48$ GeV^2

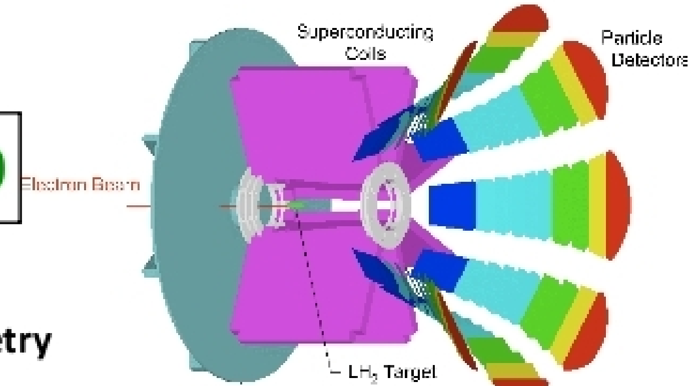
$G_E^s + 0.08\, G_M^s$ at $Q^2 = 0.1$ GeV^2

G_E^s at $Q^2 = 0.1$ GeV^2 (^{4}He)

$G_E^s + 0.48\, G_M^s$ at $Q^2 = 0.62$ GeV^2



G0



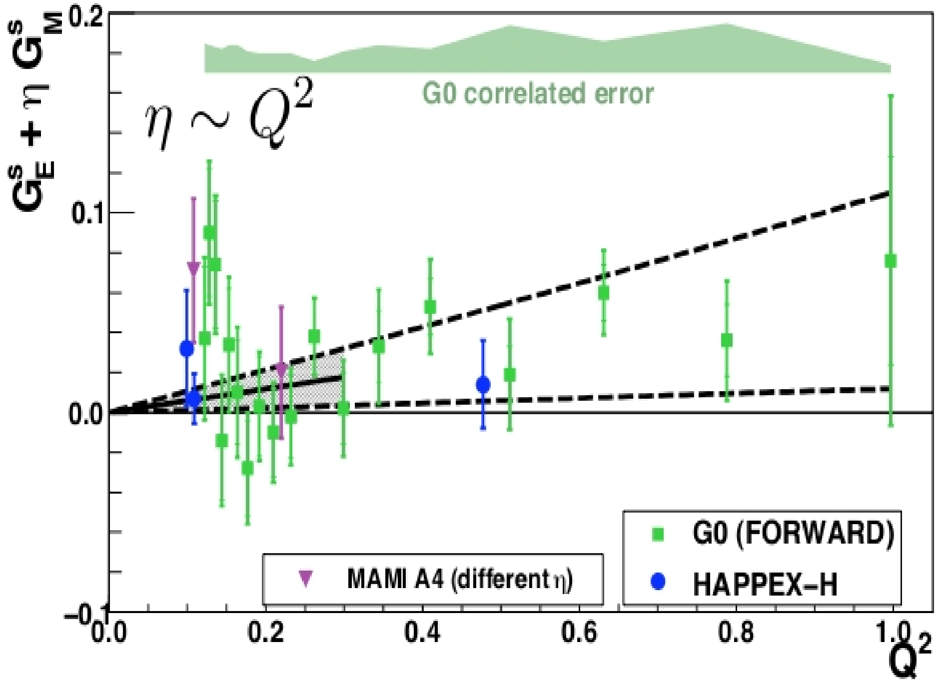
Open geometry

Fast counting with magnetic spectrometer + timing for background rejection

$G_E^s + \eta\, G_M^s$ over $Q^2 = [0.12, 1.0]$ GeV^2

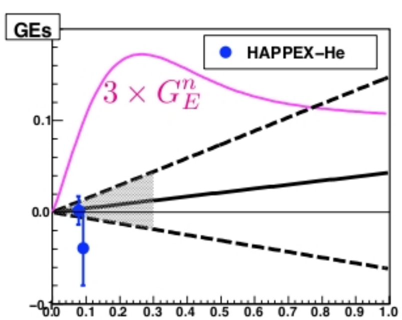
G_M^s, G_A^e at $Q^2 = 0.23, 0.62$ GeV^2

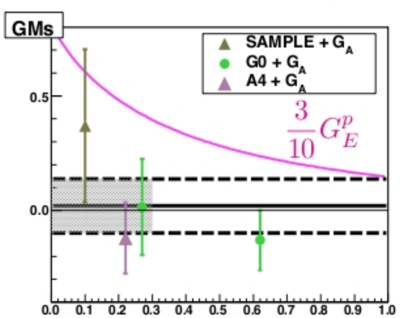
Present Data



Fit to "leading order" in Q^2, (only for $Q^2 < 0.3$ GeV^2)

$G^s_M = \mu_s$
$G^s_E = \rho_s * \tau$





G^s_M From backangle results, neglects correlation with G^s_E

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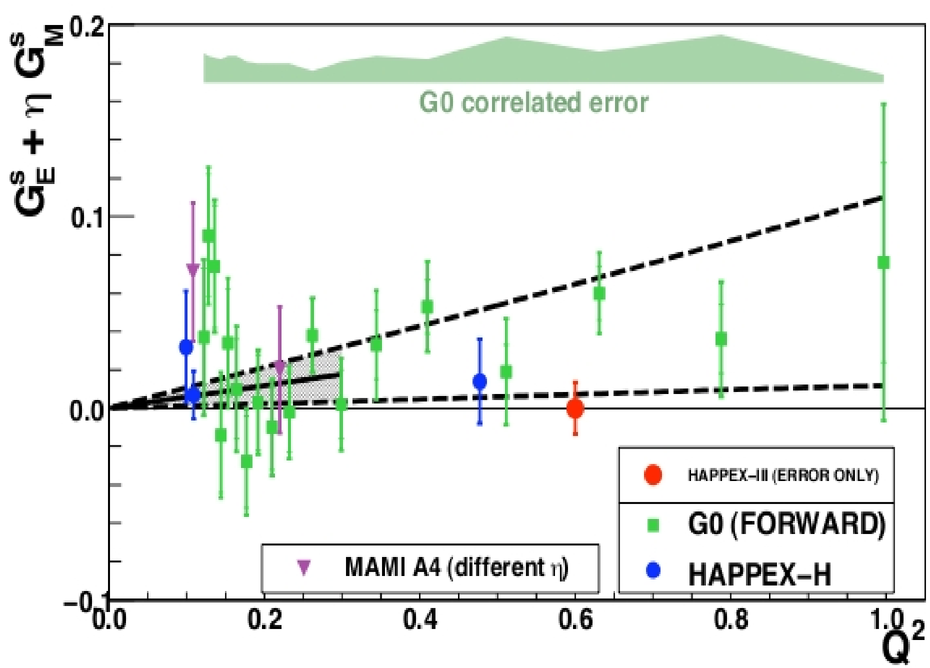

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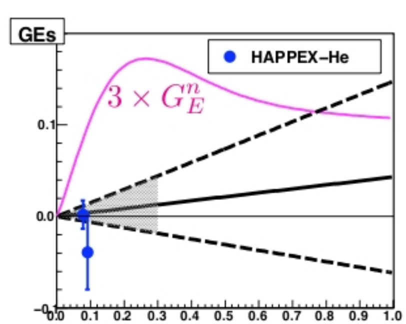
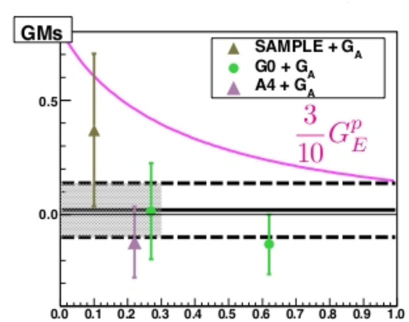
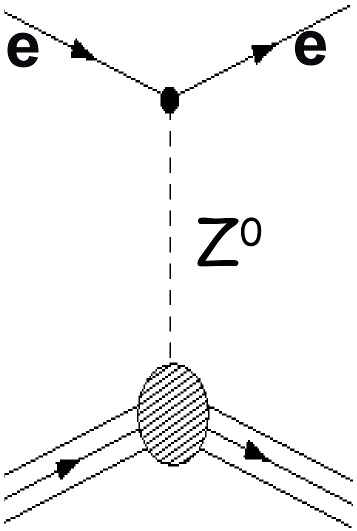


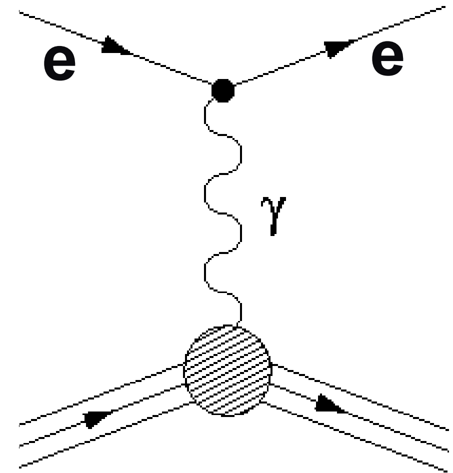


G^s_M From backangle results, neglects correlation with G^s_E

Parity Violating Measurements



	Left	Right
Z-Charge	$T - qSin^2\Theta_w$	$qSin^2\Theta_w$



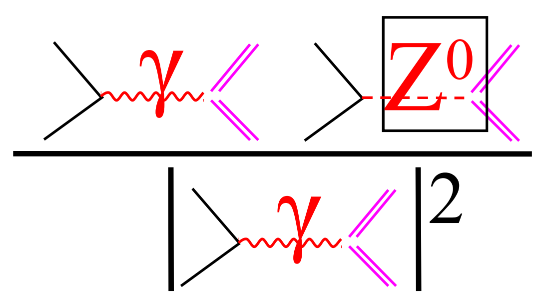
$$\sigma \;\; \alpha \left| A_{EM} + A_{weak} \right|^2$$

$$\sim \left| A_{EM} \right|^2 + 2 A_{EM} A^*_{weak} + \ldots$$

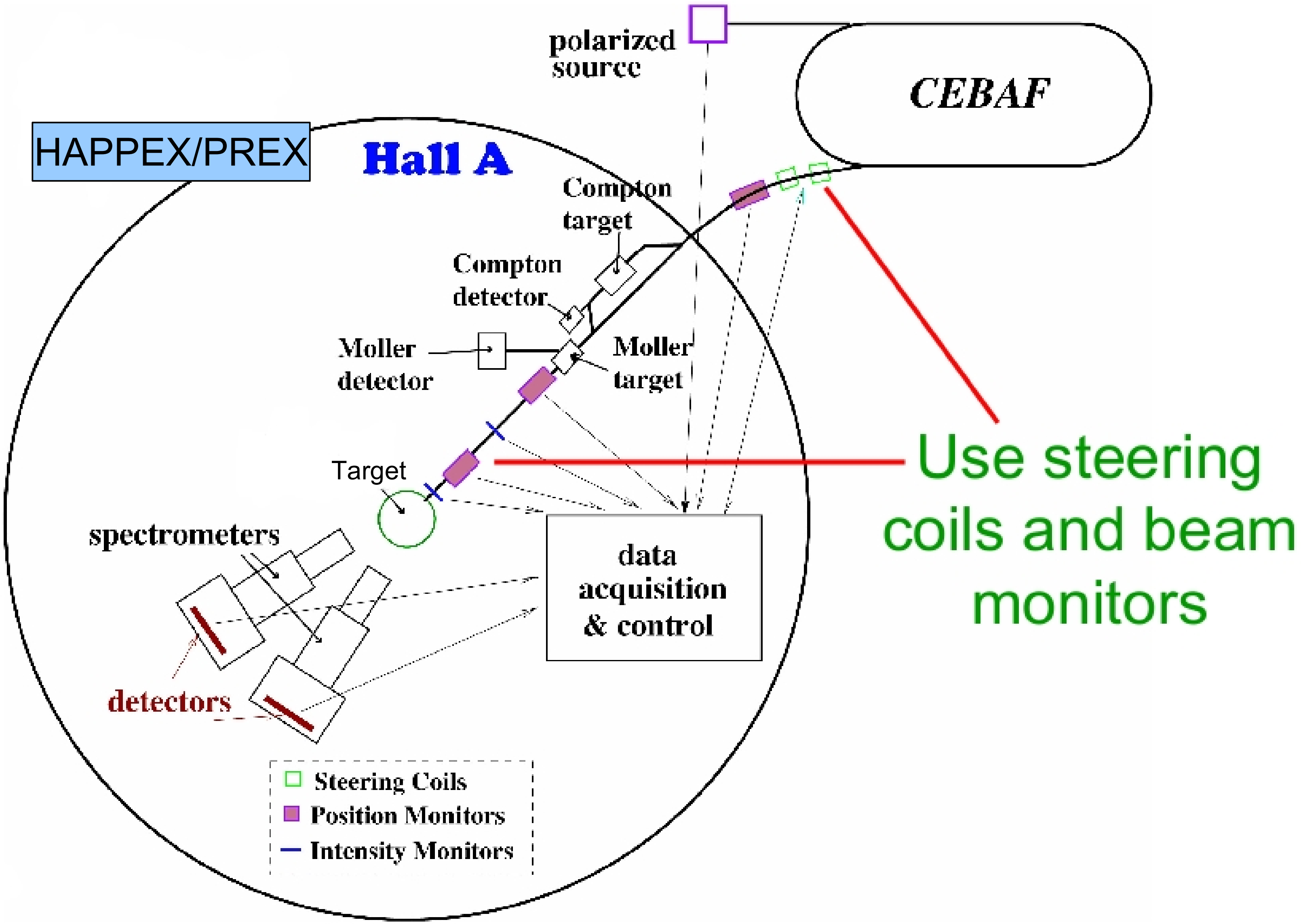
Left/Right handed longitudinally polarized electrons have different cross sections, which can vary by as much as 0.1 %

Weak amplitude is 10^{-6} smaller than the Electromagnetic amplitude, but its interference to EM makes it accessible.

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$

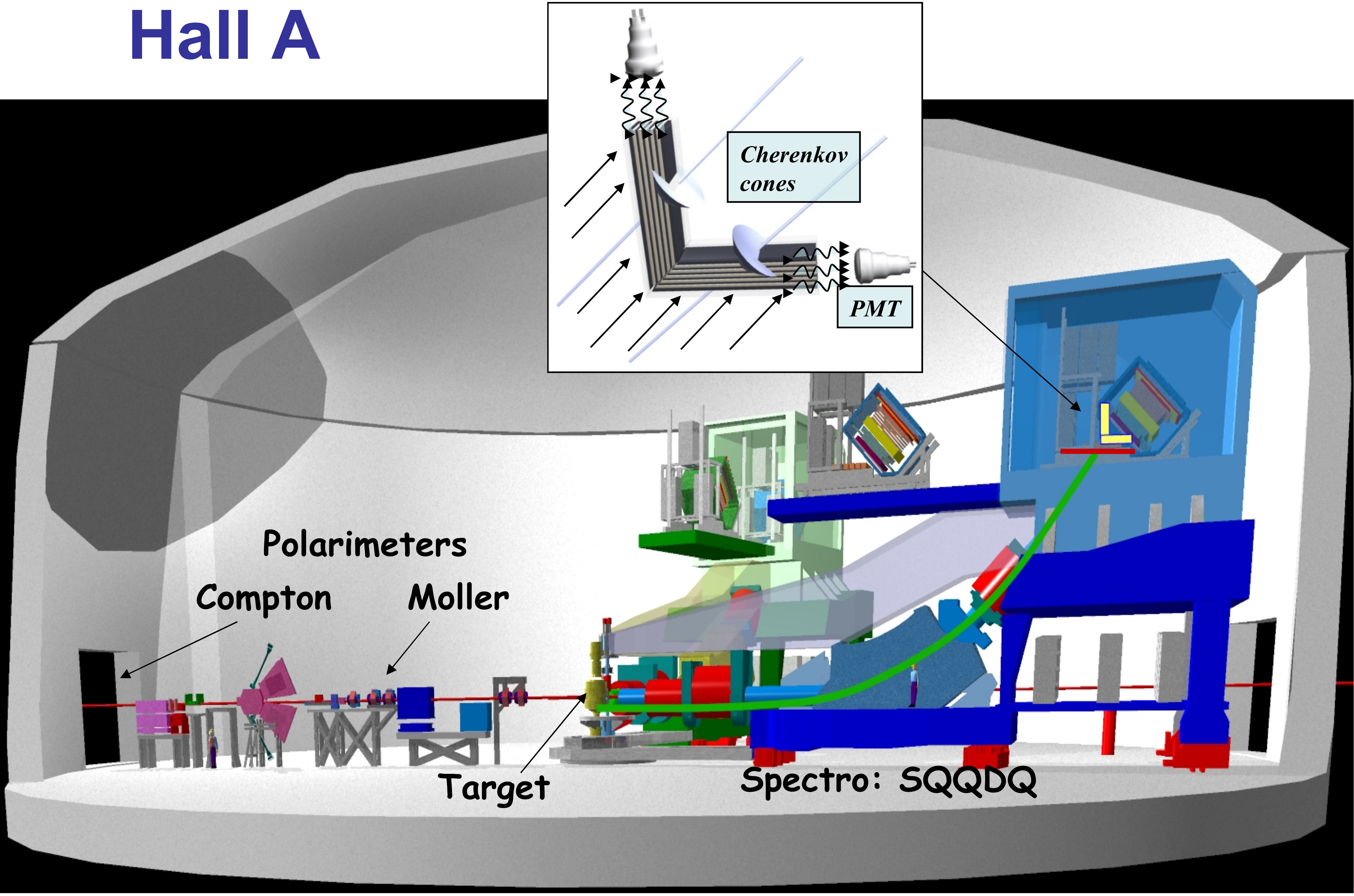


$$\approx \frac{|M_Z|}{|M_\gamma|}$$



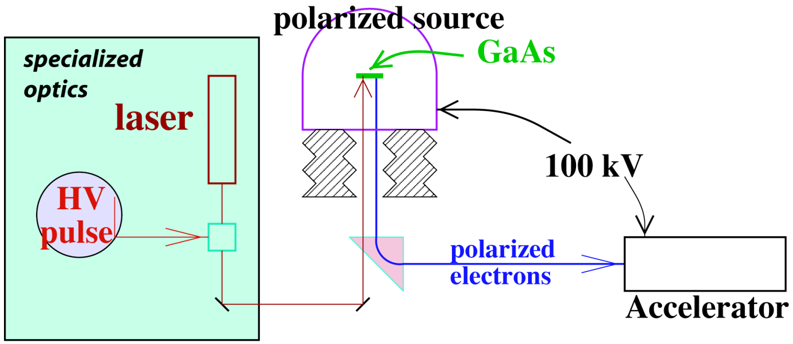
HAPPEX/PREX
Hall A
polarized source
CEBAF
Compton target
Compton detector
Moller detector
Moller target
Target
spectrometers
detectors
data acquisition & control
Steering Coils
Position Monitors
Intensity Monitors
Use steering coils and beam monitors

Hall A



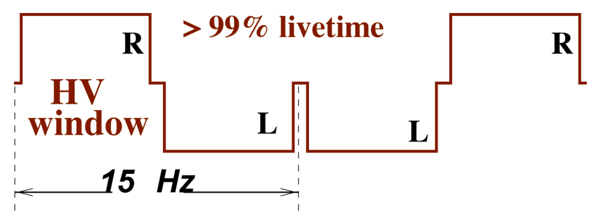
Cherenkov cones
PMT
Polarimeters
Compton
Moller
Target
Spectro: SQQDQ

Experimental Method



rapid, random, helicity flipping

Rapid, Random Helicity Flips



Measure flux F for each window

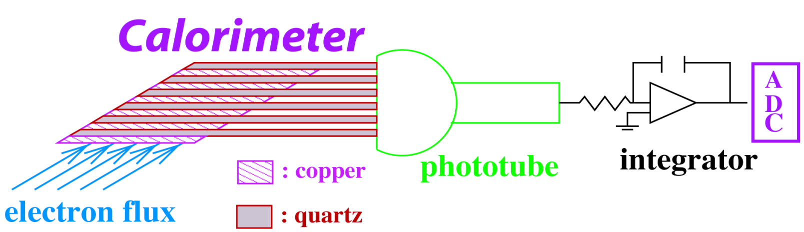
$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

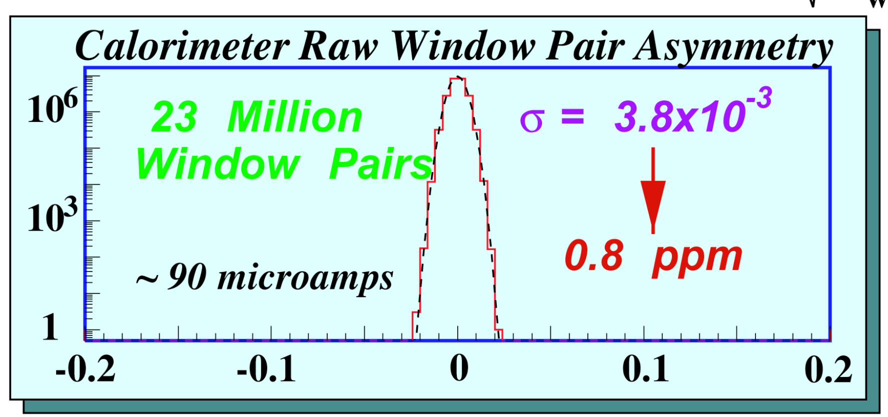
Signal Average N Windows Pairs: $A \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}$

Flux Integration Technique:

HAPPEX: 2 MHz

PREX: 850 MHz





No non-gaussian tails to +/- 5σ

Systematics

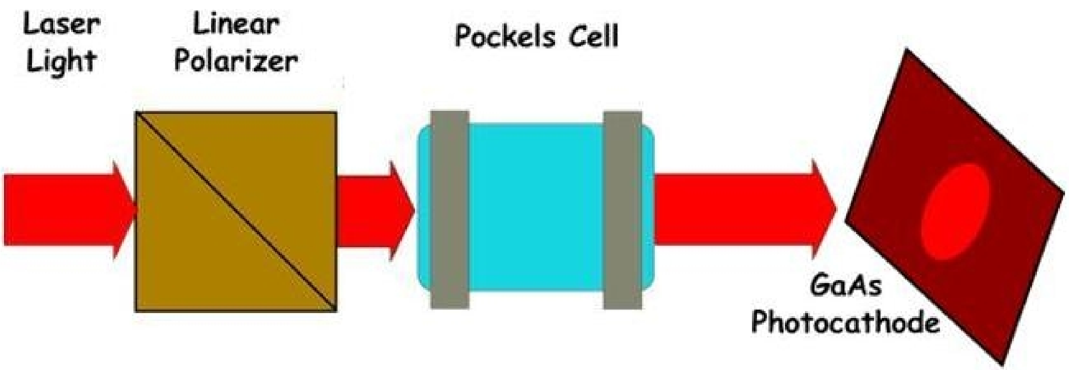
- Helicity Correlated Beam Parameters
- Detector Non-linearity/Alignment
- Background Corrections
- Polarimeters
- Radiative Corrections
- Q^2 Measurement

Helicity Correlated Beam Parameters

Helicity Correlated Beam Asymmetries (HCBA)

- The differential cross-section is sensitive to the energy and angle of beam, so any HC change in average position, angle or energy is reflected in the detected scattering rate asymmetry.
- Left unchecked, HCBA are the dominant source of systematic uncertainty.
- HC first-order effects result in HC position differences
- HC second-order effects result in HC spot size/shape differences

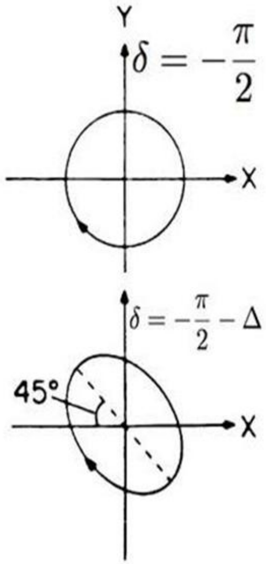
Source Setup



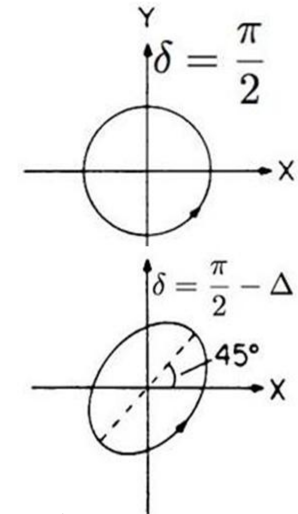
±λ/4 retardation produces
±circular polarization

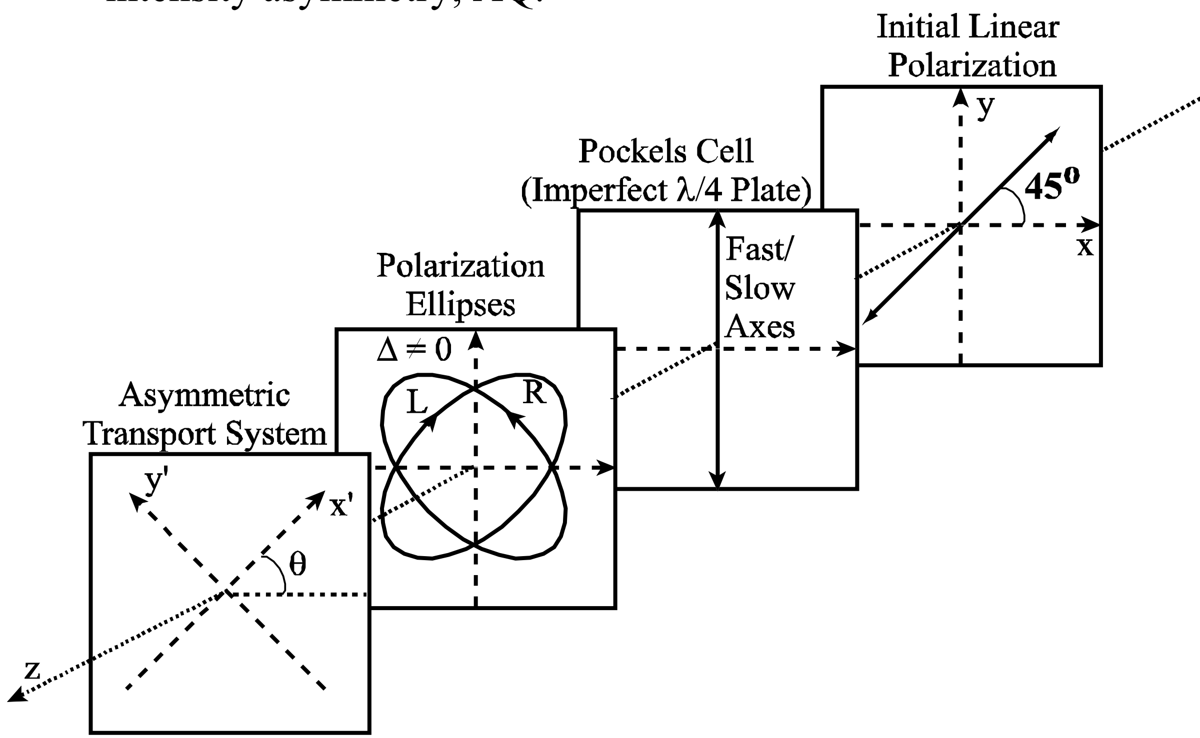
- The polarized electrons are generated by photoemission from a GaAs photocathode using Right(R)/Left(L) circularly polarized laser beam.
- The electron polarization states are determined by the laser polarization.
- The laser light polarization is prepared using an electro-optic Pockels cell.
    - ± Quarterwave phase differences are generated from ± voltages.

Polarization Effects



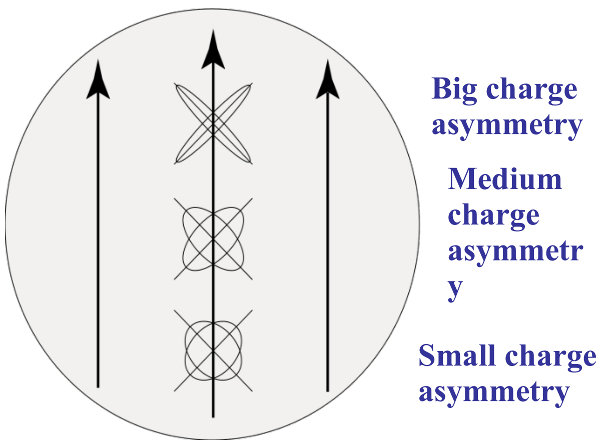
- A common retardation offset (Δ) leads to too much phase shift in one helicity state, and too little in the other.
- The QE anisotropy of the photocathode couples with the residual Δ linear polarization to produce an intensity asymmetry, AQ.





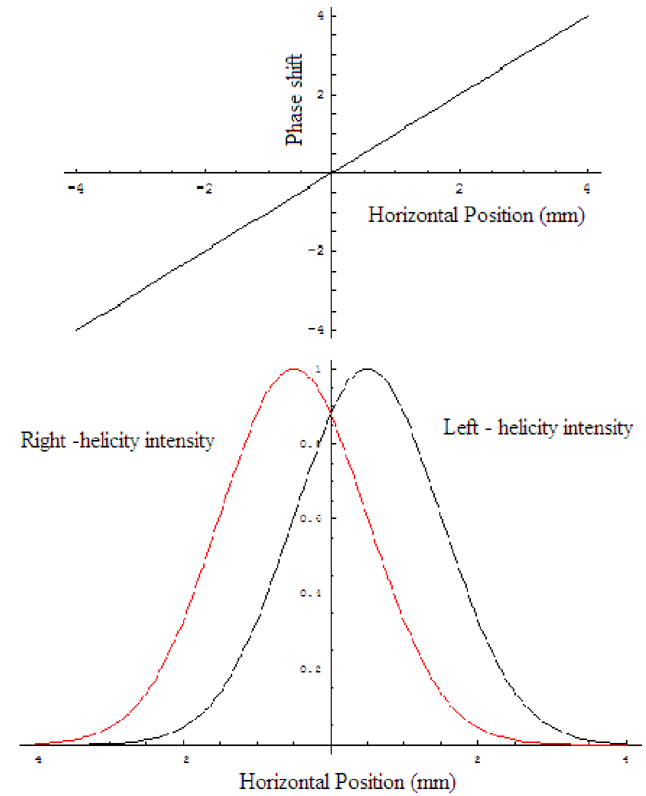
Polarization Induced Transport Asymmetry (PITA)

Phase Gradients



Beam Spot

• A spatial gradient in the Δ-phase shift results in a relative linear polarization gradient across the beam spot, which causes helicity-correlated beam centroid shifts.



• Beam divergence also causes position differences and *higher order effects*, which result in helicity-correlated spot size and shape variations.

Sources of Δ-phases

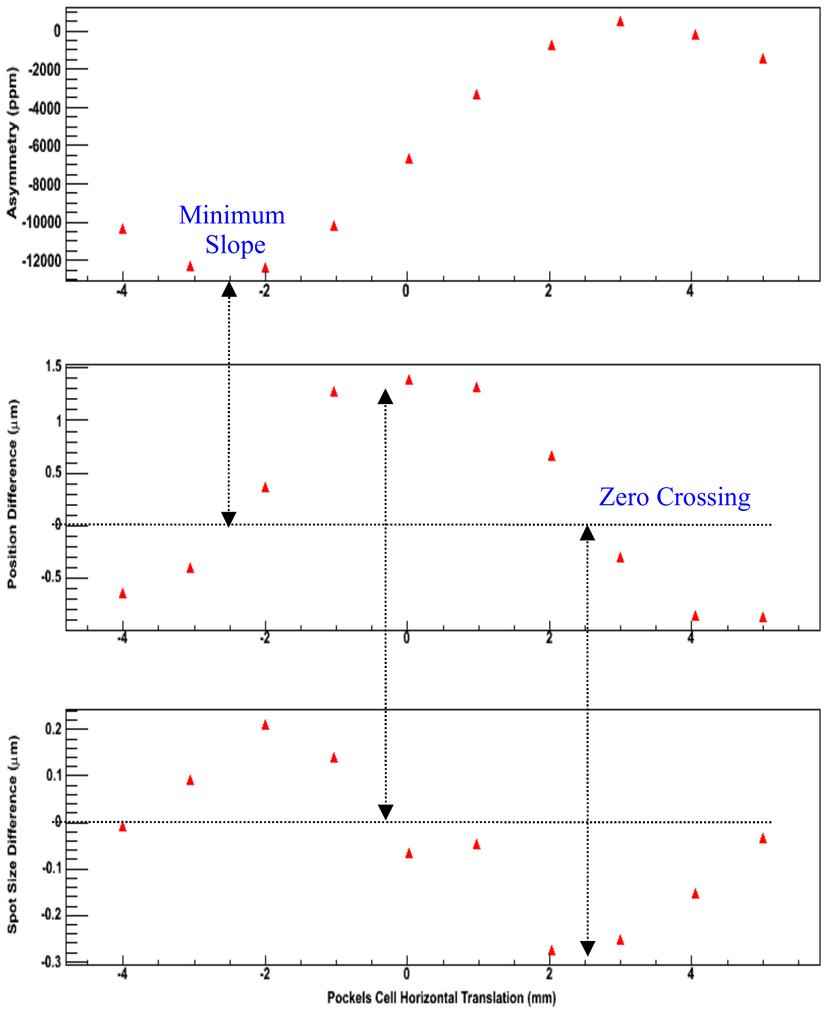
- Residual birefringence in the Pockels Cell (PC)
- Birefringence of any optical element between the PC and the photocathode, such as the vacuum window
- Birefringence due to misalignment of the PC
- Birefringence due to incorrect PC Voltages.

Δ-phases across the beam spot

Intensity Asymmetry, AQ, is proportional to the Δ-phase offset.

Position difference is proportional to the first derivative of AQ. i.e. the position difference is due to the Δ-phase gradient

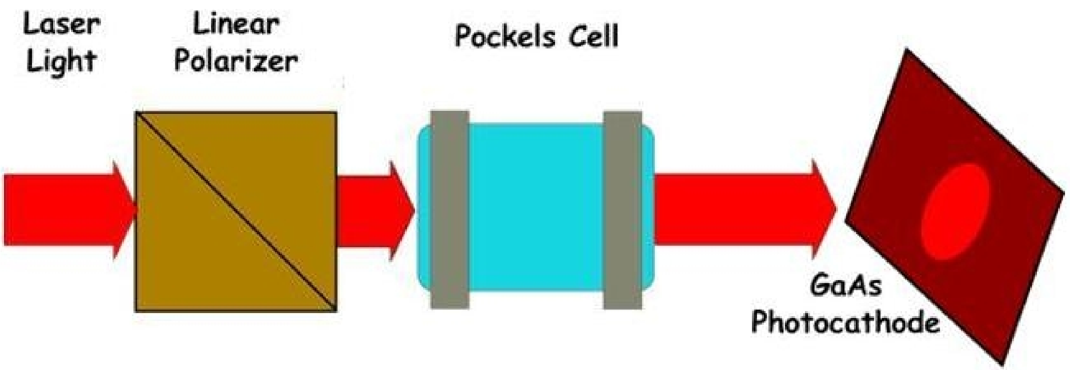
Spot Size difference is proportional to the second derivative of AQ. i.e. the spot size difference is due to *variations* in Δ-phase gradients.



Data taken on laser table on a linear-array photodiode with 100% analyzing power.

100 % Analyzer

Source Setup



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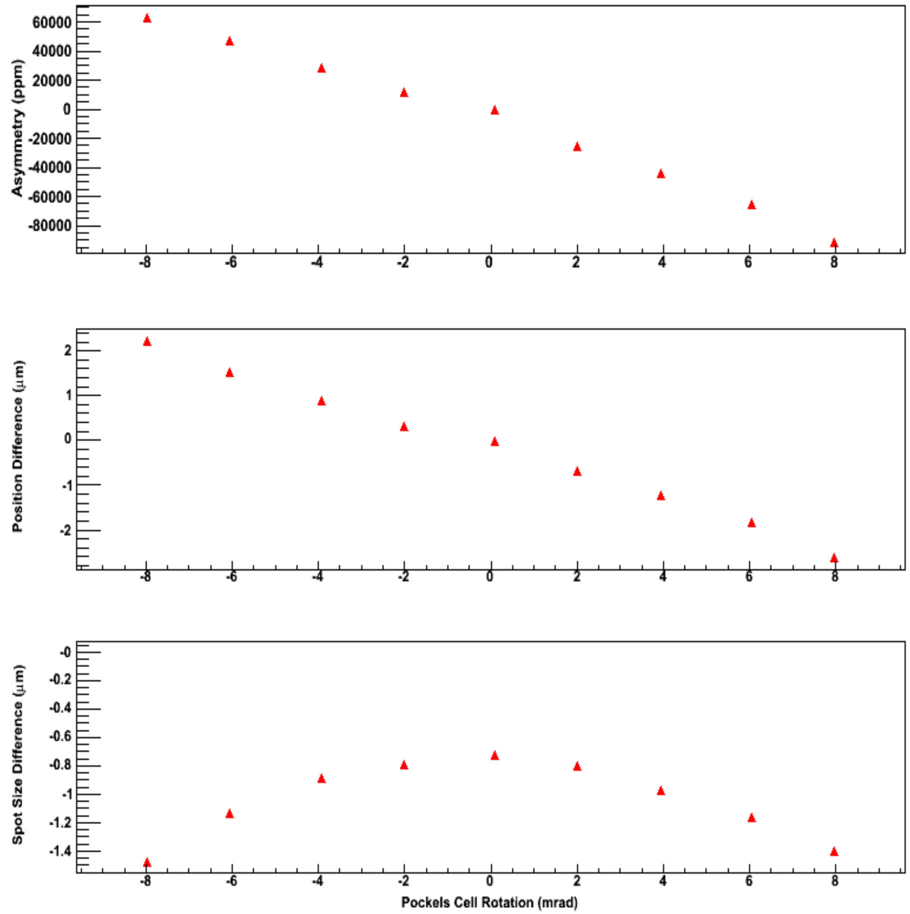
Δ-phase dependence on beam incidence angle

The HC parameters has a strong dependence on the beam incidence angle on the Pockels Cell (PC).

The position difference is linearly dependent on the angle of incidence. i.e. the Δ-phase gradient depends linearly on the beam incidence angle.

The spot size difference scales in quadrature with the incidence angle. i.e. variations in the Δ-phase gradient is related in quadrature to the incidence angle.

When observed along one of the Pockels cell birefringent axis, there is a constant non-zero offset term in spot size differences even when the PC is well aligned rotationally.



Data taken on laser table on a linear-array photodiode with 100% analyzing power. Measurement is along the PC birefringent axis.

100 % Analyzer

Suppressing Source Systematics

With 100 % analyzing power:

1. Optimize the beam incidence angle with PC yaw/pitch scans
2. Optimize the Δ-phases across the beam spot with PC translation scans
3. Optimize the PC voltages

Without any analyzer:

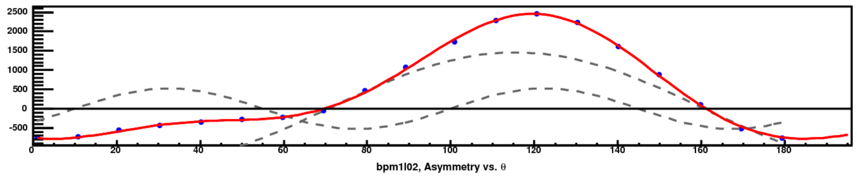
1. Setup point-to-point focusing, if needed.

With electron-beam:

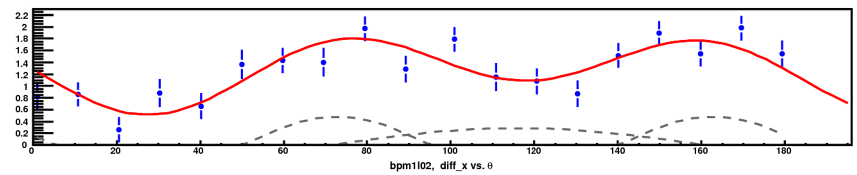
1. Optimize the photocathode orientation, to cancel the Δ-phases due to the vacuum window

HAPPEX III / PREX Setup

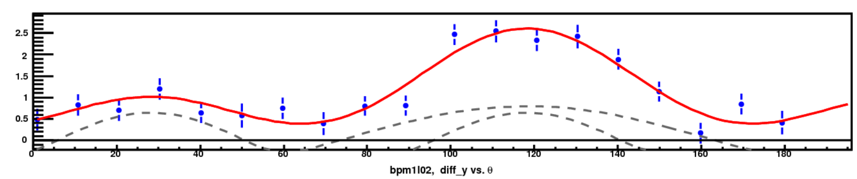
RHWP scan, Run 1239, IHWP IN, bpm1I02, PITA=0



$Aq = 496.42 + -1458.75 \sin(2\theta + 38.68) + -523.42 \sin(4\theta + 140.16)$



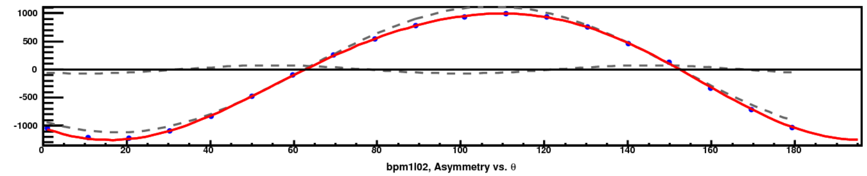
$Dx = 1.29 + -0.29 \sin(2\theta + 38.02) + 0.48 \sin(4\theta + 159.12)$



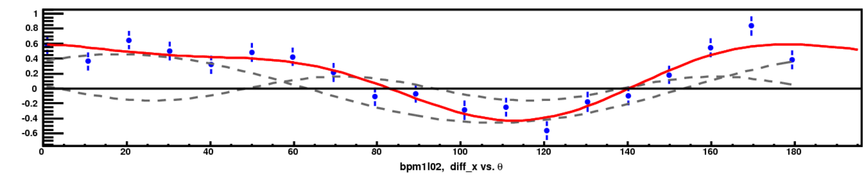
$Dy = 1.16 + -0.80 \sin(2\theta + 33.33) + -0.65 \sin(4\theta + 157.04)$

Before Optimization

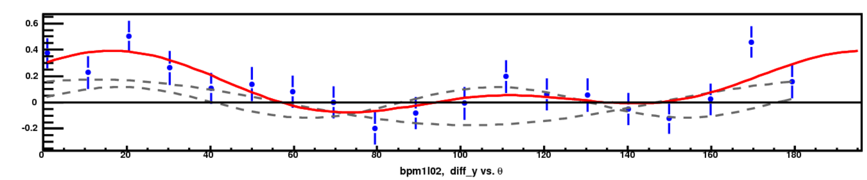
RHWP scan, Run 1841, IHWP IN, bpm1I02, PITA=0



$Aq = -68.34 + -1121.38 \sin(2\theta + 54.95) + -71.91 \sin(4\theta + 49.84)$



$Dx = 0.18 + 0.46 \sin(2\theta + 53.55) + 0.16 \sin(4\theta + 165.46)$



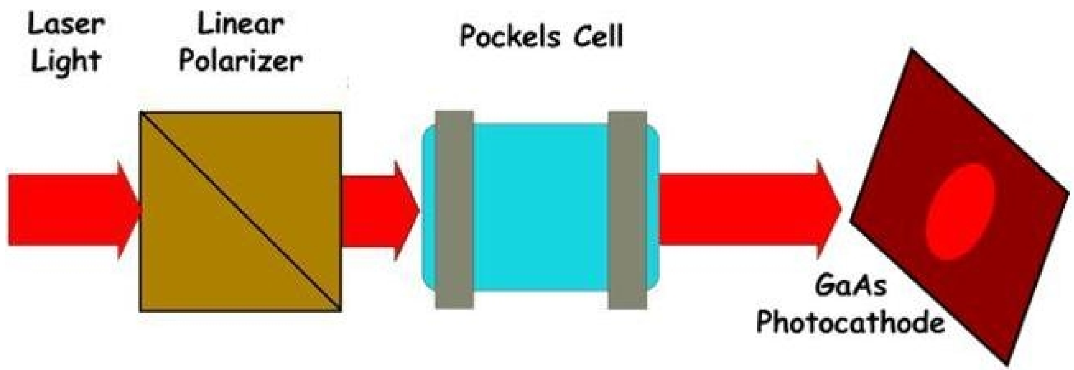
$Dy = 0.11 + 0.17 \sin(2\theta + 65.89) + 0.12 \sin(4\theta + 16.98)$

After Optimization

- Δ-phases due to the vacuum window (the offset-term) is minimized by judicious cathode orientation adjustment.
- Δ-phases due to the PC (4θ-term) is minimized by PC orientation and voltages optimization.

Electron Beam Data

Source Setup



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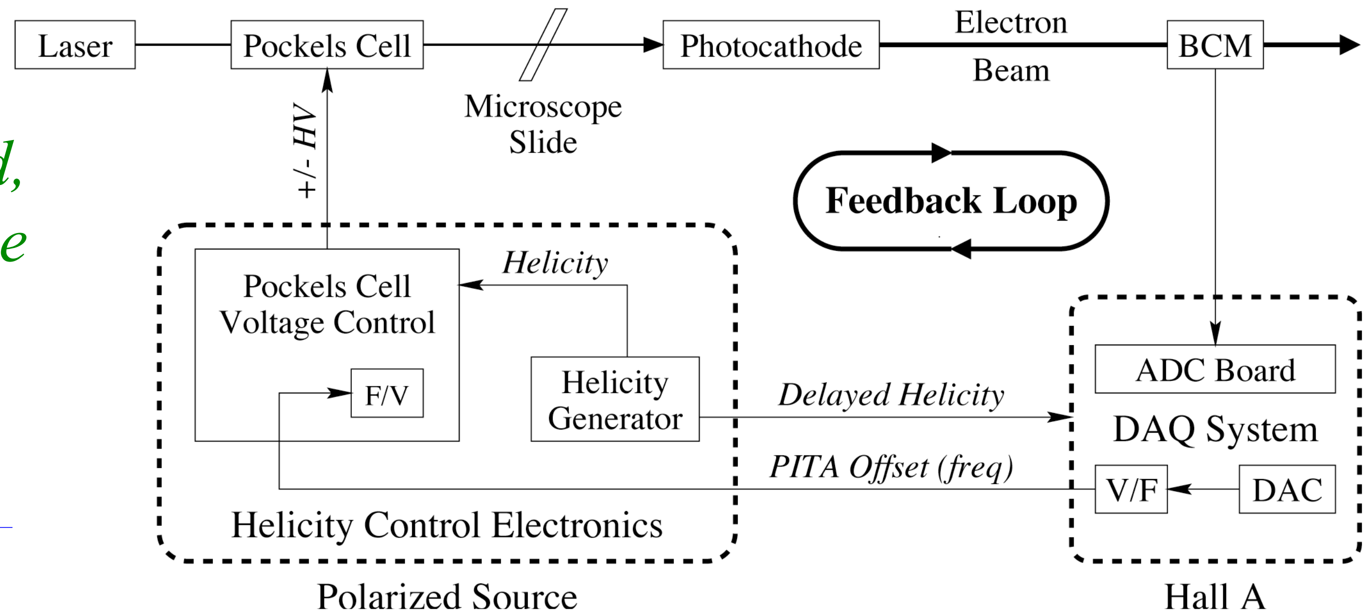
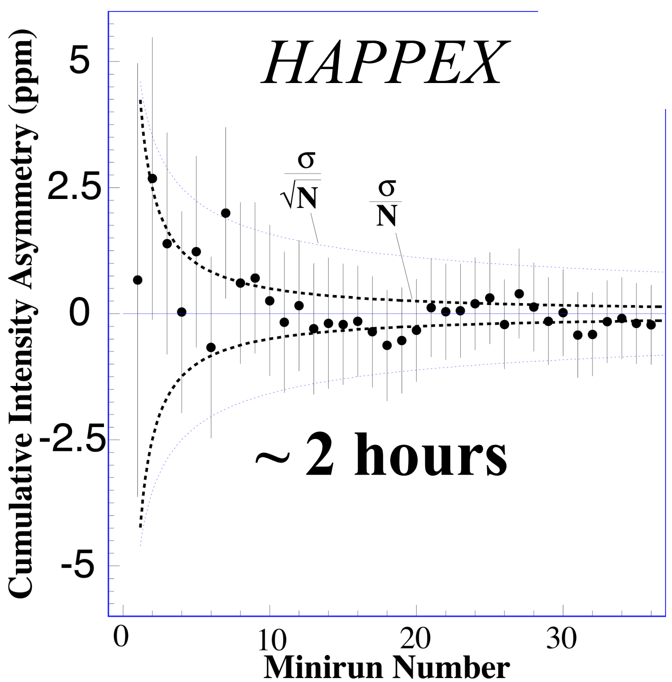
Intensity Feedback

With passive measures optimized, Feedback zeroes the helicity-correlated effects even further

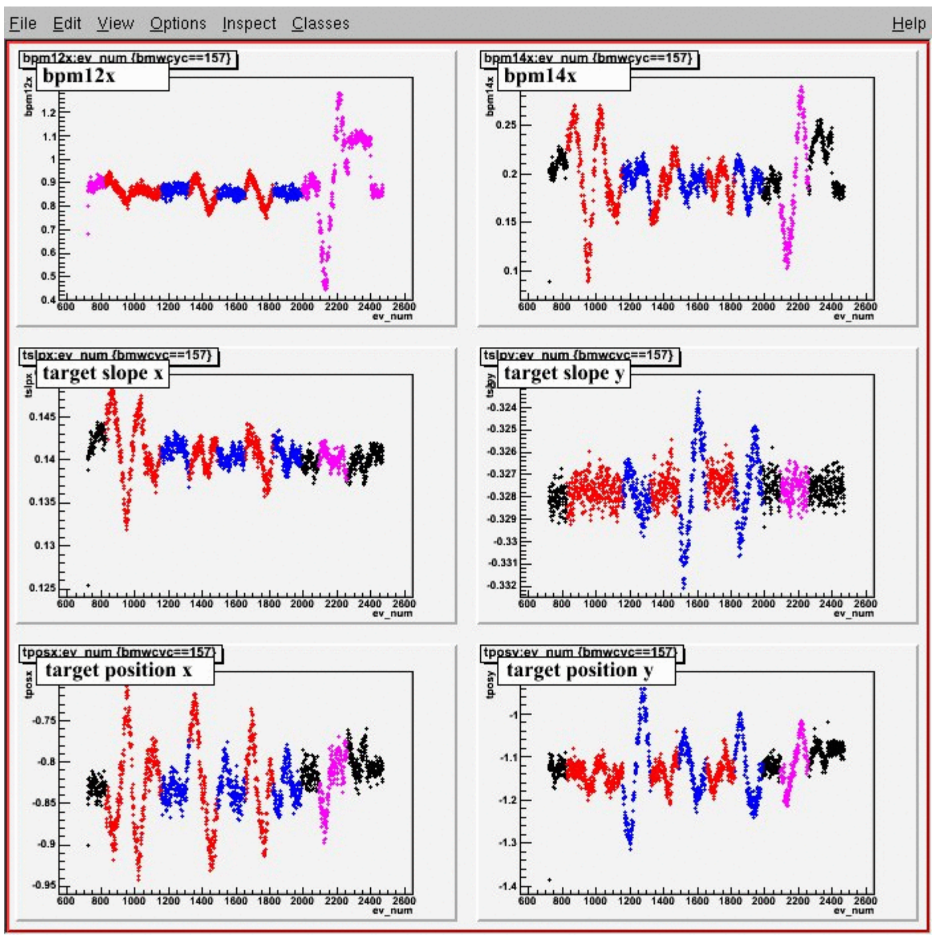




Low jitter and high accuracy allows sub-ppm Cumulative charge asymmetry in ~ 1 hour

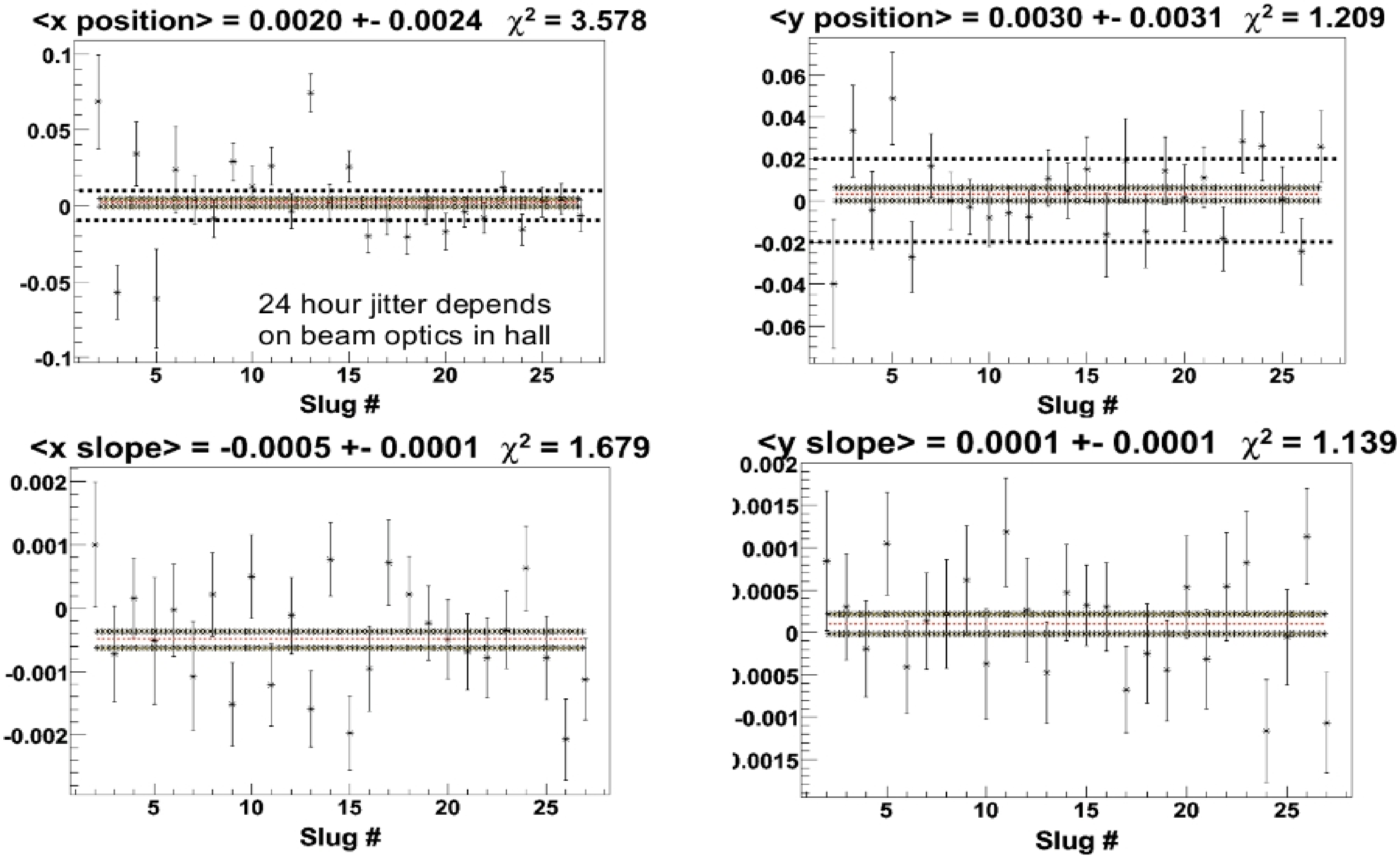
Scales as σ/N, not σ/√N as one might naively expect.

Beam Modulation



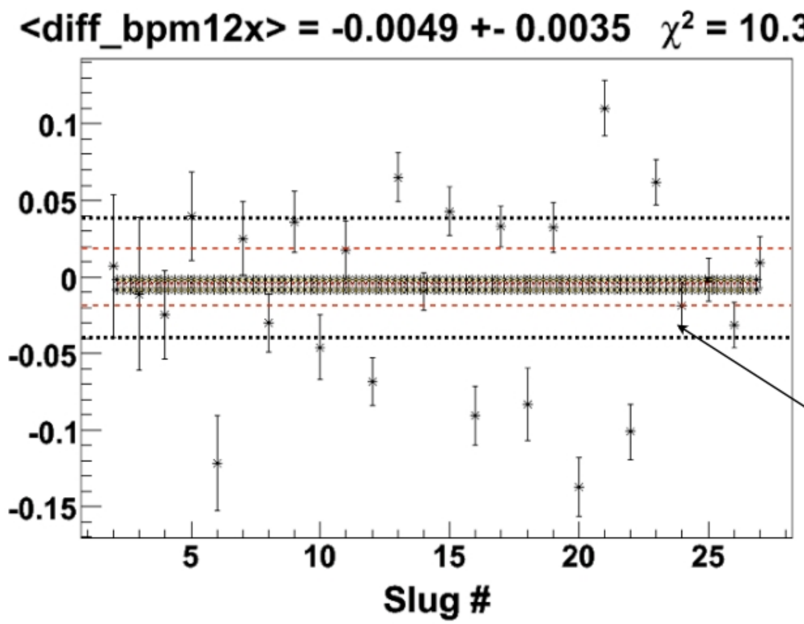
- Helicity Correlated fluctuations in the physical properties of the beam introduce substantial false asymmetries.
- Response of the detectors to these fluctuations can be calibrated by intentionally varying the beam parameters concurrently with data taking.
- Relevant parameters: beam position x and y at the target, angle x and y at the target, and beam energy.
- The energy of the beam is varied by applying a control voltage to a vernier input on a cavity in the accelerator's South Linac.

Beam Position Fluctuations



HAPPEX III, Fall 2009

Beam Energy Fluctuations



Dispersion ~4 :
4x larger than dE/E

PREX jitter requirement

injector configuration fixed to reduce MS interception

Is this good enough?

For HAPPEX III, yes.

For PREX, *almost* there...

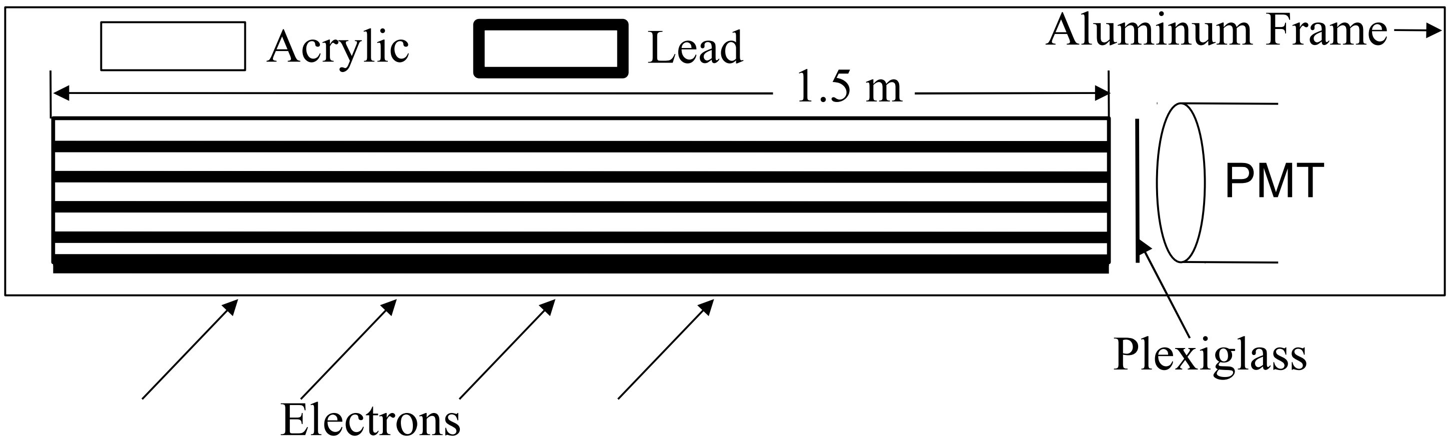
Need:

< (2, 4) nm (x,y) position differences

< (0.3,1.0) nrad (x,y) angle differences

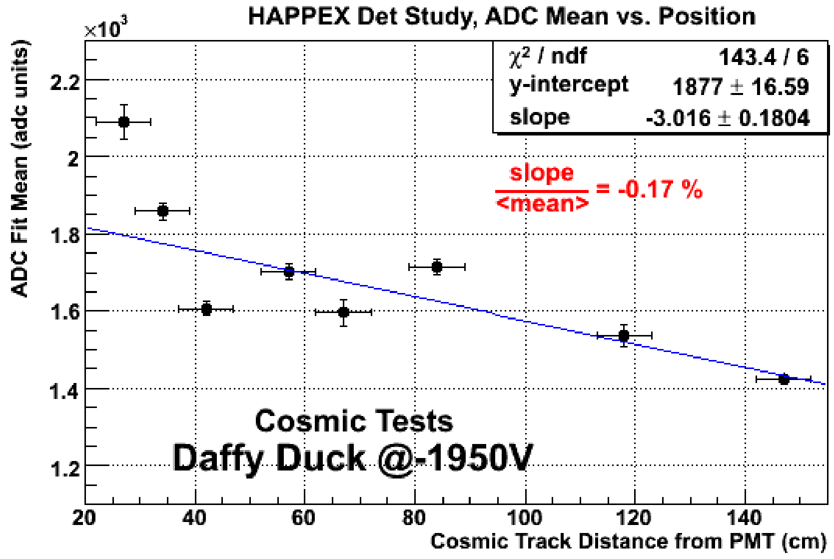
HAPPEX III Detectors

Detectors



- Lead-Acrylic sandwich calorimeters
- Cherenkov light from each detector stack is collected by a PMT
- Segmentation chosen to provide sufficiently good energy resolution (~15% sigma)
- Dimensions chosen to contain the image of elastically scattered electrons, and much of the radiative tail, yet not events from the inelastic scattering.
- Detector orientation adjusted so that the part of the Cherenkov cone is pointed directly at the PMT.

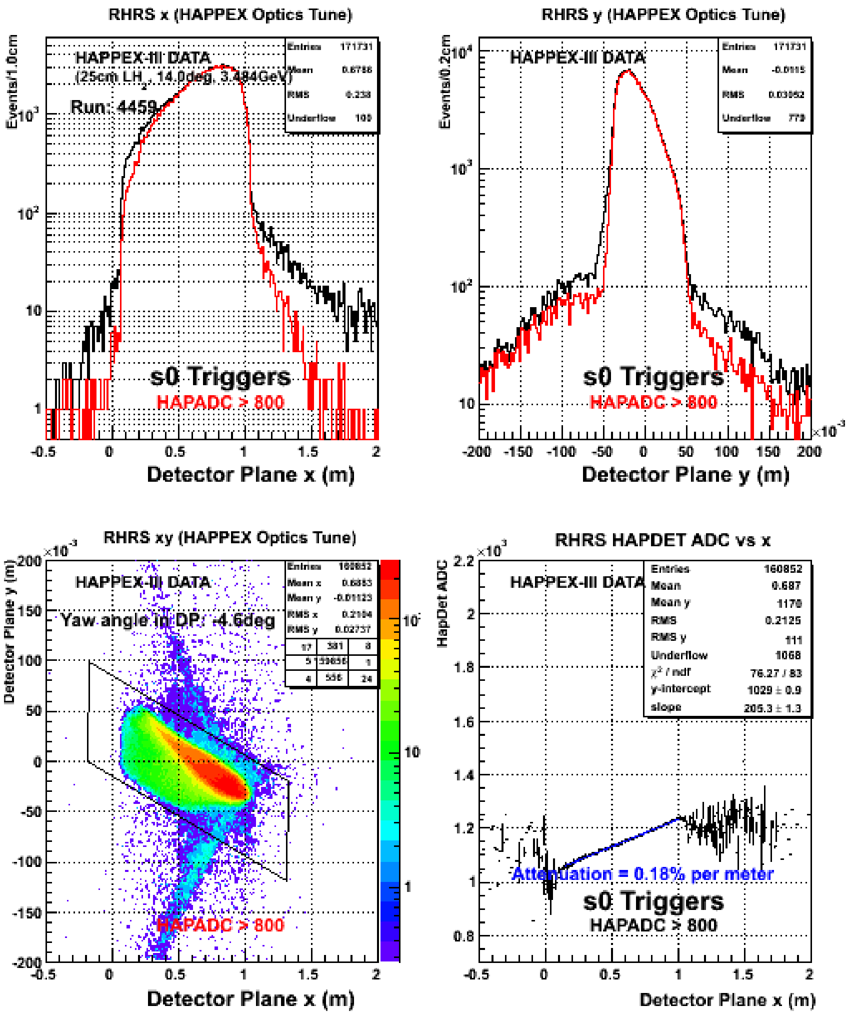
Detector Efficiency



Cosmic Test

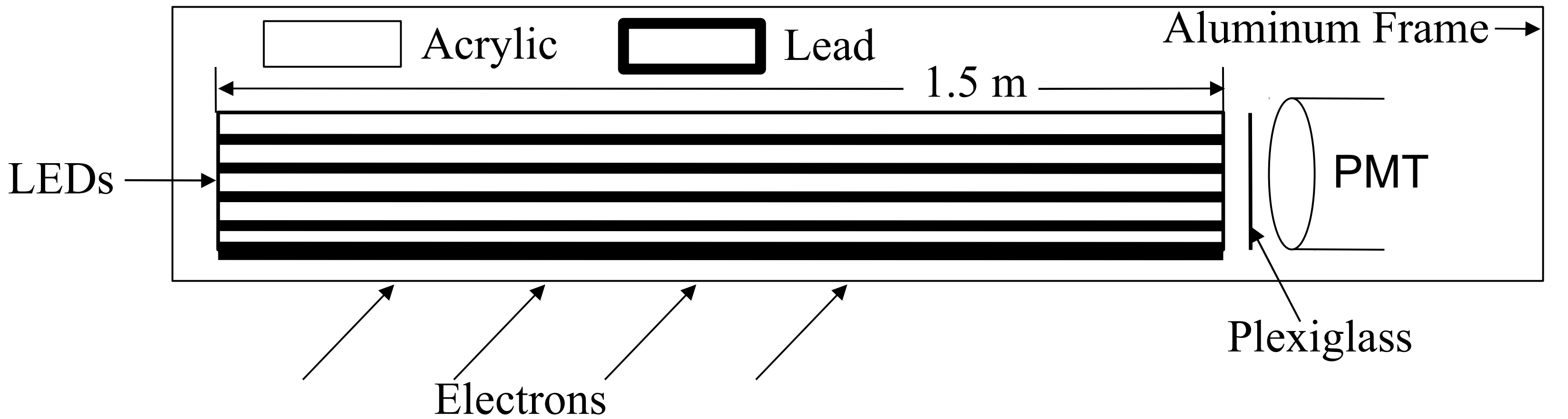
- Signal output is a strong function of the particle's position along the detector's length.
- Characterizing this dependence is important for calibrating asymmetry measurements.
- Measured 50%/m decrease in light output.
- Solution: Install a single sheet of Plexiglass directly in front of the PMT to filter out UV radiation.
- Total signal size reduced, but the dependence of light out along the detector decreased to about 17%/m

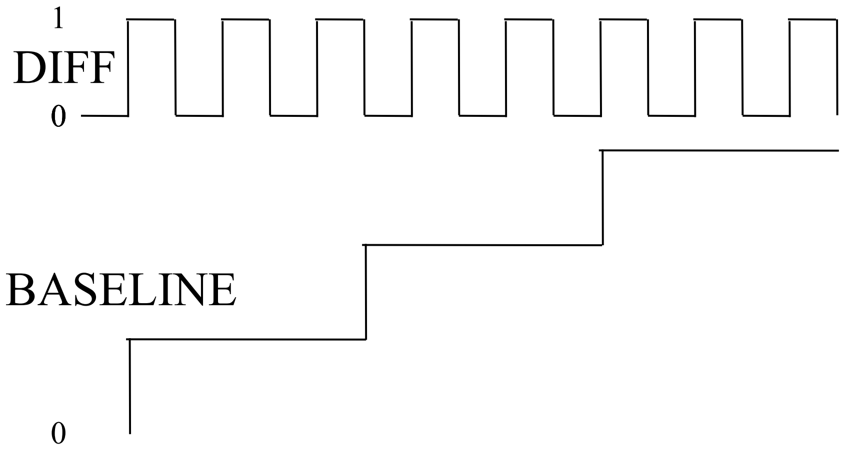
Detector Alignment



- Entire image of the elastic peak in the focal plane is contained in the detector.
- The inelascitcs fall outside the detector
- Attenuation along the detector's length is 18%/m, which is slightly bigger than the cosmic tests value of about 17%/m.

Detector Linearity test setup

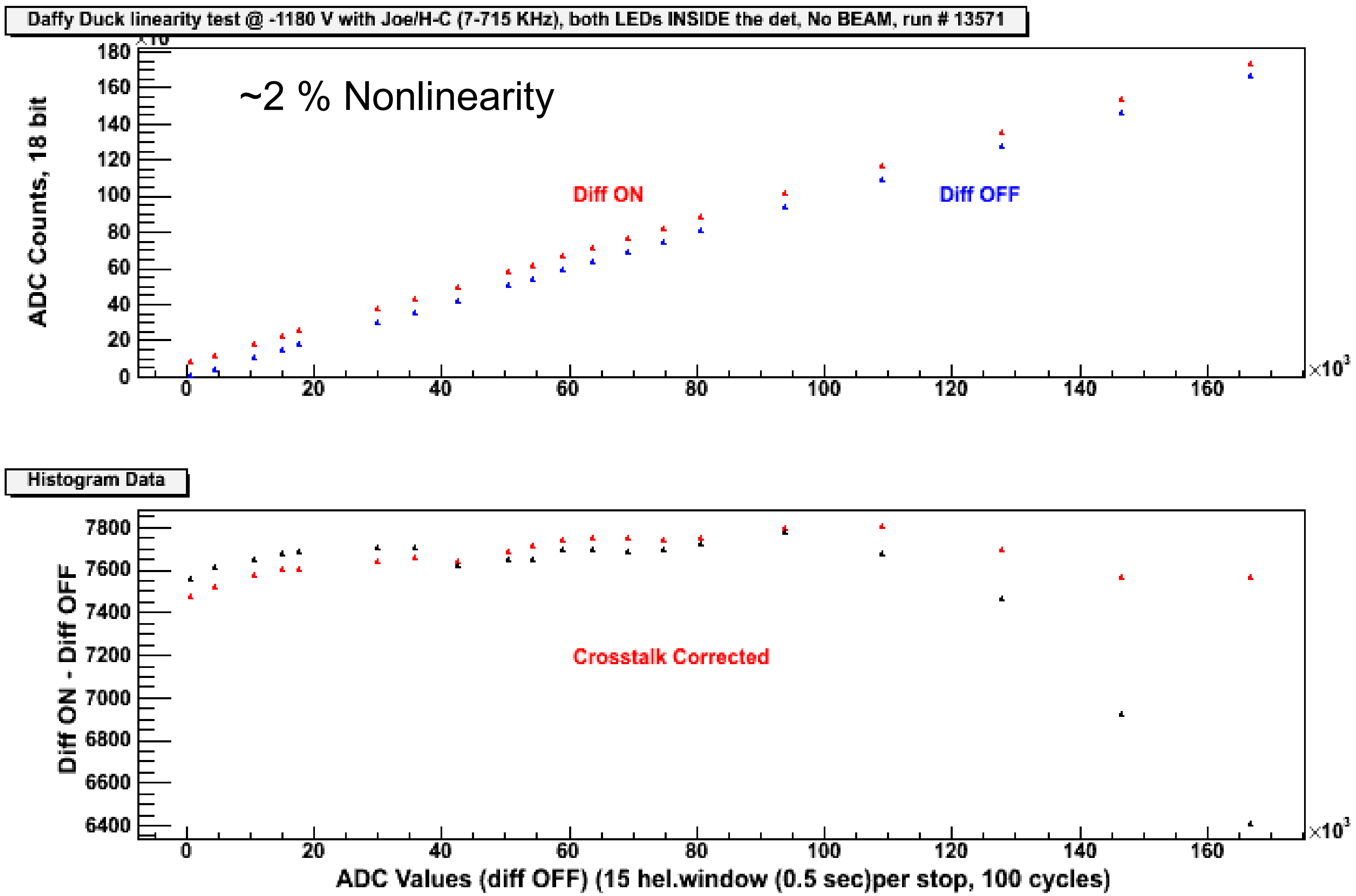




LED operation schematic

- A pair of blue LEDS is mounted in the middle acrylic layer opposite to the PMT
- DIFF LED: toggled at a constant freq.
- BASELINE LED: driven at varying freq. of up to 800 KHz (observed electron rate @ 100 uA)
- The pulses of both LEDs are adjusted to be about the size of the electron pulses

Detector Linearity



HAPPEX III Error Budget

Source	$\delta A_{PV} / A_{PV}$	$\delta(G^s E + \eta G^s M)$
Polarimetry	1.00%	0.0027
Q2	0.50%	0.0013
Backgrounds	0.30%	0.0008
Linearity	0.60%	0.0016
Finite Acceptance	0.30%	0.0008
False Asymmetries	0.30%	0.0008

Questions??

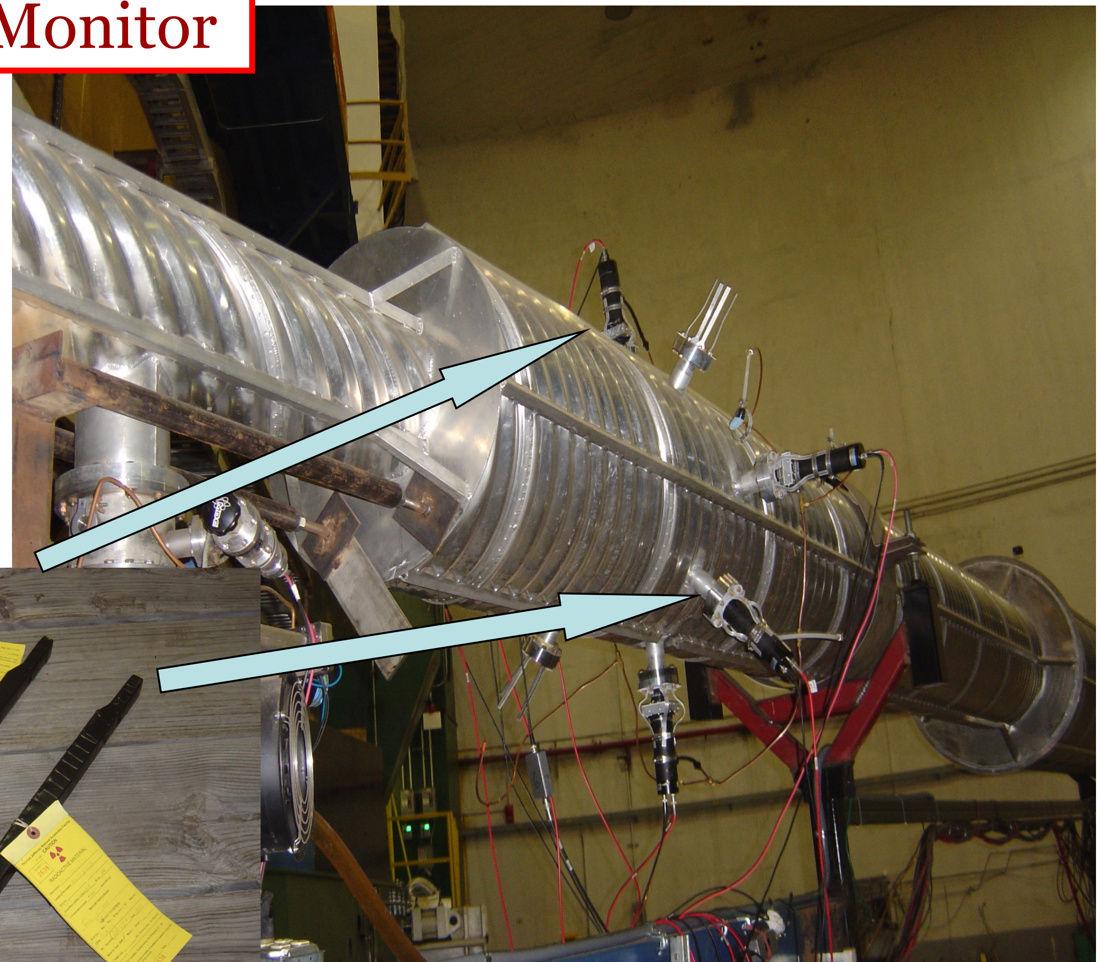
EXTRA SLIDES

PREX Error Budget

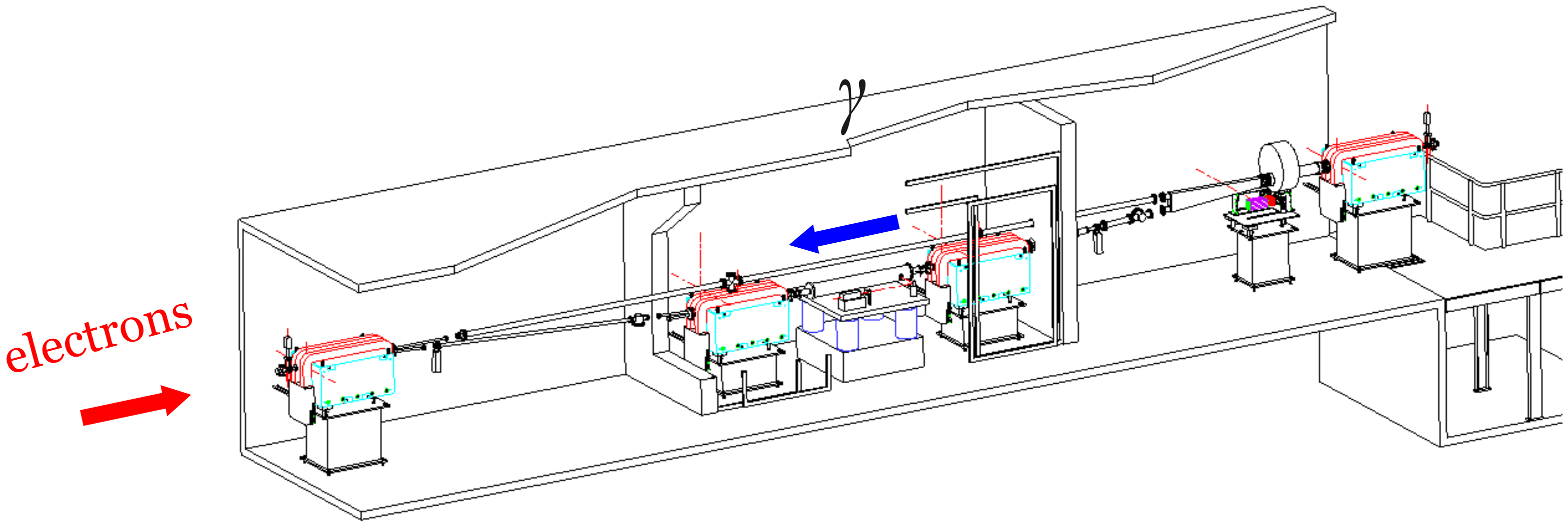
Luminosity Monitor

A source of extremely high rate

→ *establish noise floor, and check boiling widths*

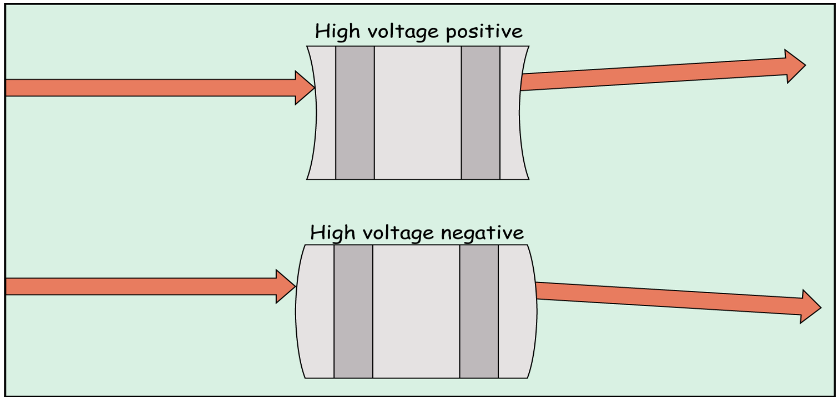


Compton Polarimeter



1-2% Polarization Measurement

Non-Polarization Effects

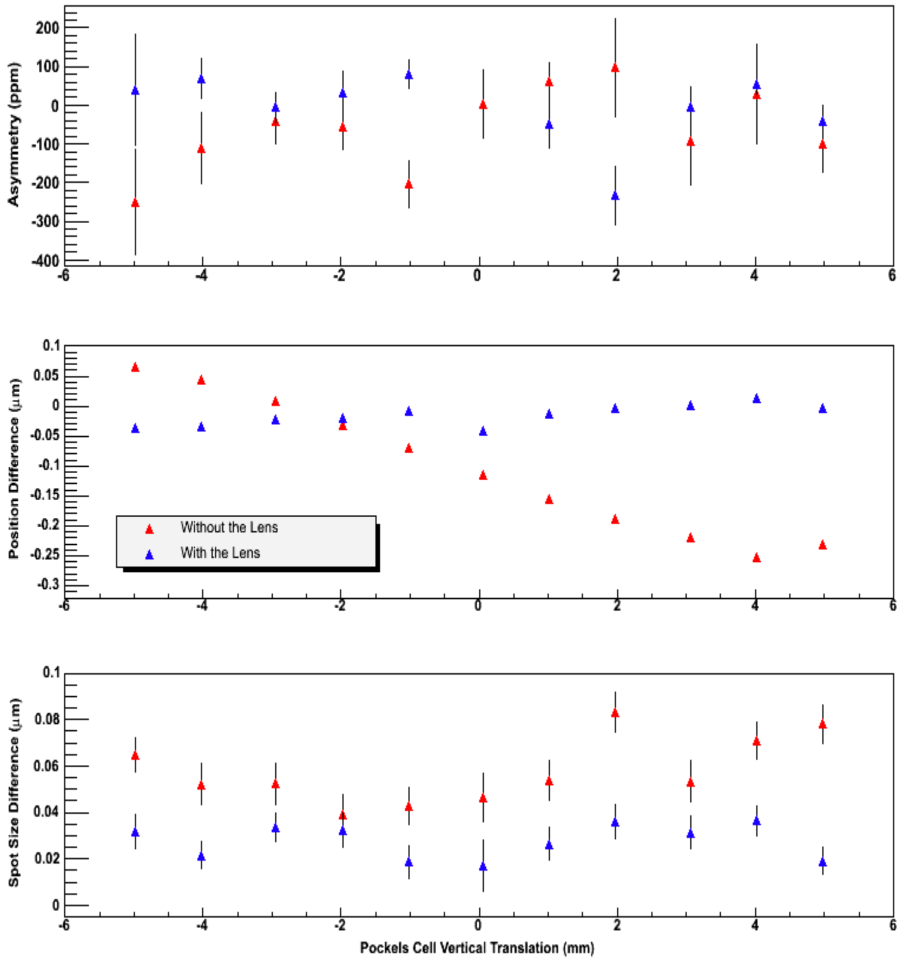


• Mechanical pulsing of the HV at high/low causes the Pockels cell to behave as a *Voltage activated* lens, resulting in helicity-correlated beam steering.

Left unchecked, these effects are huge, and can result in HC position differences on the order of couple of microns, and fractional spot size asymmetry as big as $\partial\sigma/\sigma \sim 10^{-2}$.

Controlling Non-Polarization Effects

- The HC asymmetry, position and spot size differences are much smaller, but non-zero, indication of the HC *lensing* effect.
- Point-to-point focusing by a lens (placed between the Pockels cell and the detector) can reduce the position differences by as much as ~ 5-10.
- Point-to-point focusing can also decrease the spot size differences by a much smaller amount of ~ 2.
- With point-to-point focusing, beam spot size asymmetry can be constrained to as much as $\partial\sigma/\sigma \sim 4 \times 10^{-4}$.



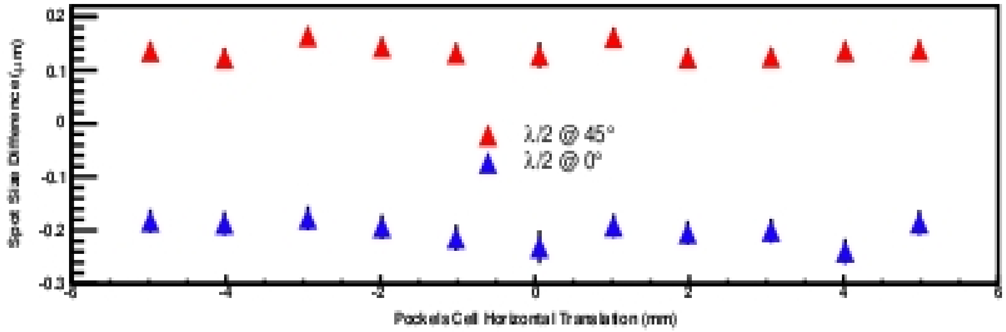
Data taken on laser table on a linear-array photodiode with *no* analyzing power.

Slow Reversal

- Flip the sign of the physics effects relative to the electron polarization to cancel the false asymmetries.
- This can be done through either laser beam polarization reversal or electron spin manipulation.
- Does not filp the sign of non-physics effects such as the lensing effects and cross-talk.

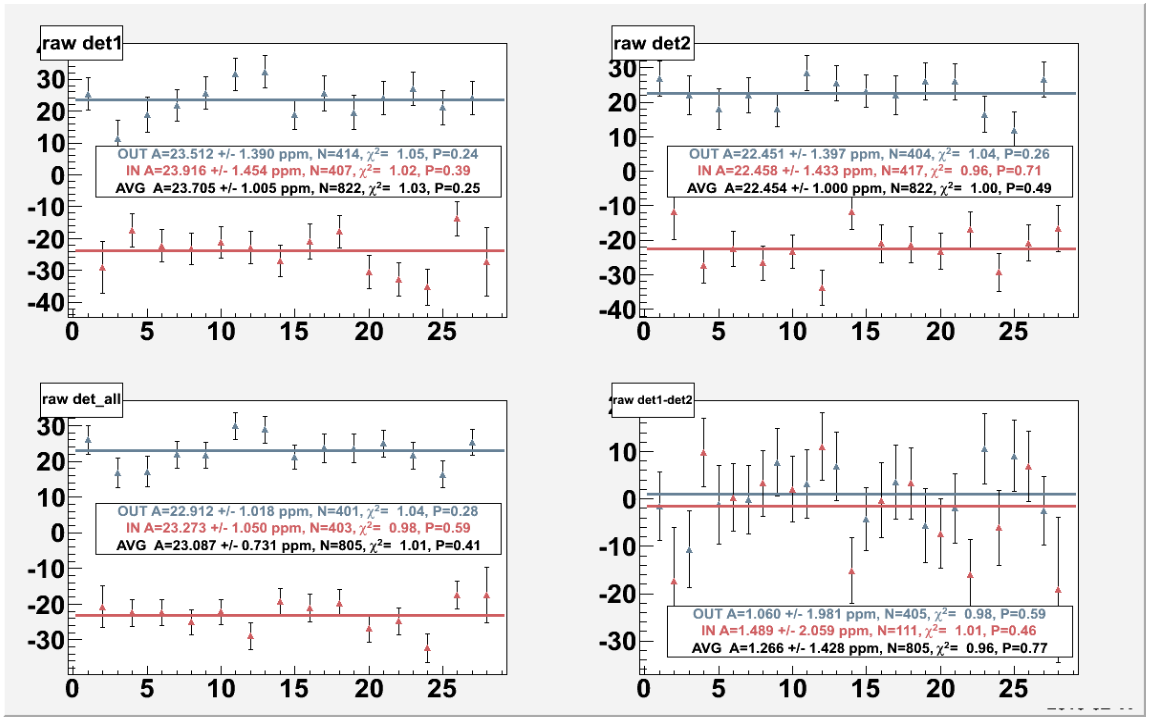
"*Slow Reversal*" will help cancel some of the higher order effects due to non-polarization effects.

Spot size asymmetry can be constrained to within $\partial\sigma/\sigma \sim \mathbf{10^{-4}}$ with slow reversal.

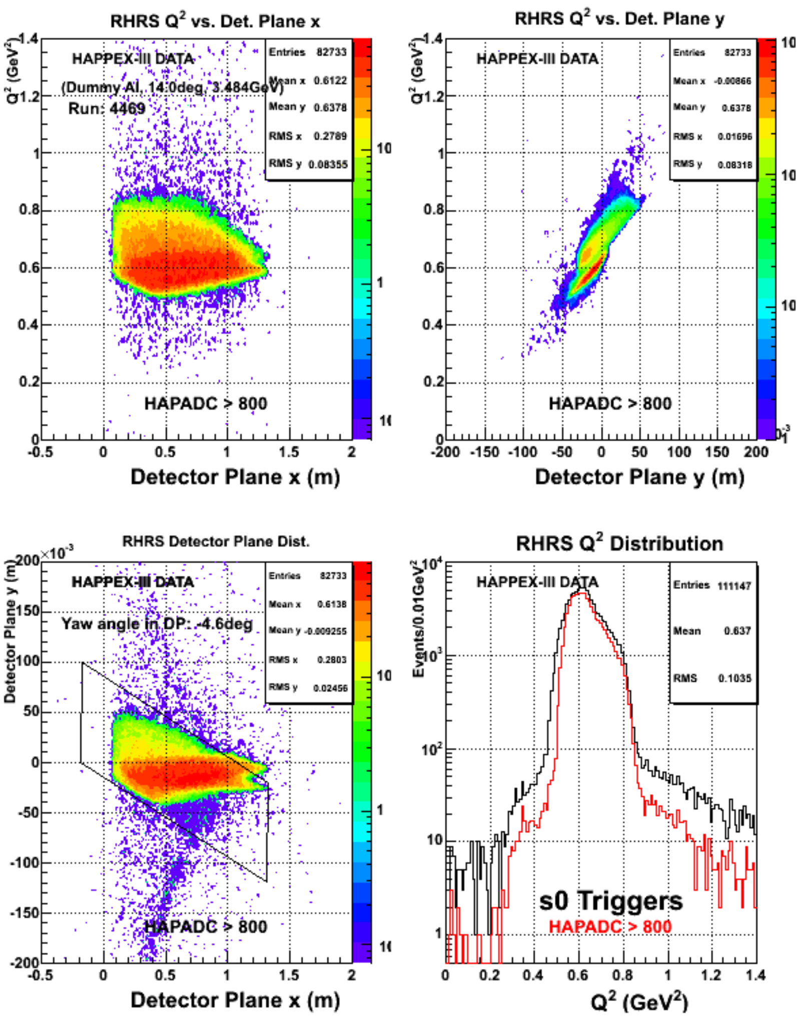


Data taken on laser table on a linear-array photodiode with *no* analyzing power. The λ/2 @ 0 deg is sign-filpped.

Preliminary Data

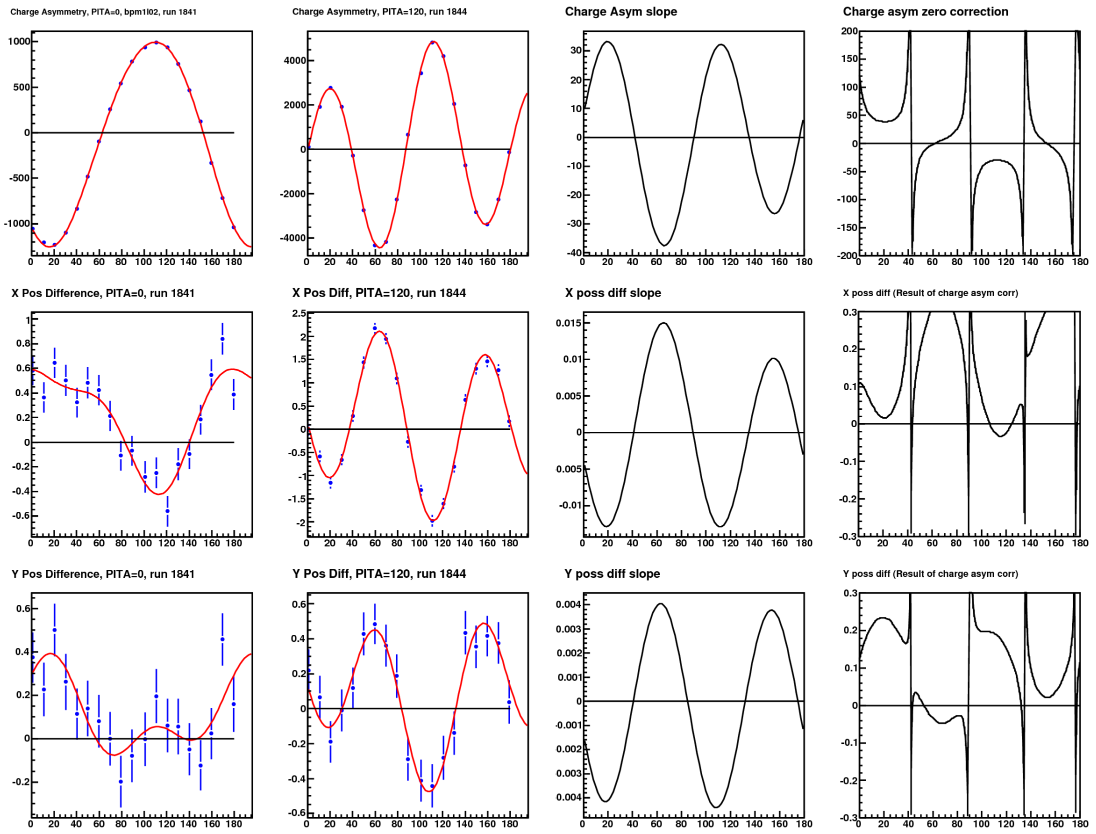


Q2 Spread



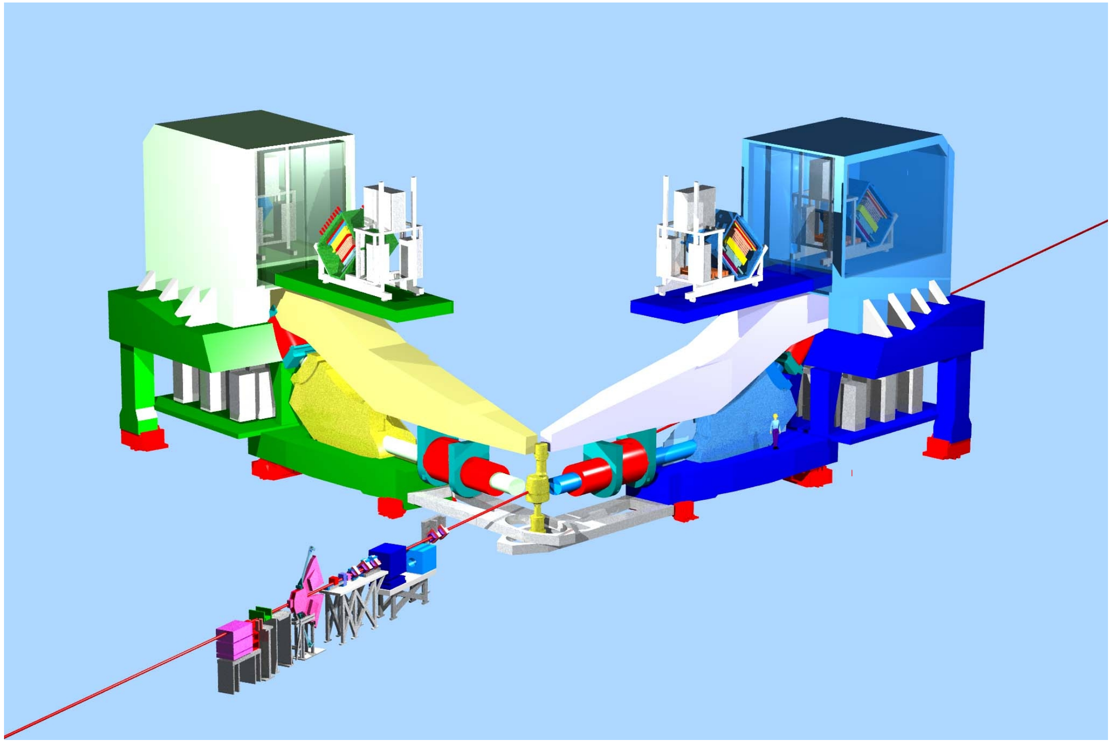
RHRS Q^2 vs. Det. Plane x
HAPPEX-III DATA
(Dummy Al, 14.0deg, 3.484GeV)
Run: 4469
HAPADC > 800
Detector Plane x (m)
RHRS Q^2 vs. Det. Plane y
HAPPEX-III DATA
HAPADC > 800
Detector Plane y (m)
RHRS Detector Plane Dist.
HAPPEX-III DATA
Yaw angle in DP: -4.6deg
HAPADC > 800
Detector Plane x (m)
RHRS Q^2 Distribution
HAPPEX-III DATA
s0 Triggers
HAPADC > 800
Q^2 (GeV^2)

RHWP Position Optimization



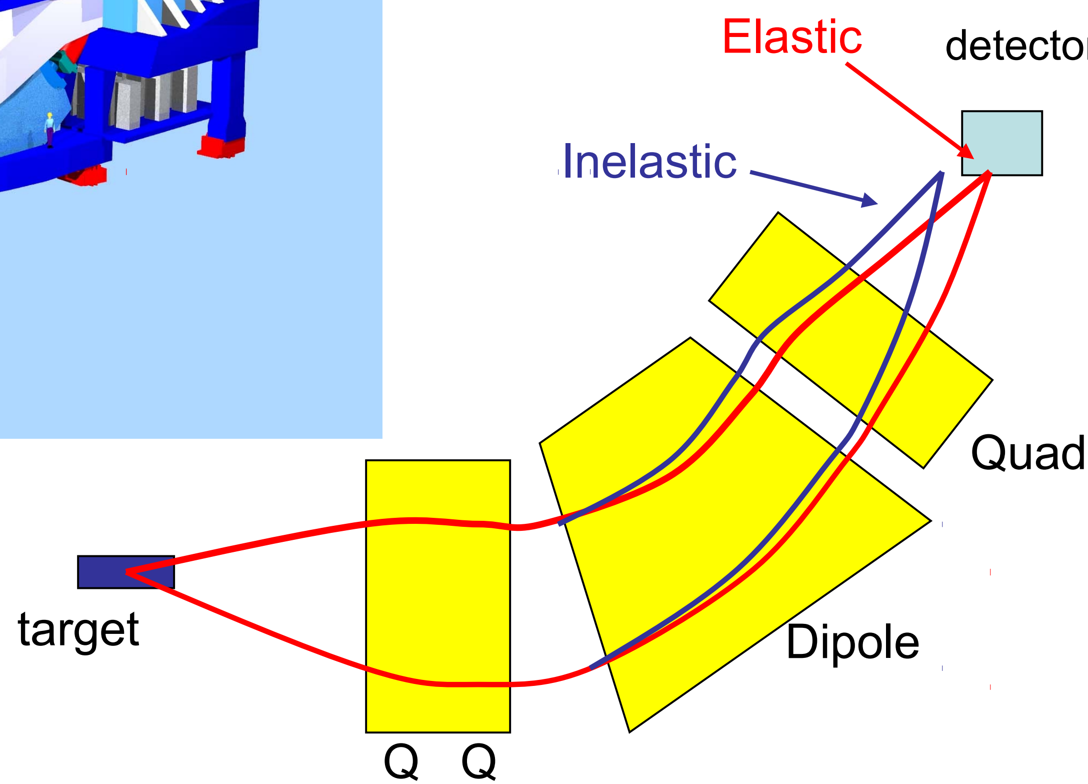
- Want RHWP position with small HC position differences, yet slope big enough for charge feedback

High Resolution Spectrometers



Left-Right symmetry to control transverse polarization systematic

Spectrometer Concept:
Resolve Elastic



PREX Beam Summary				
Beam Property	Nominal Value	Maximum Run-averaged Helicity-correlation	HC One-day ("slug") Average	Maximum Jitter at 30 Hz
Average Current $\langle Q \rangle$	50-100 μA[1]	200 ppb	1 ppm	1000ppm
Energy	1.05 GeV	$\langle \frac{\Delta E}{E} \rangle \leq 1$ ppb	5 ppb	5 ppm
Energy spread σ_E/E	10^{-3}	-	-	-
Position x at target	0	< 2 nm	10 nm	10 μm
Angle y' at target	0	0.3 nrad	1.5 nrad	1.5 μrad
Position y at target	0	4 nm	< 20 nm	20 μm
Angle y' at target	0	1 nrad	5 nrad	5 μrad
Spot Size [2] at target	$100 - 300\,\mu m$ (r.m.s., unrastered) 4mm x 4mm (box, rastered)	$\delta\sigma/\sigma < 10^{-4}$	10^{-3}	-

- **Nominal Value:** This is the usual desired central value of the beam property.

[1] Running current will be optimized during commissioning, in the range from 50-100μA.

[2] The helicity-correlated spot size variations cannot be measured well. An upper bound must be established from an understanding of the source configuration and cancellations. Specifications here assume spin flipper cancellation.