Controlling Helicity-Correlated Asymmetries in a Polarized Electron Beam

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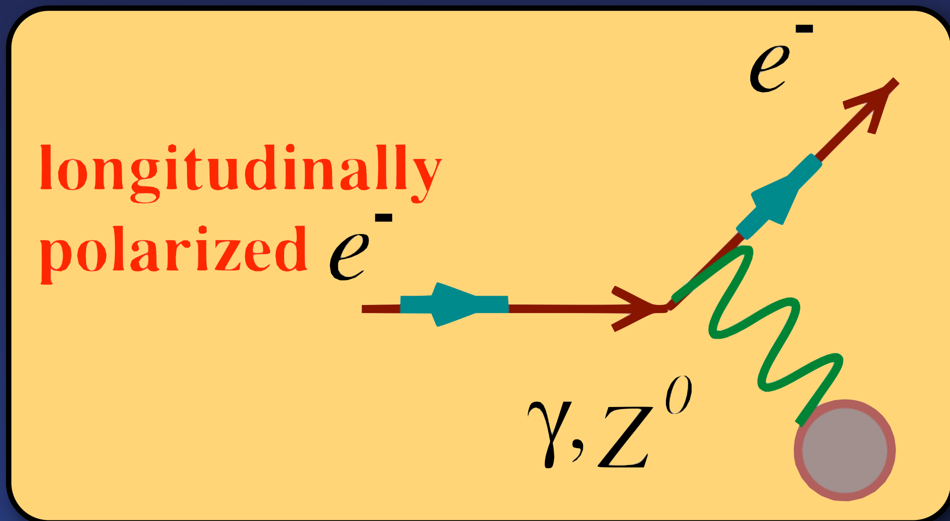
University of Virginia

Includes recent work by Lisa Kaufman, Ryan Snyder, T.B. Humensky, K.D. Paschke, G.D. Cates, and the JLab EGG group

Parity-Violating Electron Scattering



$$\sigma = |M_\gamma + M_Z|^2$$

$$A_{PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \sim \frac{M_Z}{M_\gamma} \sim \frac{G_F\, Q^2}{4\,\pi\,\alpha} \left(g_A^e g_V^T + \beta g_V^e g_A^T\right)$$
$$\sim \left[10^{-5} - 10^{-4}\right] Q^2$$

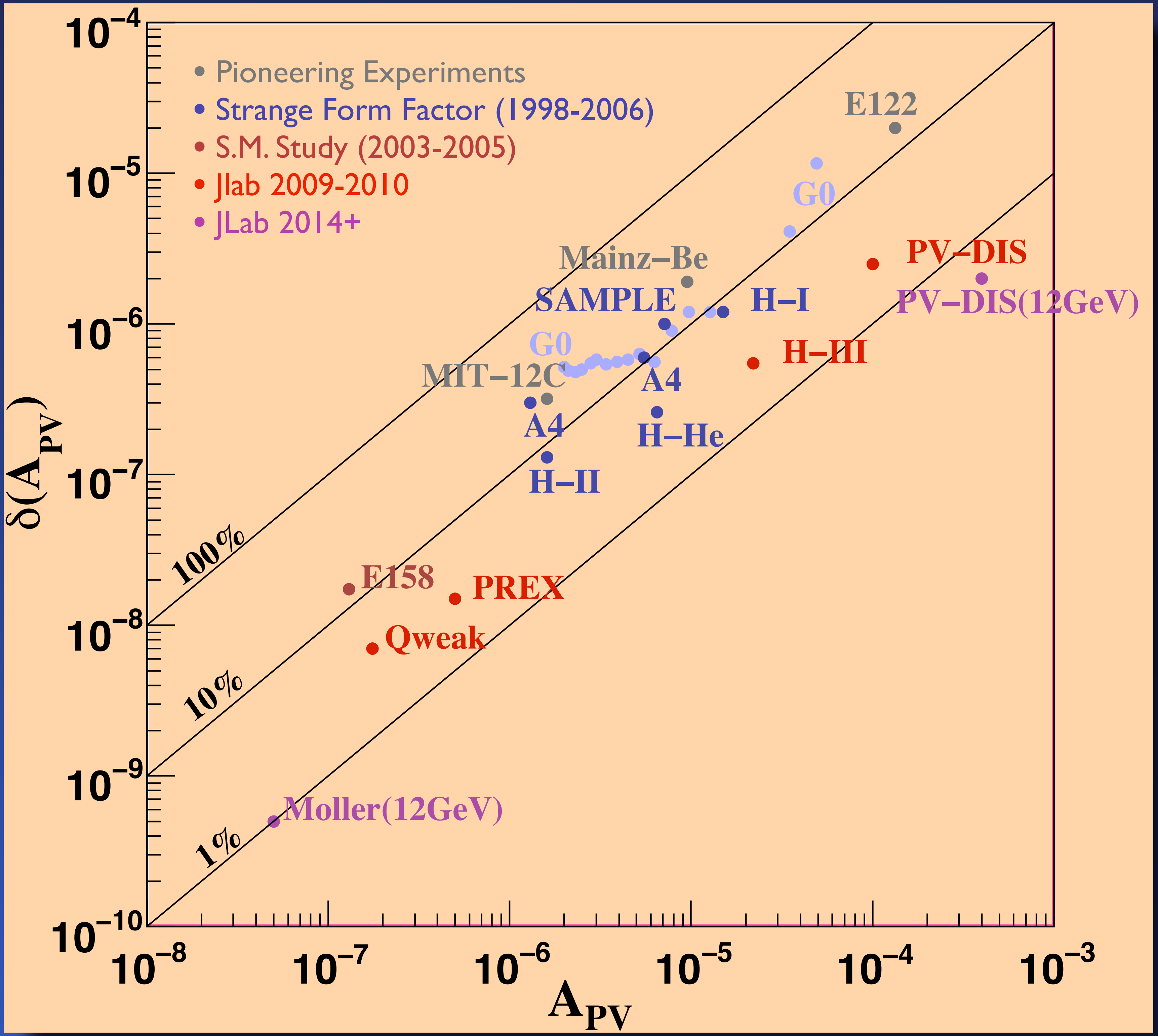
For electrons scattering off nuclei or nucleons:

Z couplings provide access to different linear combination of underlying quark substructure

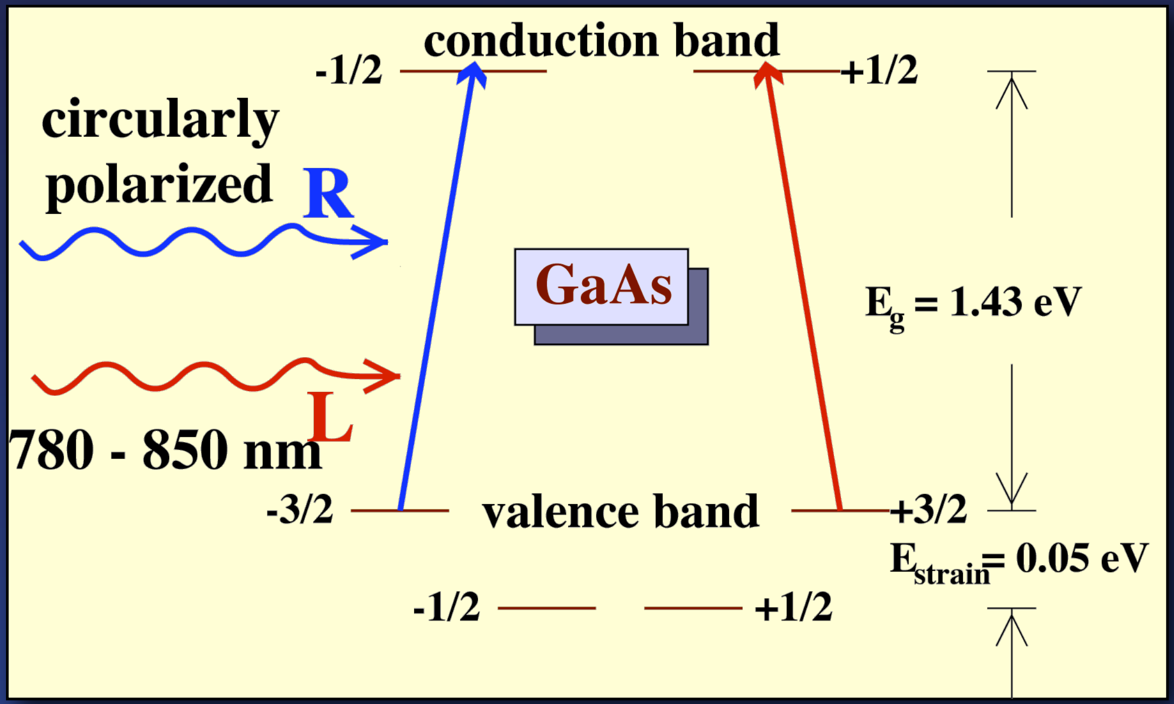
For very low Q^2, or e^-/e^- scattering:

comparison to Standard Model couplings provides access to possible effects from "new" physics

Precision of PVeS Experiments



The Polarized e⁻ Source



Photoemission

... from strained GaAs cathode produces highly-polarized e⁻ beam.

Developed and first used for SLAC E122

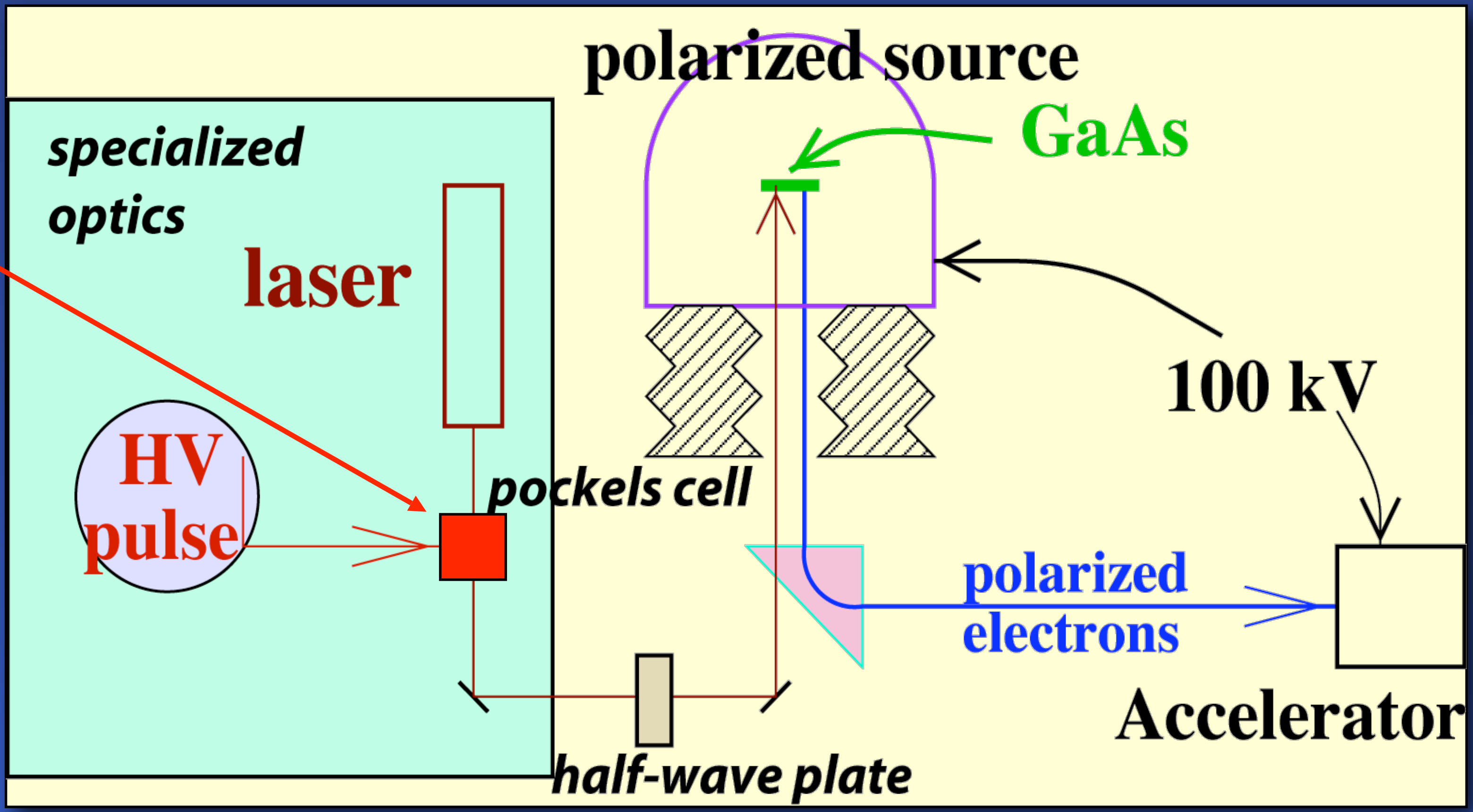
Preparation of Circularly-polarized Light

Pockels Cell:

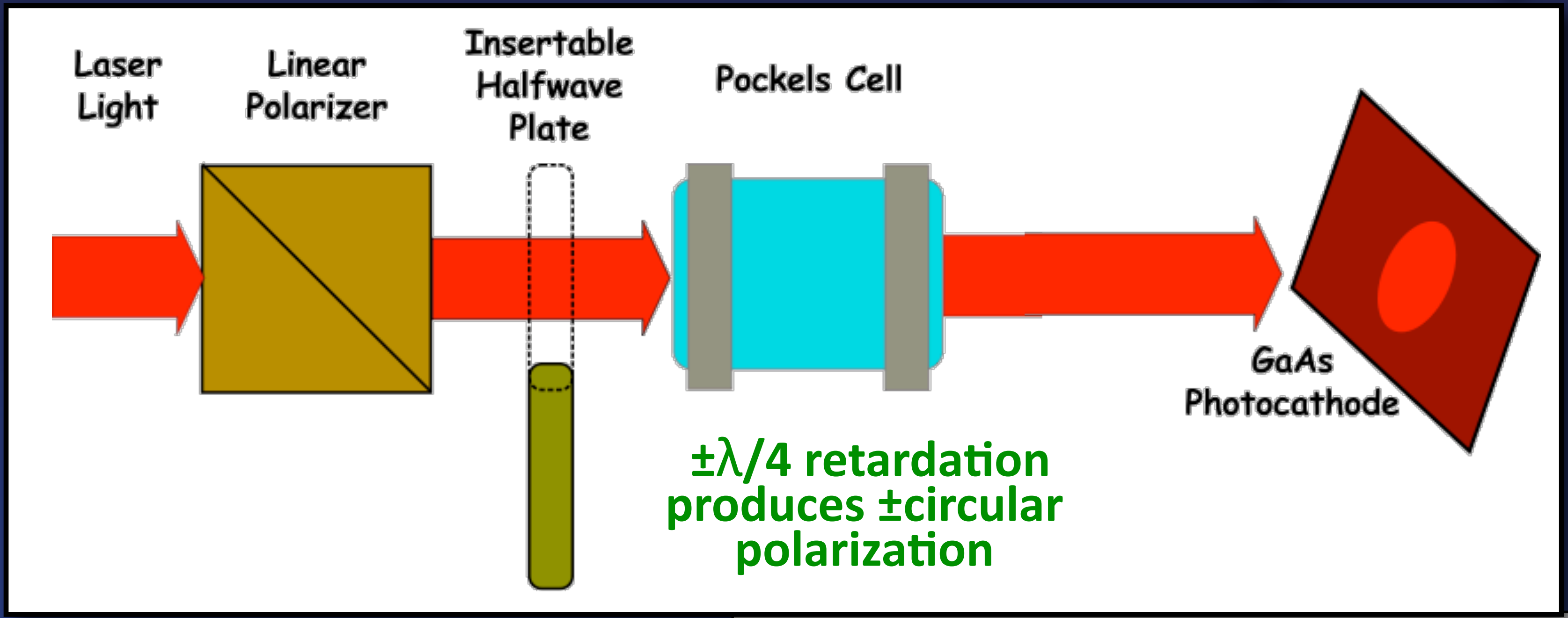
Allows rapid helicity flip which is key to the measurements

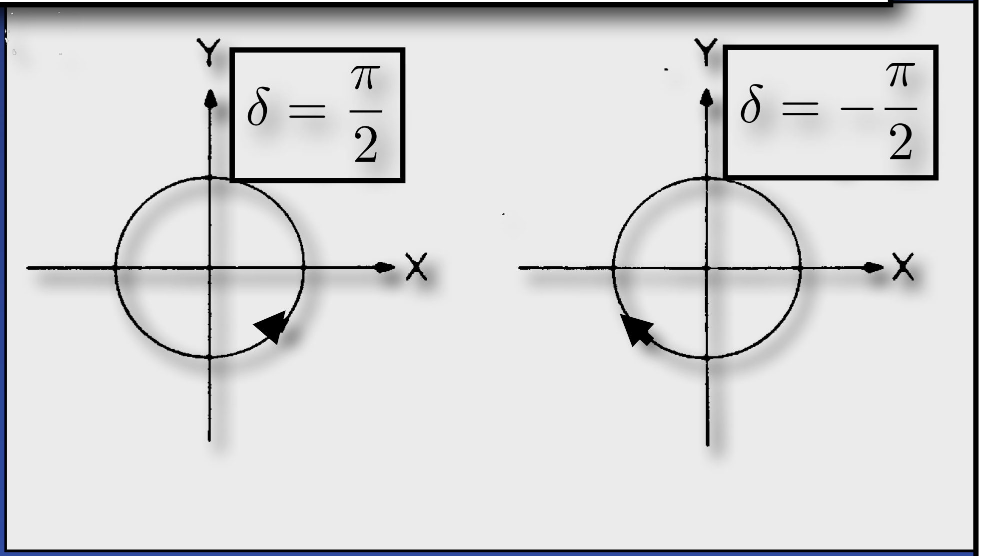
HC beam asymmetries are generated by differences in preparation of circularly polarized laser light.

HV Extraction and Injection

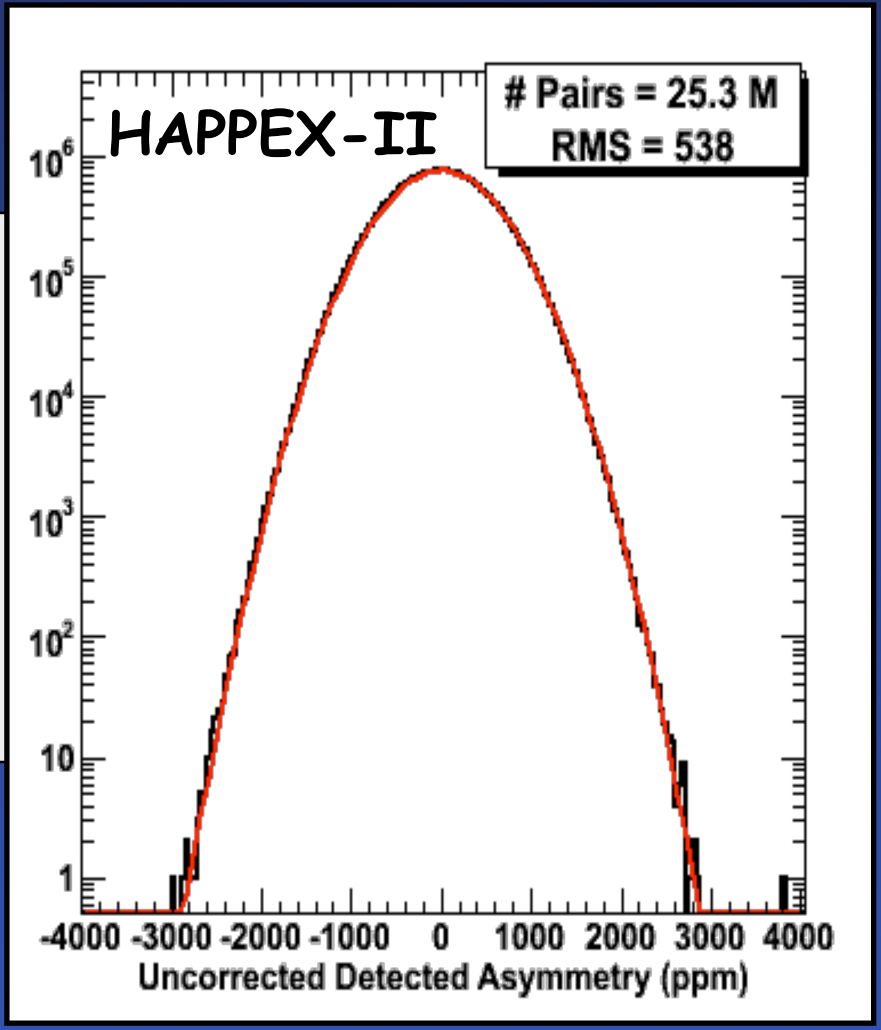


Helicity Flip

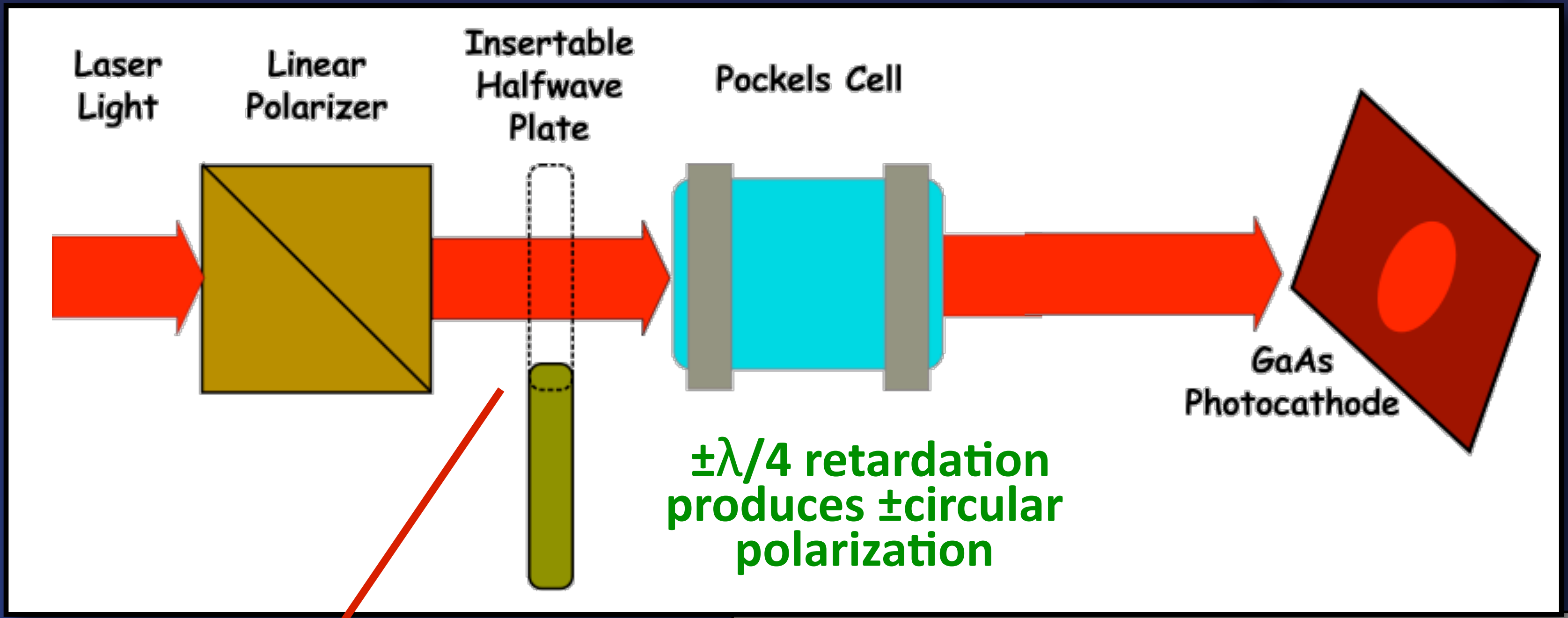




To avoid slow-drifts (calibrations, target density, etc), use a **rapid helicity flip** to measure the asymmetry at 5 Hz - 1 kHz



Helicity Flip



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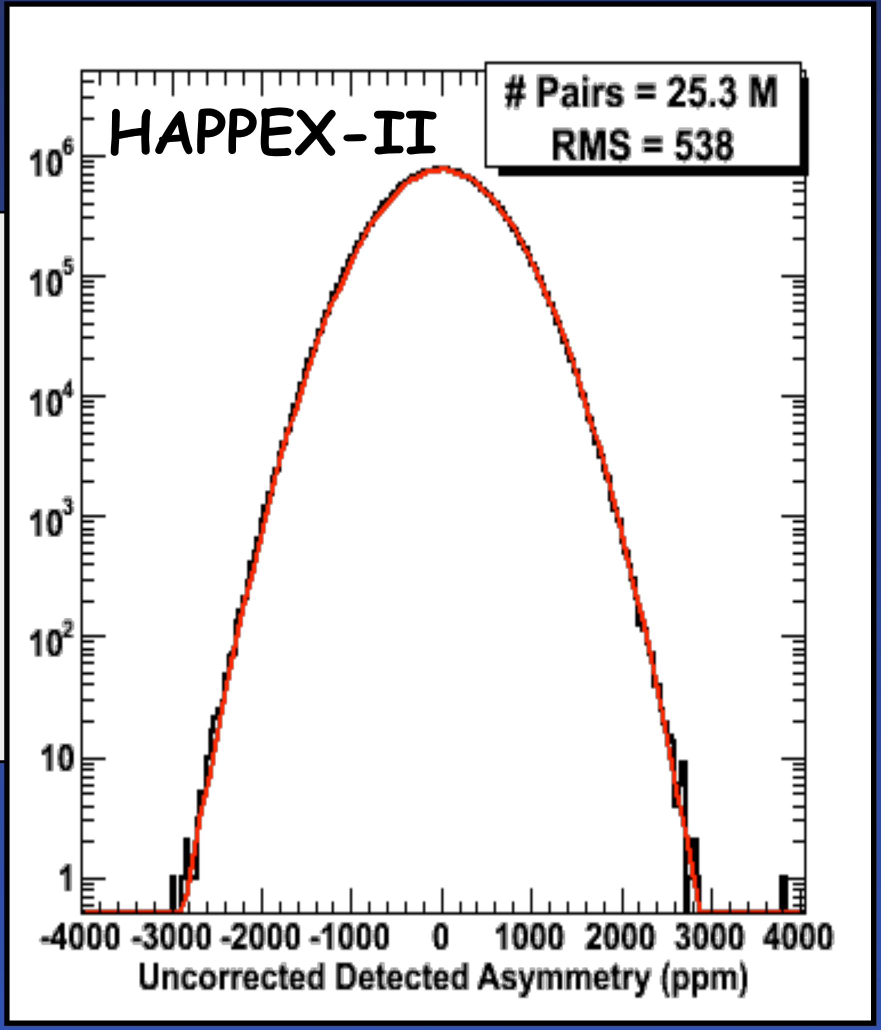
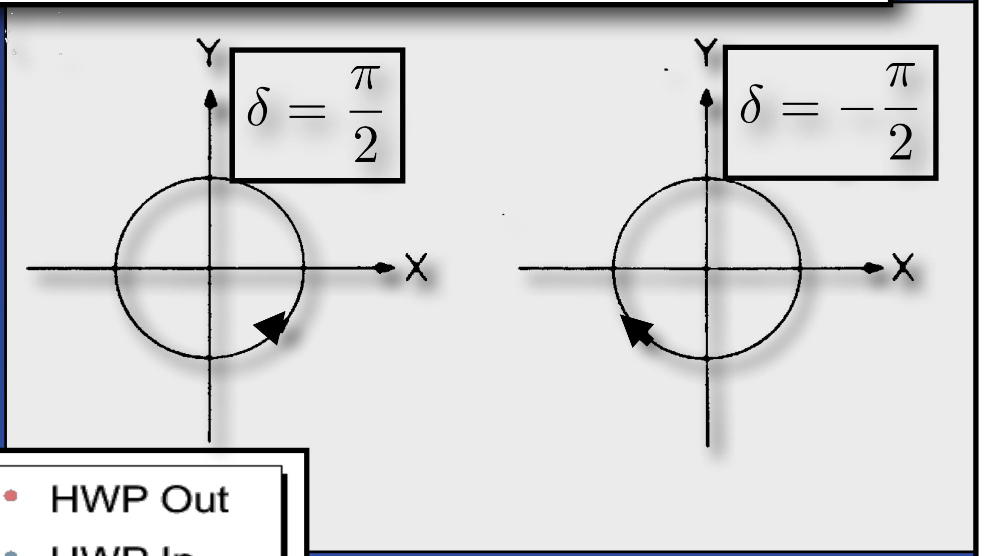
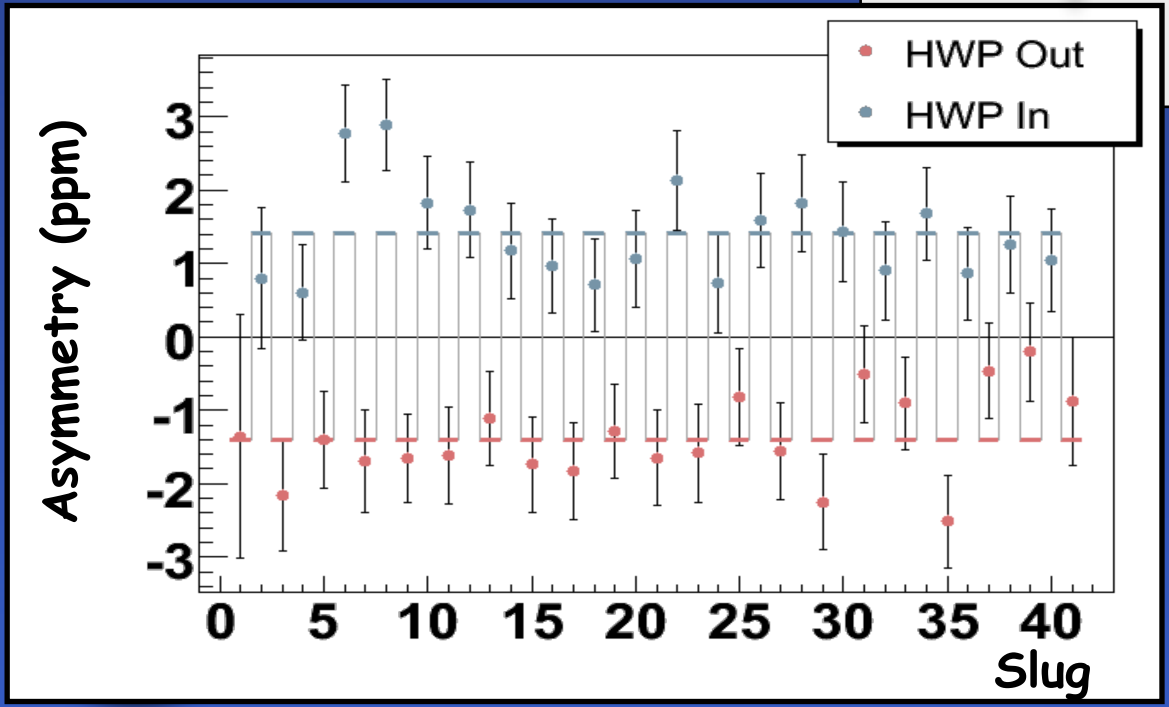


Slow Reversal:

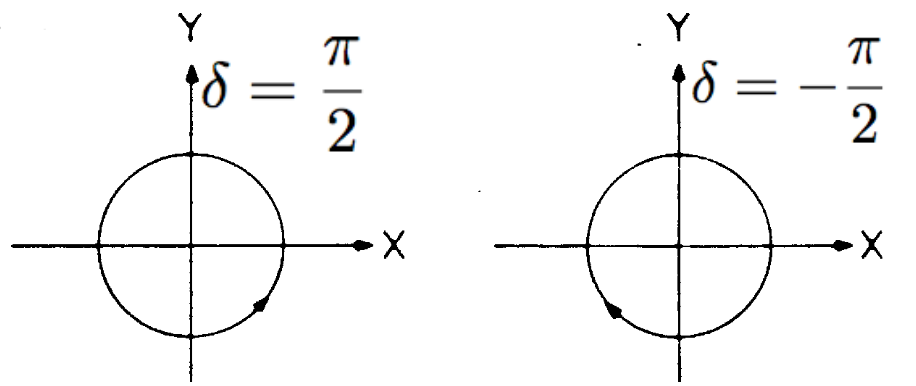
Inserting Half-wave plate flips initial linear polarization, and the final circular polarization



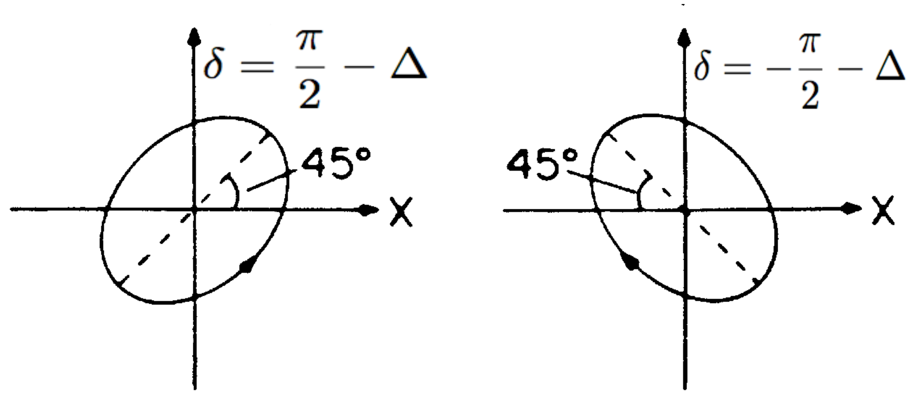


Consequences of Imperfect Circular Polarization

Perfect ±λ/4 retardation leads to perfect D.o.C.P.



A common retardation offset creates too much phase-shift in one state, too little in the other



This is called the Δ phase

(the other degree of freedom, the asymmetric phase shift, cancels in the asymmetry)

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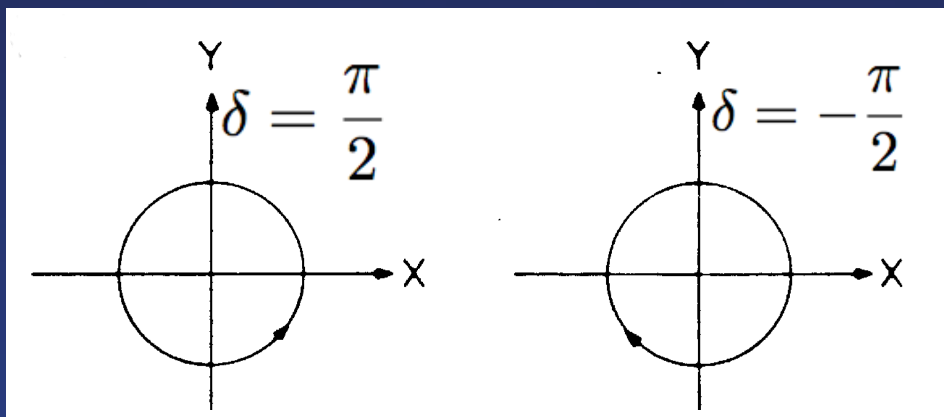

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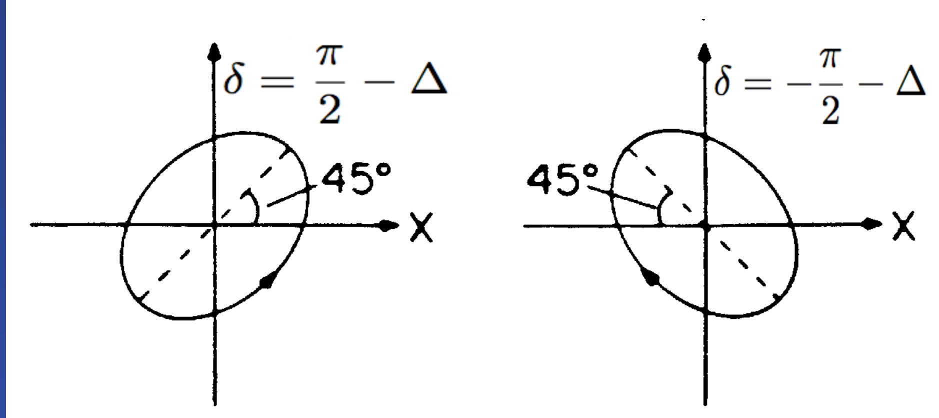

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Δ phase leads to residual linear polarization, with the opposite sign in the L/R states

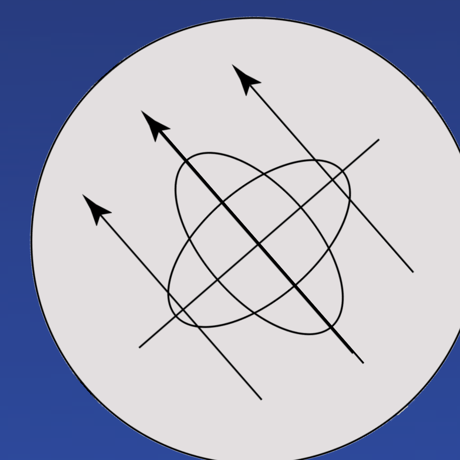
Significant DoLP with small change in DoCP

$$(\text{DoLP})^2 = 1 - (\text{DoCP})^2$$

In the photocathode, there is a preferred axis: Quantum Efficiency is higher for light that is polarized along that axis

QE anisotropy couples to residual "Δ" linear polarization to produce an intensity asymmetry A_Q.

(Historically called "PITA" effect)



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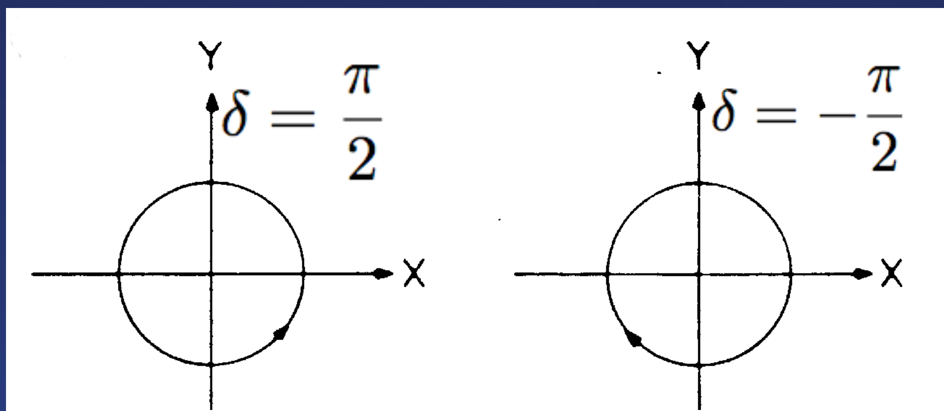

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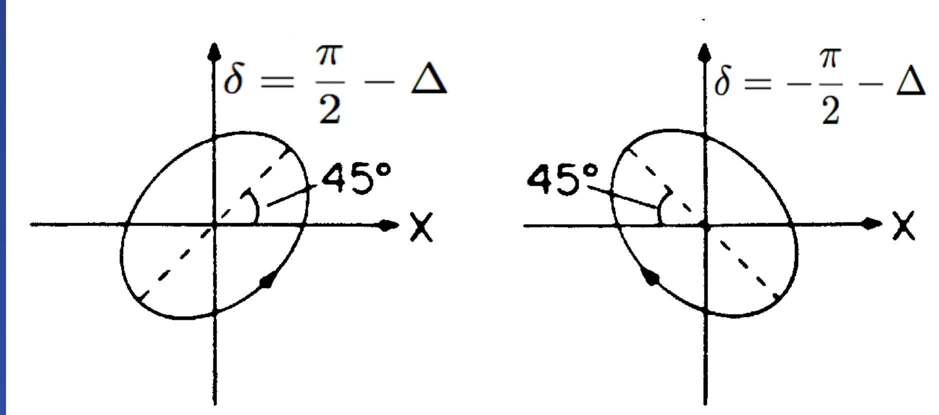

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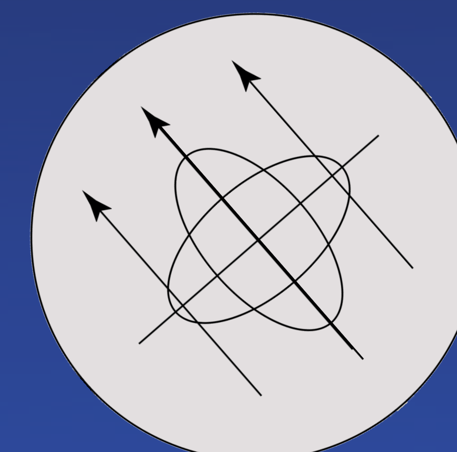
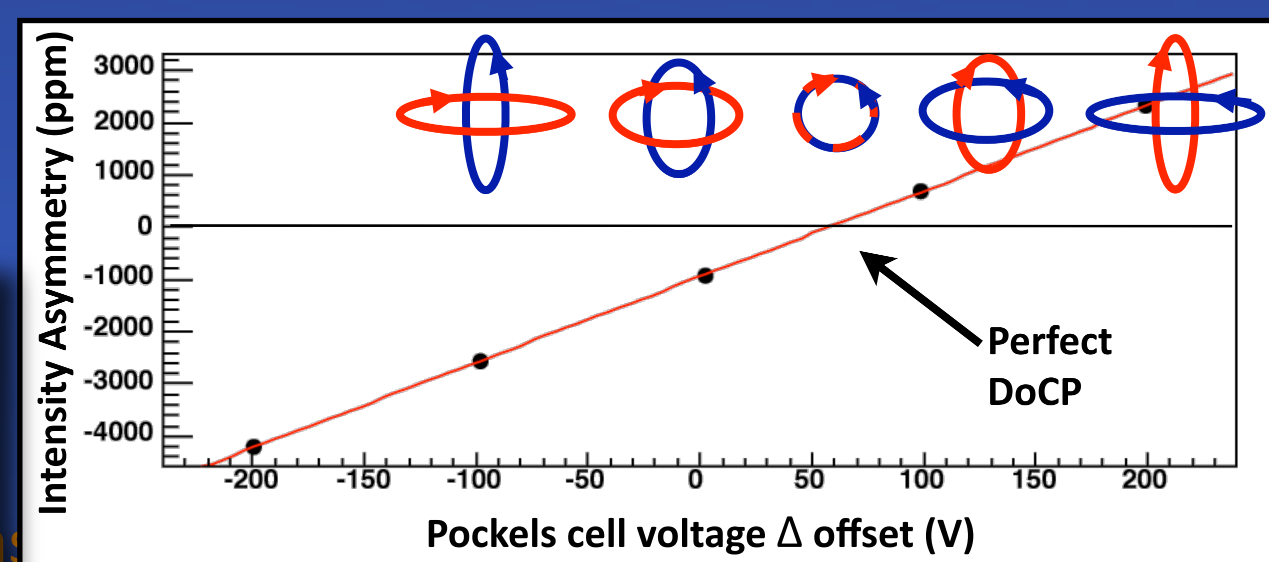
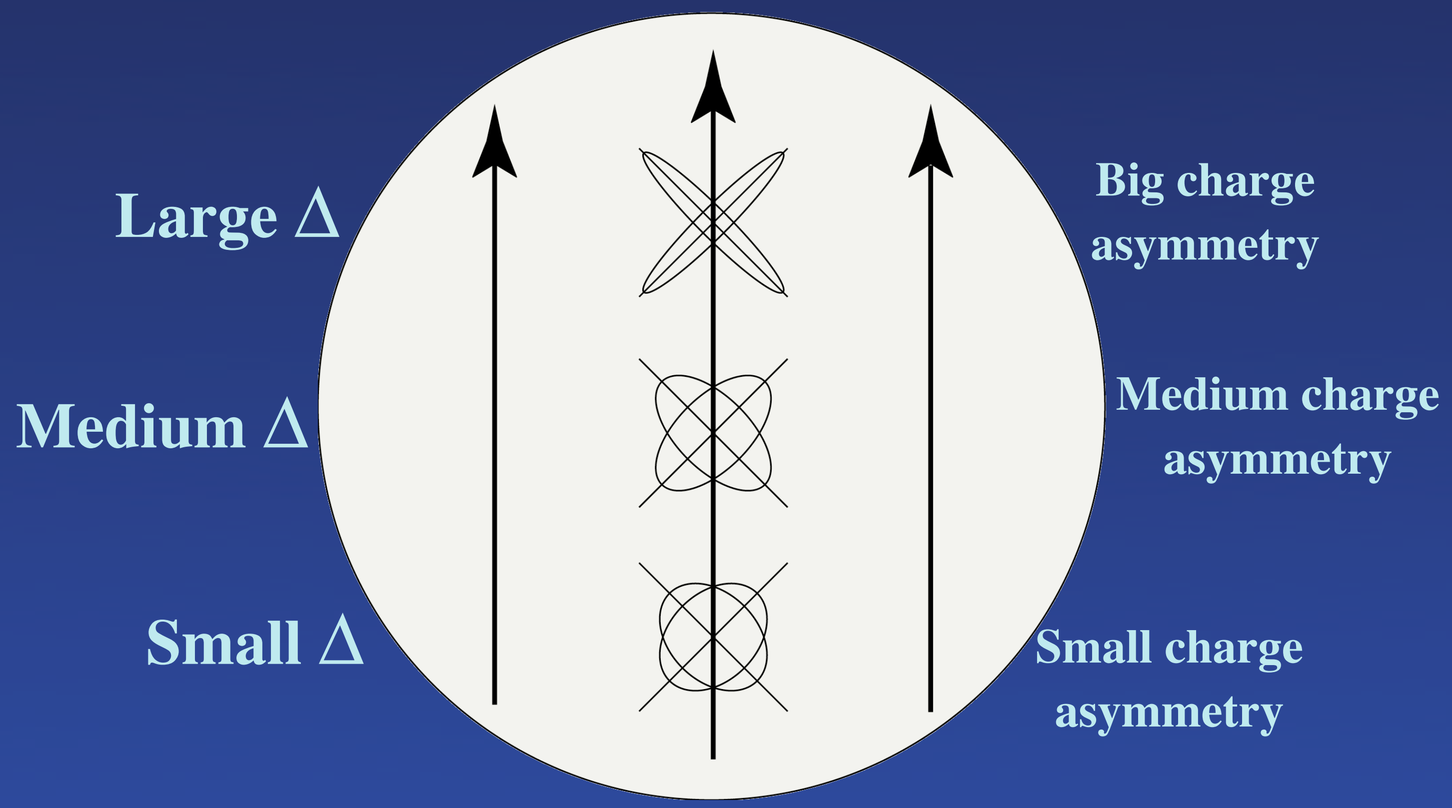


Scanning the Pockels Cell voltage
= scanning the retardation phase
= scanning residual DoLP

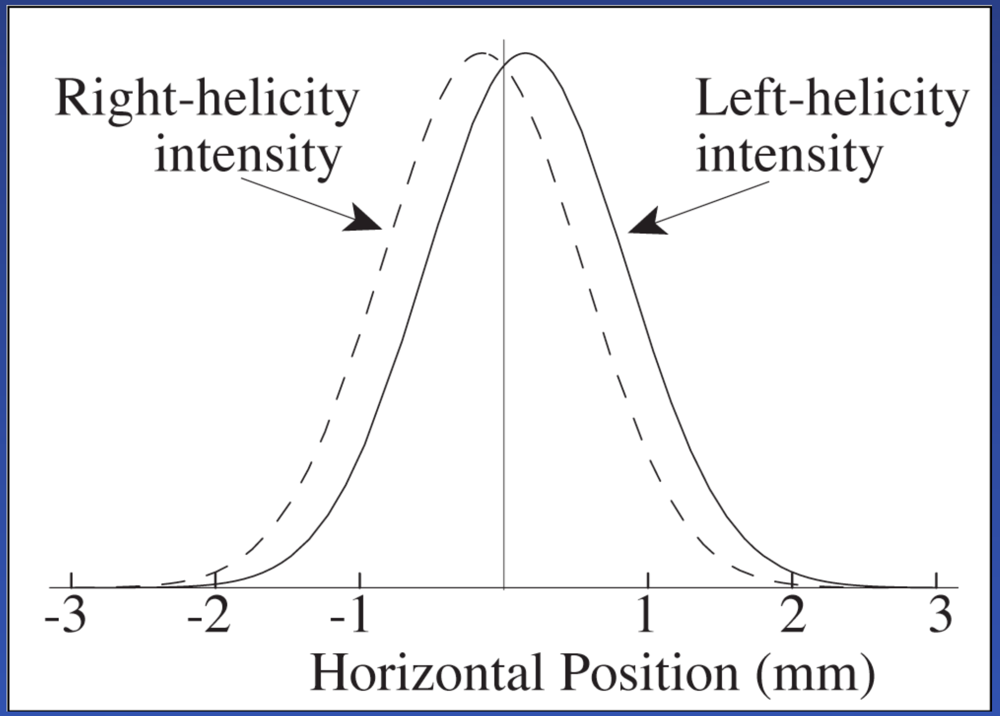


Consequences of Phase Gradients

A spatial gradient in the phase shift results in a relative linear polarization gradient across the beamspot.



Gradient in charge asymmetry creates a helicity-dependent beam profile centroid.



Spatial non-uniformity in Δ phase shift also creates higher moments (i.e. spot size or shape asymmetries)

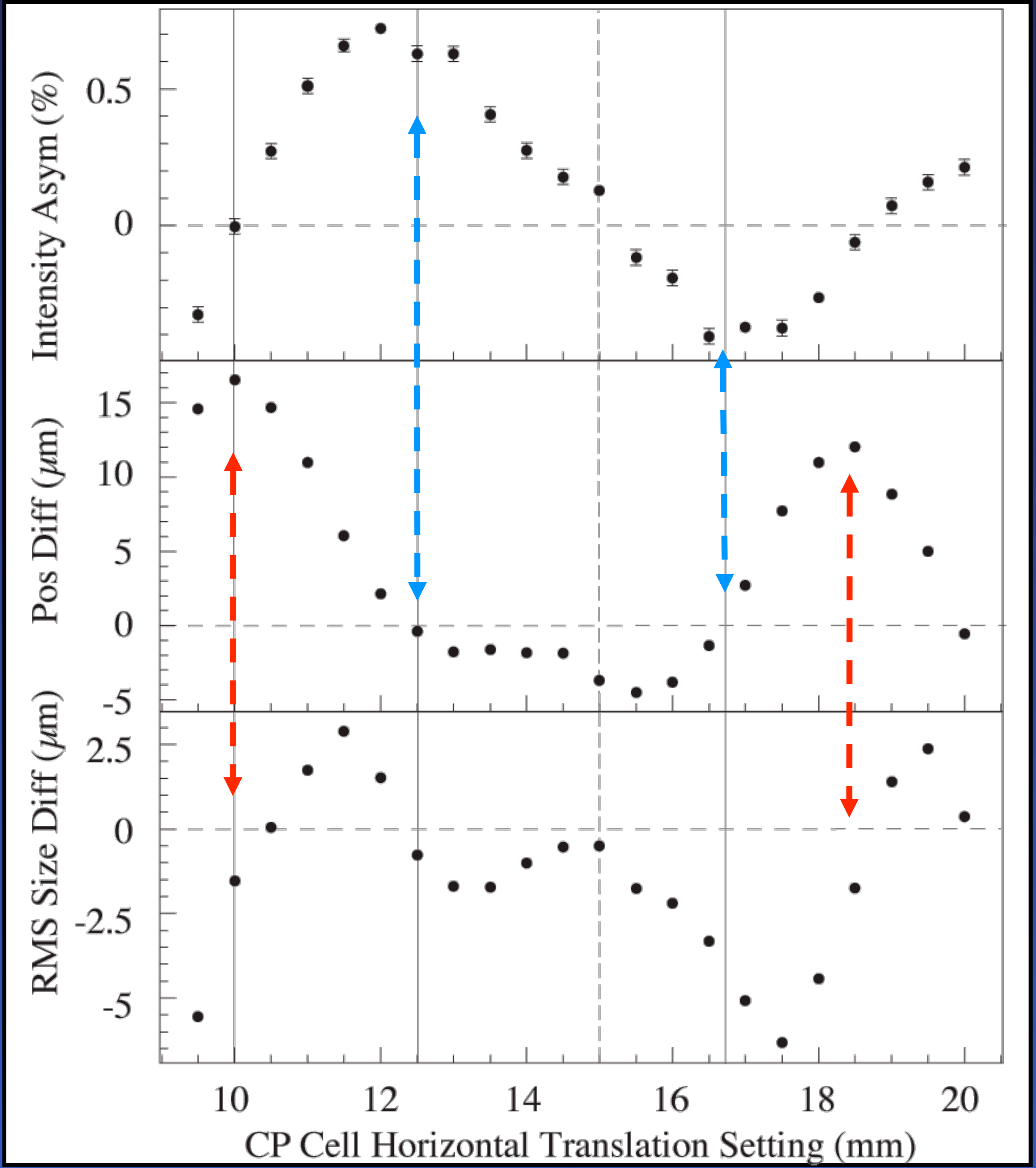
Phase gradients and their effects

Optics-table data looking at asymmetries while translating Pockels cell
(see small effects with rapid-flip asymmetry DAQ, 100% analyzer)

Intensity asymmetry is proportional to the phase Δ.

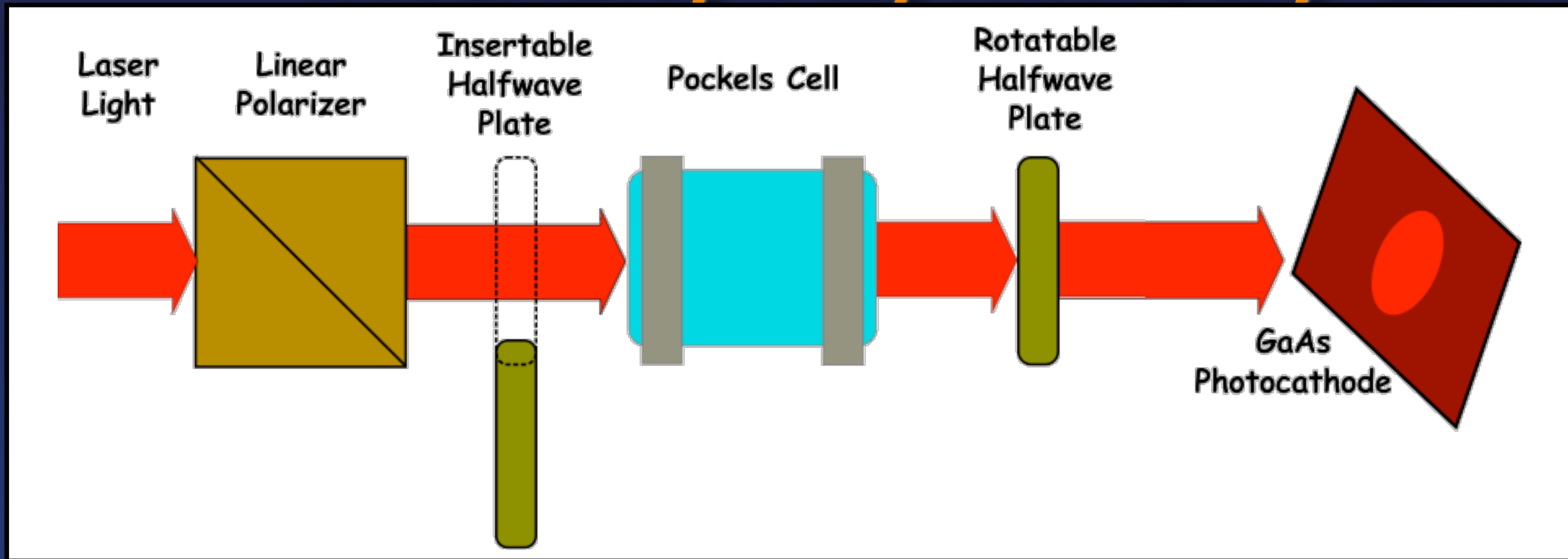
Position difference is roughly proportional to the derivative of the intensity asymmetry.

Spot size difference is roughly proportional to the derivative of the position difference.

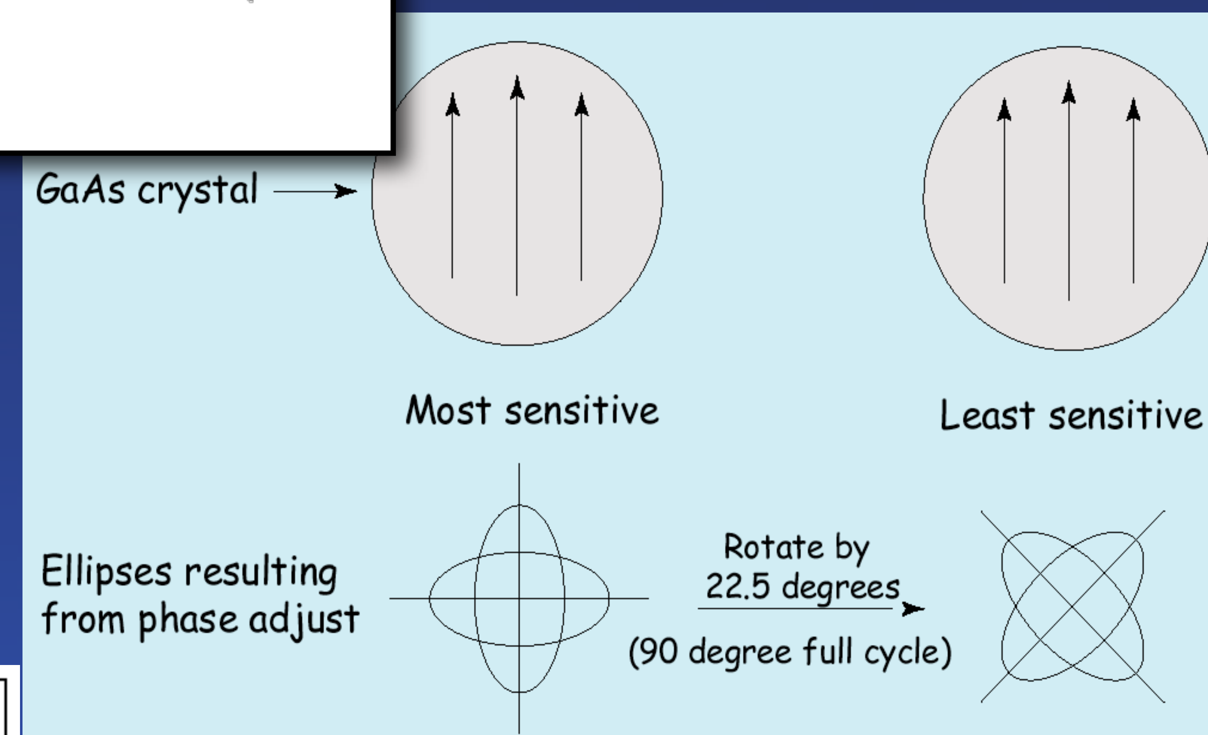


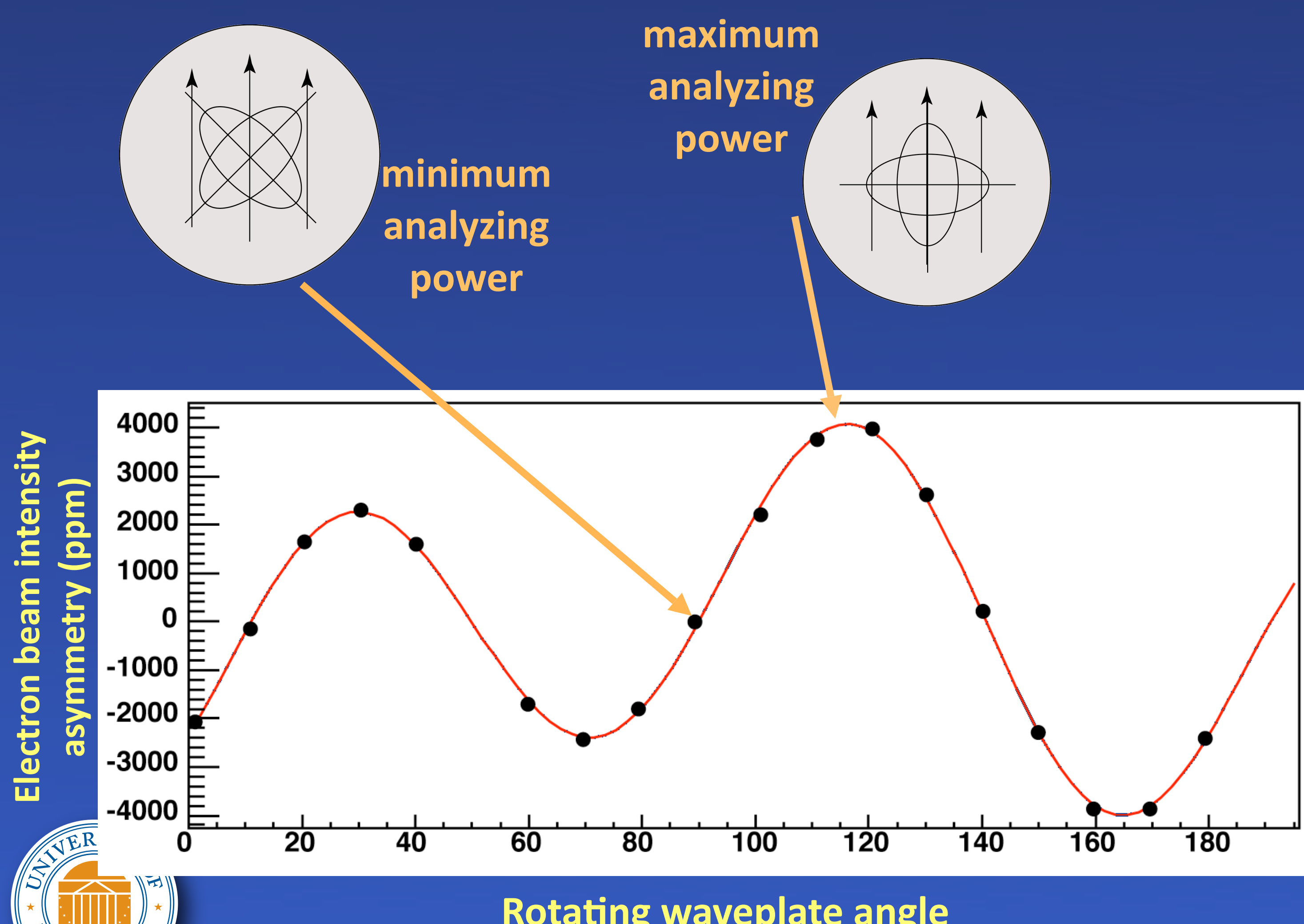
Data from:
T.B. Humensky et. al., NIM A 521, 261 (2004)

Intensity Asymmetry using RHWP



A rotatable λ/2 waveplate downstream of the P.C. allows arbitrary orientation of residual linear polarization



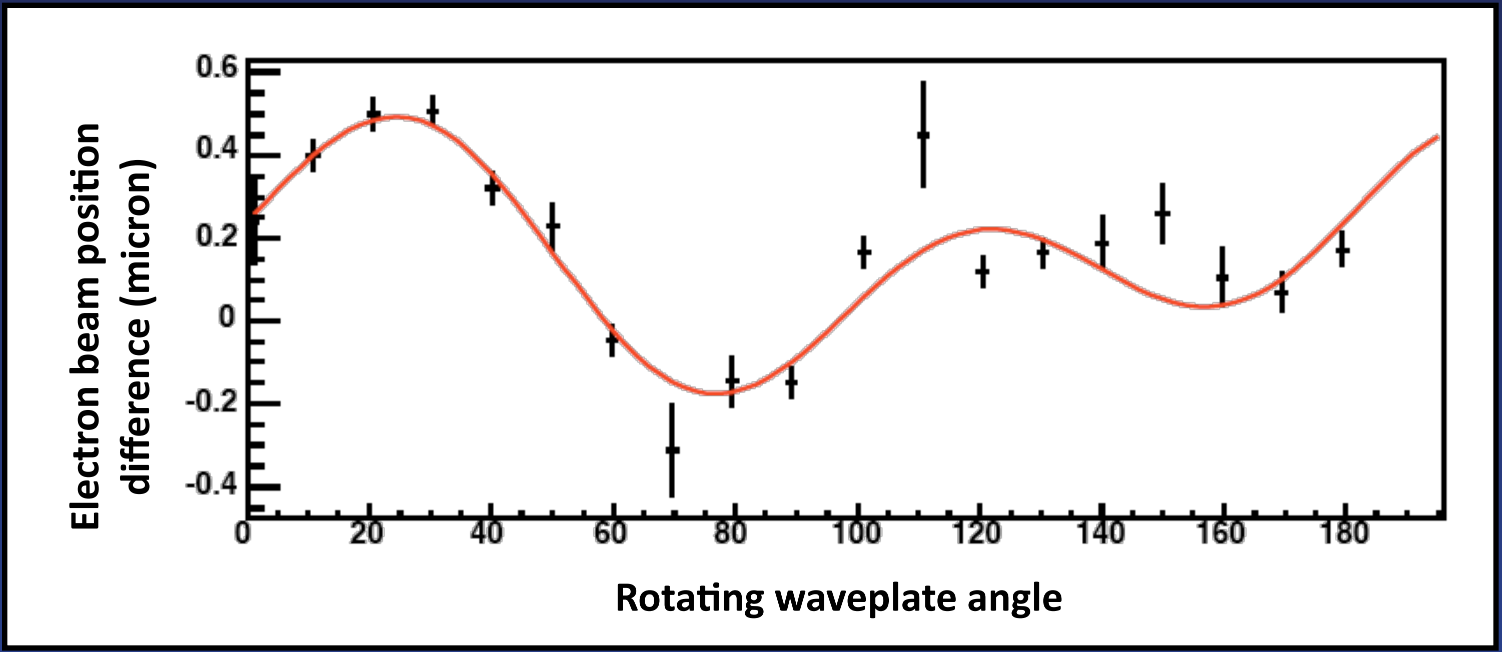


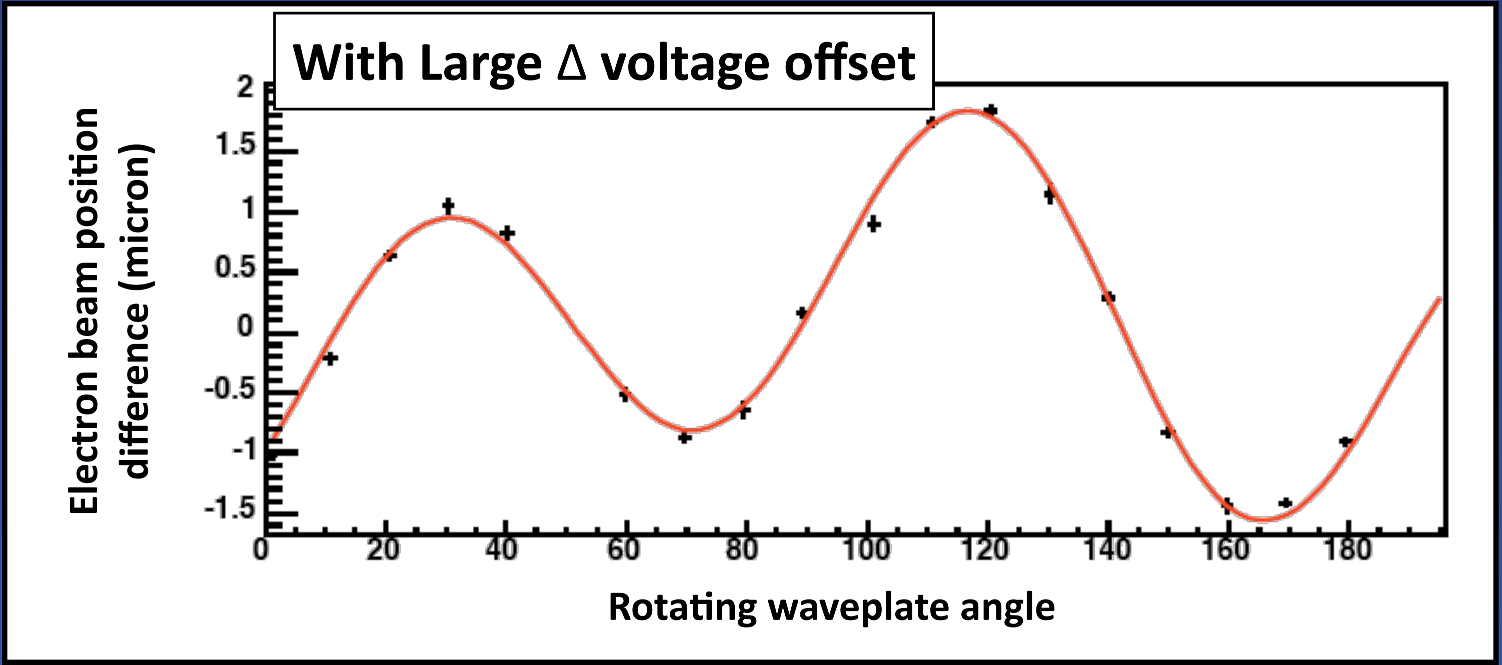
A + B sin(2θ) + C sin(4θ)

sin(2θ) term: imperfections in RHWP

sin(4θ) term: analyzing power*DoLP

Position Differences using RHWP





A_Q and position differences both follow "sin(2θ) + sin(4θ)" fit.

4θ term measures:
analyzing power*(gradient in DoLP)
+
(gradient in analyzing power)*DoLP

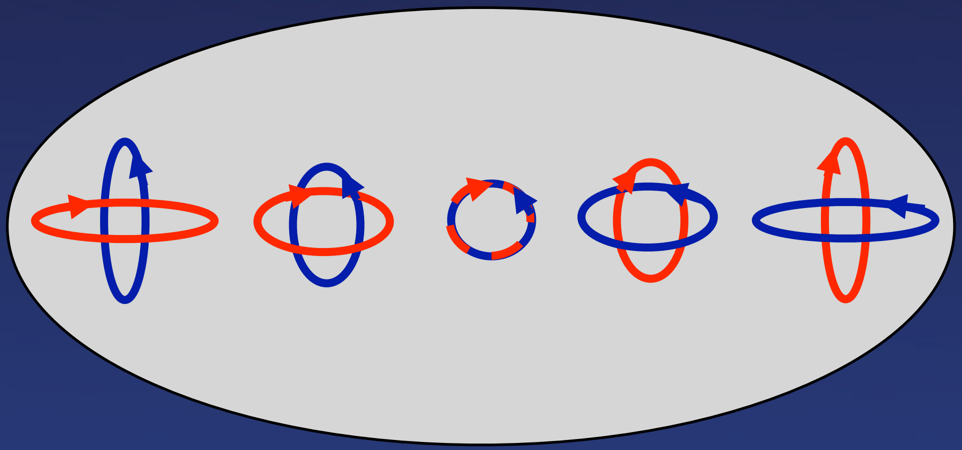
Large DoLP = large position difference

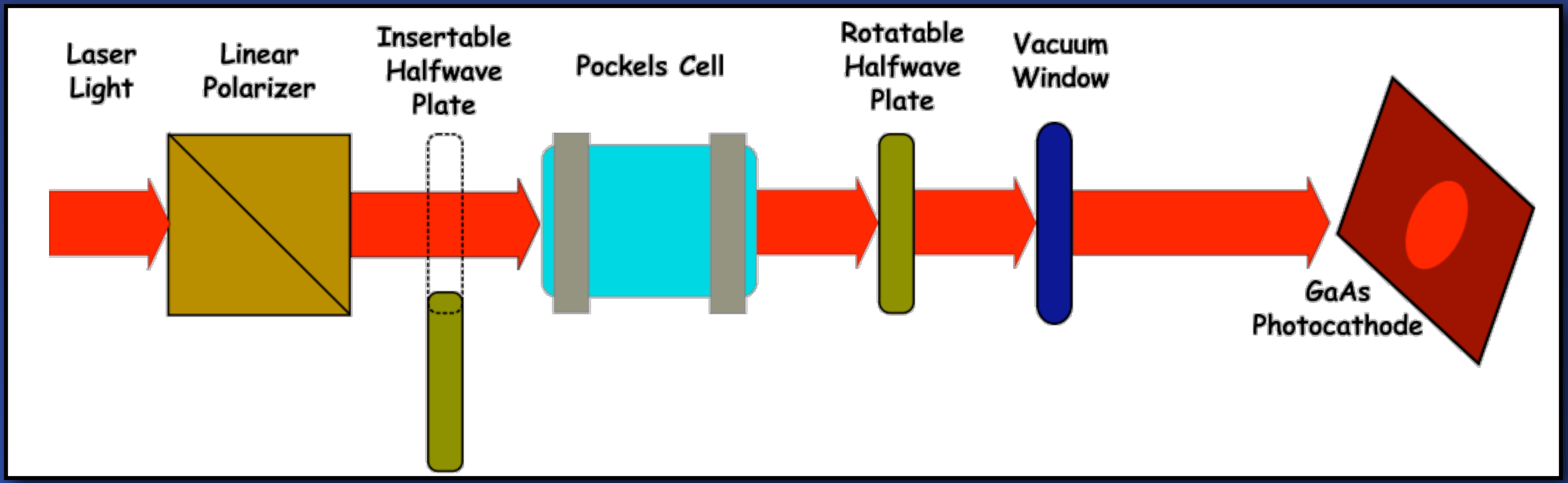
-> Gradient in cathode analyzing power

To minimize all effects, keep DoLP small and stay at small effective analyzing power

Two reasons why DoLP=0 is not simple

DoLP = 0 doesn't mean the spatial variation of LP is zero





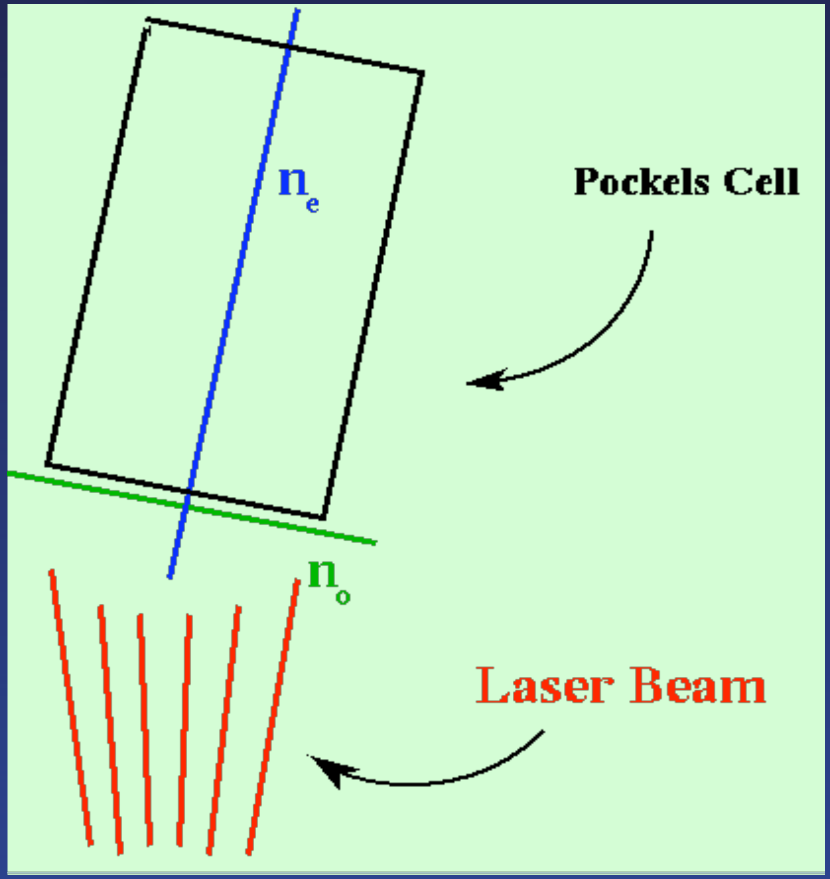
Strained vacuum window is birefringent.

One must use upstream devices to counteract vacuum window contribution, so gradients in those devices are important!

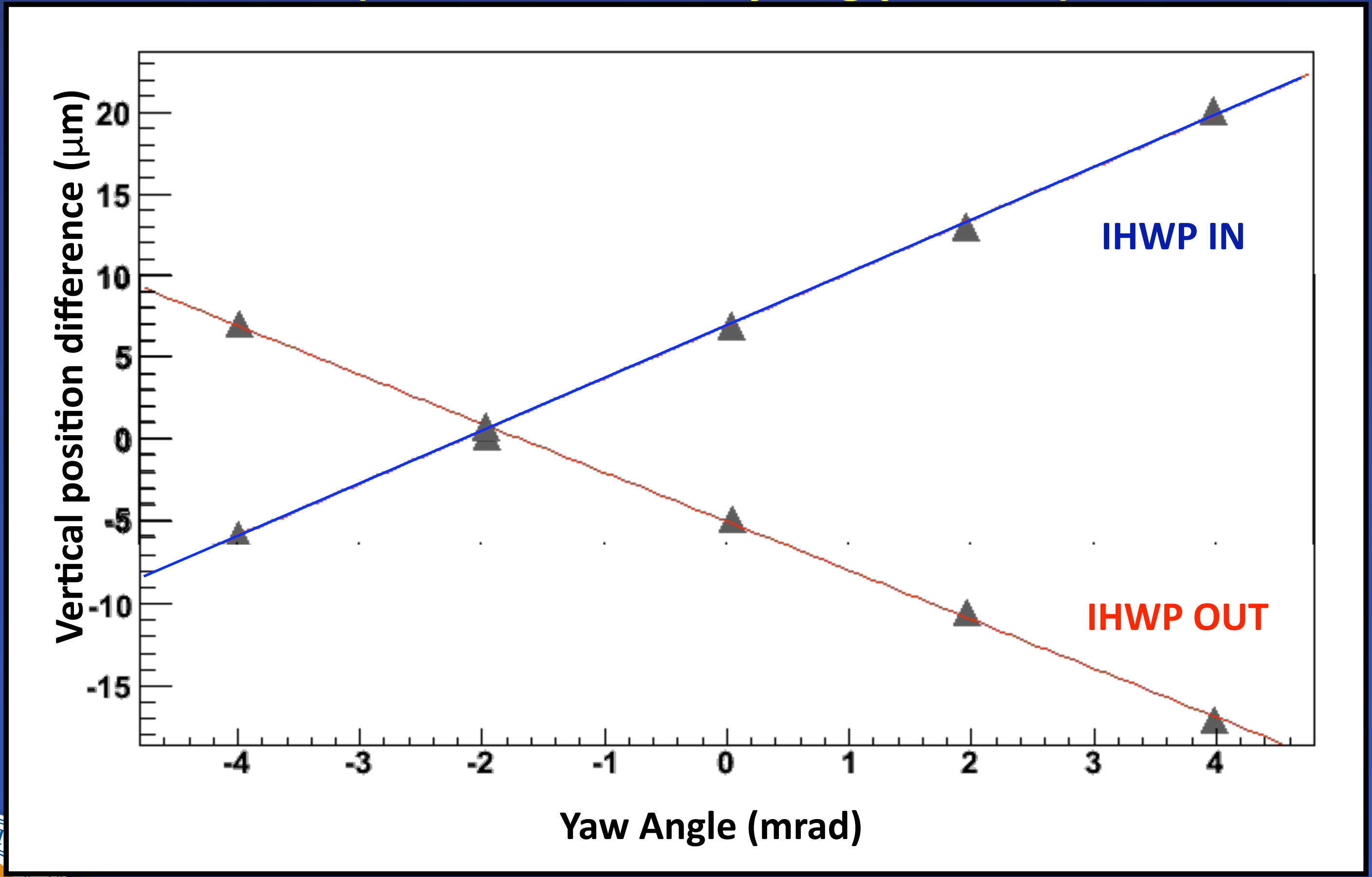
Beam Divergence and Cell Alignment

- Off-axis beam mixes index of refraction between optic and extraordinary axes
- Divergent beam couples Δ-phaseshift to angle
- Angle couples to position

Result: a position-sensitive Δ-phase



Laser spot centroid difference, after linear polarizer (maximum "analyzing power")



Simultaneous zero position differences for pitch and yaw angles (same for both waveplate states) can be found, representing best average alignment along optic axis.

Higher order: when alignment is complete, this effect will lead to "quadrapole" breathing mode of beam spot.

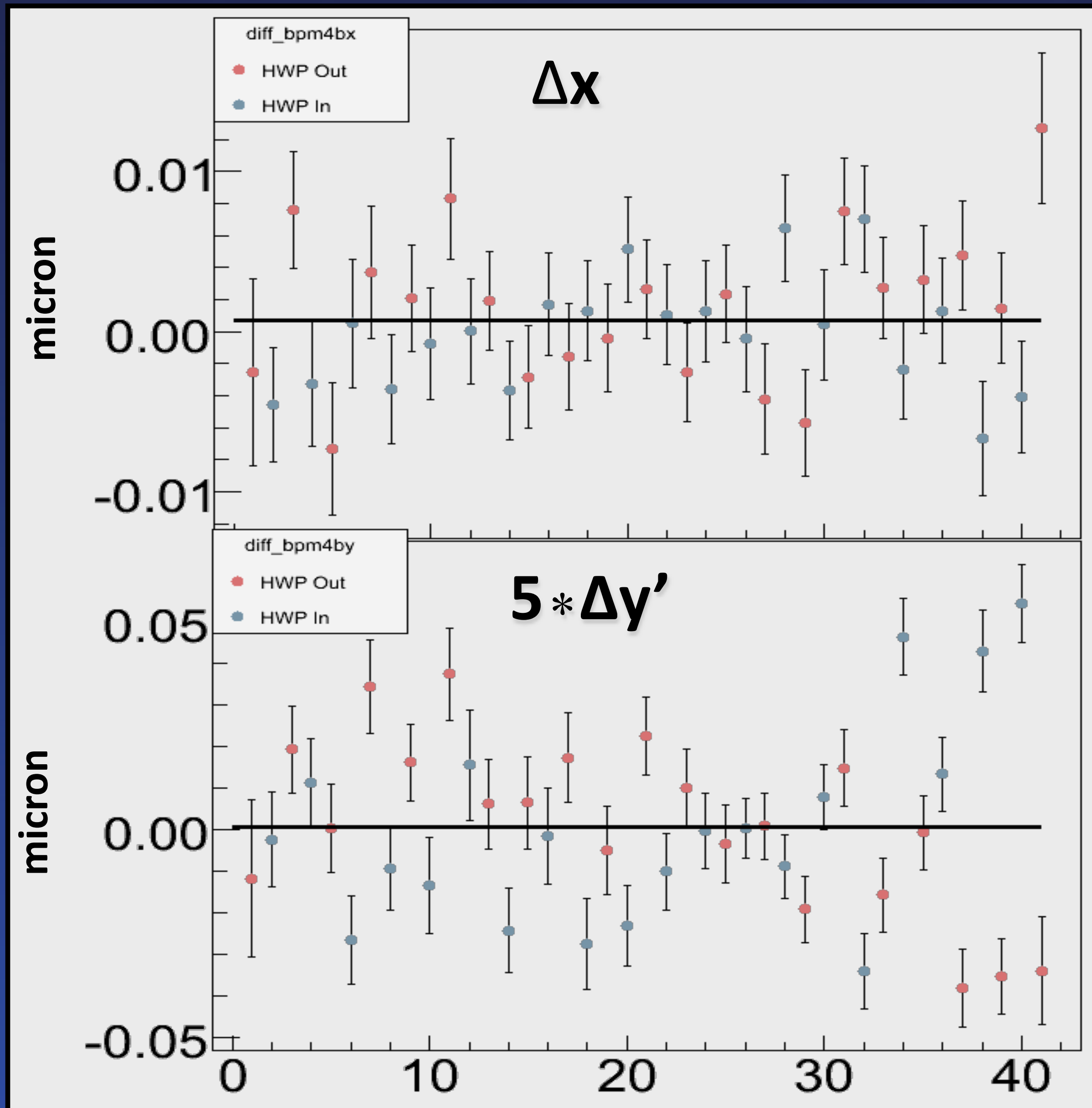
Strategy for success

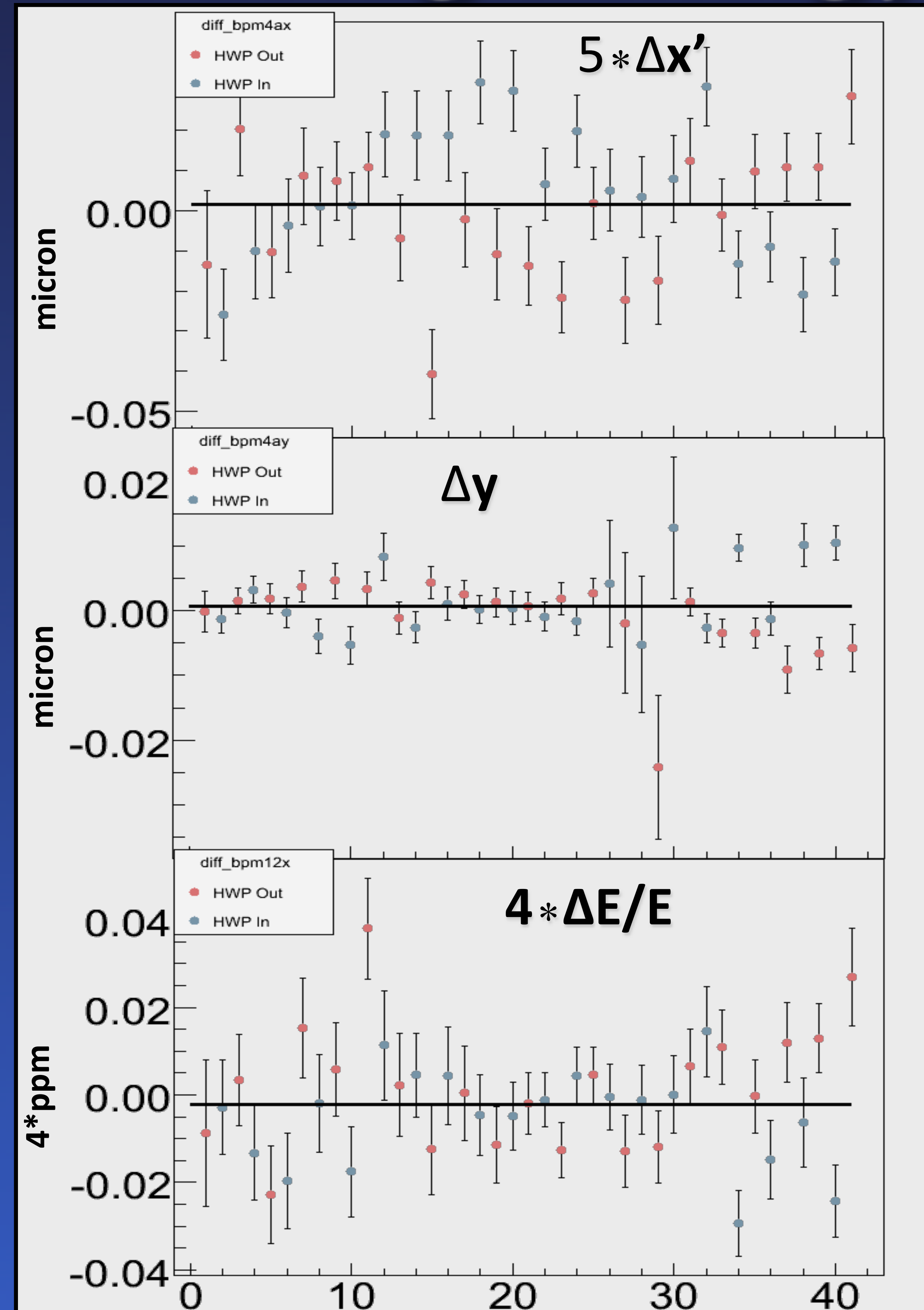
- Well chosen Pockels cells and careful alignment minimize effects.
- Balance RHWP to reduce effective analyzing power but allow moment arm to counteract vacuum window
- Use feedback on PC voltage to reduce charge asymmetry.
  - Pockels cell voltage feedback maximizes circular polarization, which is good for both "zeroth" AND higher orders

More possible causes than "knobs" to zero them

…so have sufficient diagnostics to identify the biggest problems, and tune the configuration to remove those.

Position differences at high energy





HAPPEX-II (2005)

Run Averaged:

Energy: -0.25 ppb

X Target: 1 nm

X Angle: 2 nm

Y Target : 1 nm

Y Angle: <1 nm

Good progress, but new challenges

- **Significant progress has been made by thoroughly understanding the origins of the effects, with nanometer level of position difference control.**

- **The next generation experiments at JLab (QWeak and PREx) will increase demand to understand and control higher order effects.**

  - Increased control of intensity and position difference
  - Robust limits on spot size/shape asymmetries
  - Multi-user facility makes this more challenging:
    - Efficient and robust configuration techniques
    - Understand effects of multiple beams on cathode
    - Understand effects of cathode degradation (200 uA currents for QWeak!)
  - Gun/injector improvements in near future
    - Rotation of photocathode in new JLab load-lock gun
    - Improved slow reversals

Slow Helicity Reversal

Not all HCBA are measured: spot size/shape, phase space correlations...

"slow" helicity reversals are an important component of a comprehensive strategy to control HCBA

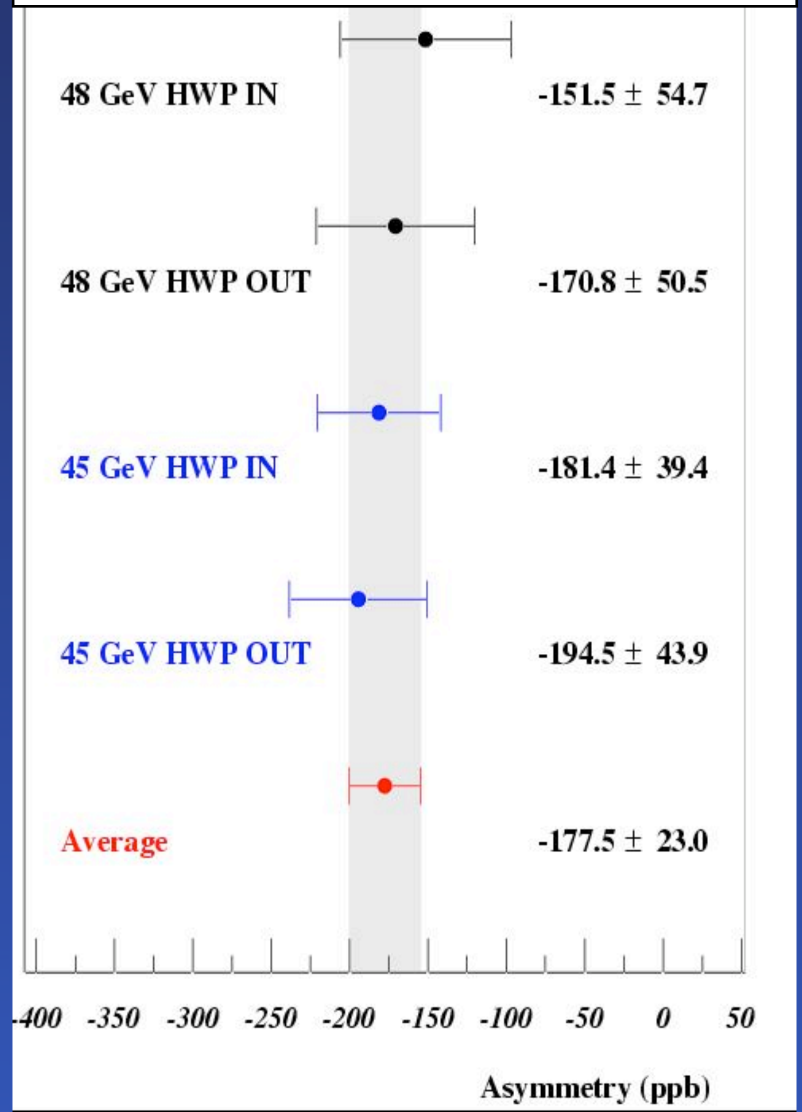
Why use slow reversal:

- Comparison to two data sets rules out gross problems, at the level of ~4σ of final error bars
- Addition of two data sets implies cancellation of subtle problems (at least those susceptible to cancellation under the reversal)

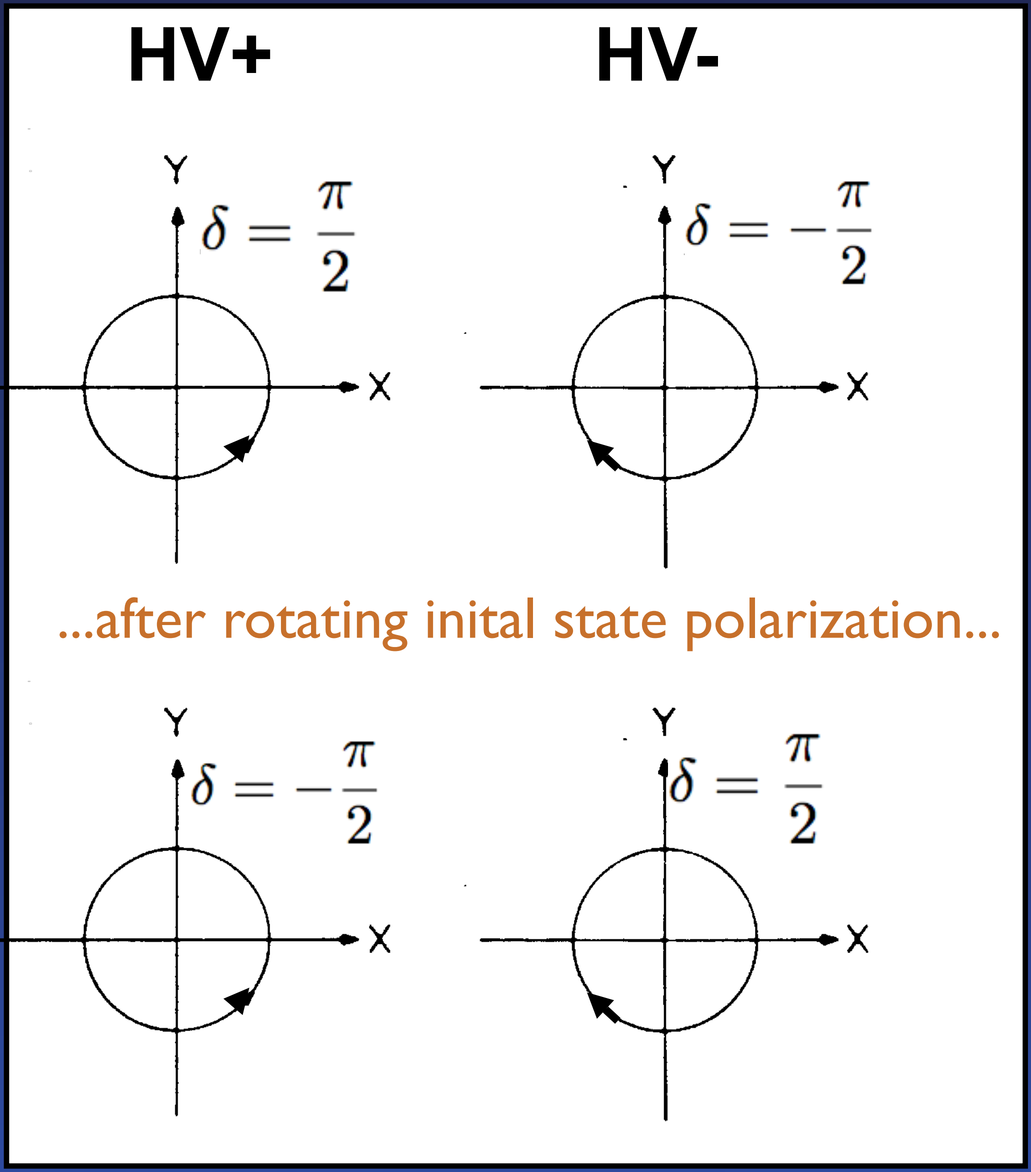
Why use more than one:

- Effectiveness relies on flipping helicity without changing systematic effect... you need the right flip for the specific possible systematic effect

SLAC E158 used an energy change to create a g-2 spin flip into End Station A



Insertable Half-wave plate



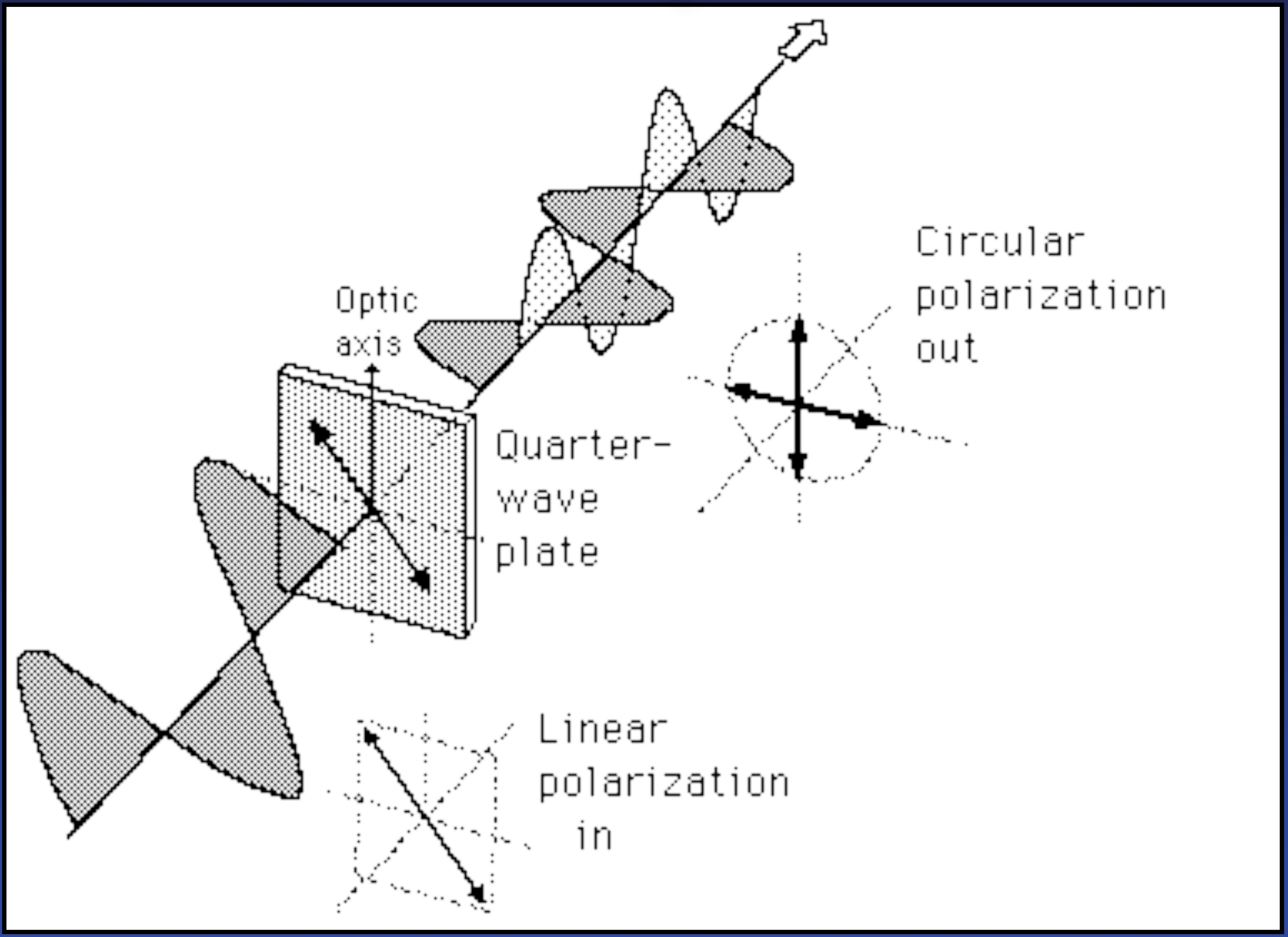
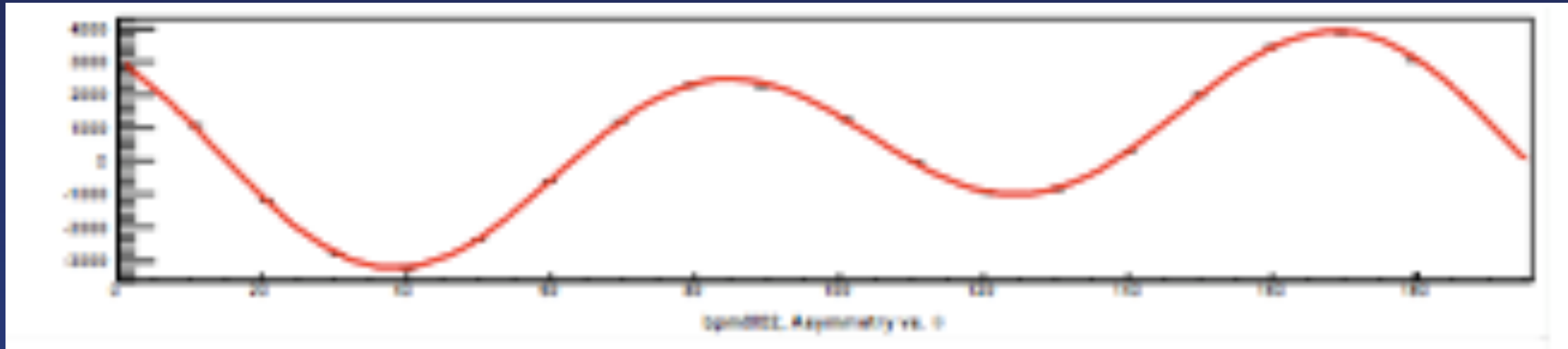


Image from HyperPhysics:
http://hyperphysics.phy-astr.gsu.edu/Hbase/hph.html

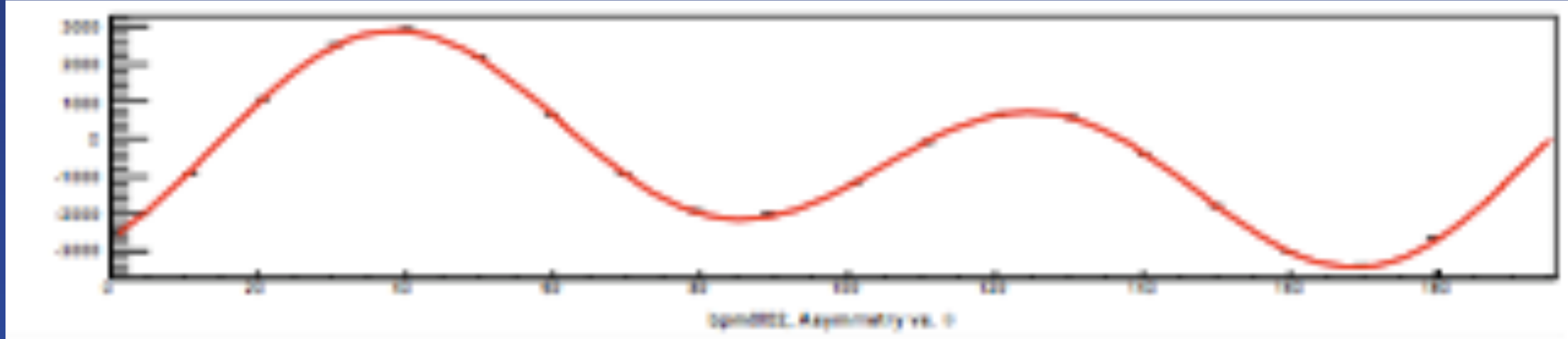
IHWP flips sign of circular polarization, but also of the cathode analyzing power with respect to the Pockels cell voltage...

...after sign correction, "polarization effects" DO NOT cancel!

IHWP Slow Helicity Reversal



$$A_q = 527.20 + 1321.17 \sin(2x + 163.85) + 2612.01 \sin(4x + 123.70)$$



$$A_q = -472.87 + -1260.73 \sin(2x + 165.58) + -2248.33 \sin(4x + 122.67)$$

IHWP flips sign of cathode analyzing power with respect to Pockels cell voltage, but also:

- all analyzing power with respect to Pockels cell, and
- all birefringence downstream of PC

Most beam asymmetries ARE NOT cancelled by the IHWP

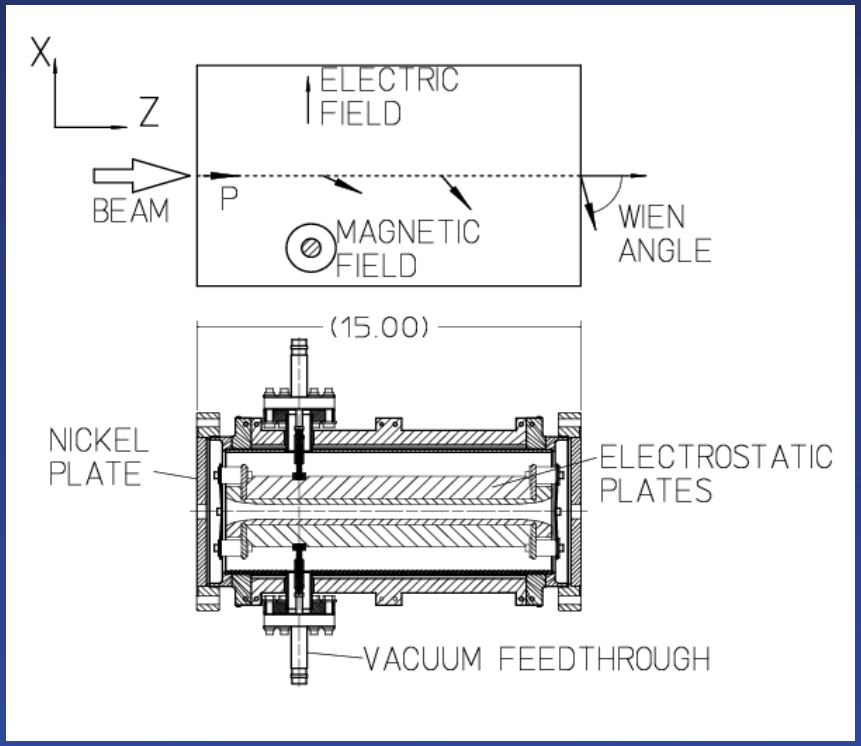
Alternative Slow Reversal

Wein Spin Rotator

• g-2 from energy change sometime impractical, especially at lower energies... can the common Wein rotator be used?

• Crossed E/B fields intrinsically focus the beam. 180° spin flip will not perserve the beam properties!

• Solution: incorporate Wein with solenoids, and accomplish spin flip with +/-90 degree solenoid rotation. Solenoids focus as B^2, so this is less invasive.



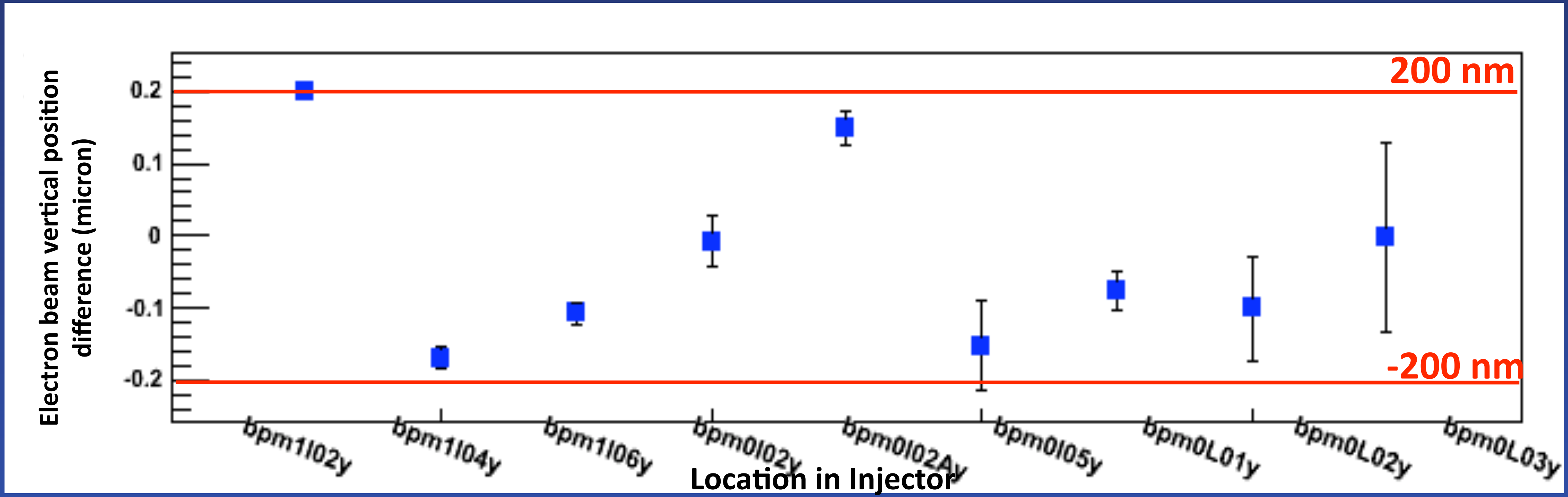
Wein upgrade project now underway at JLab to support the 2010 experiments

Backup

Injector Position Differences for HAPPEX-H (2005)

After configuration:

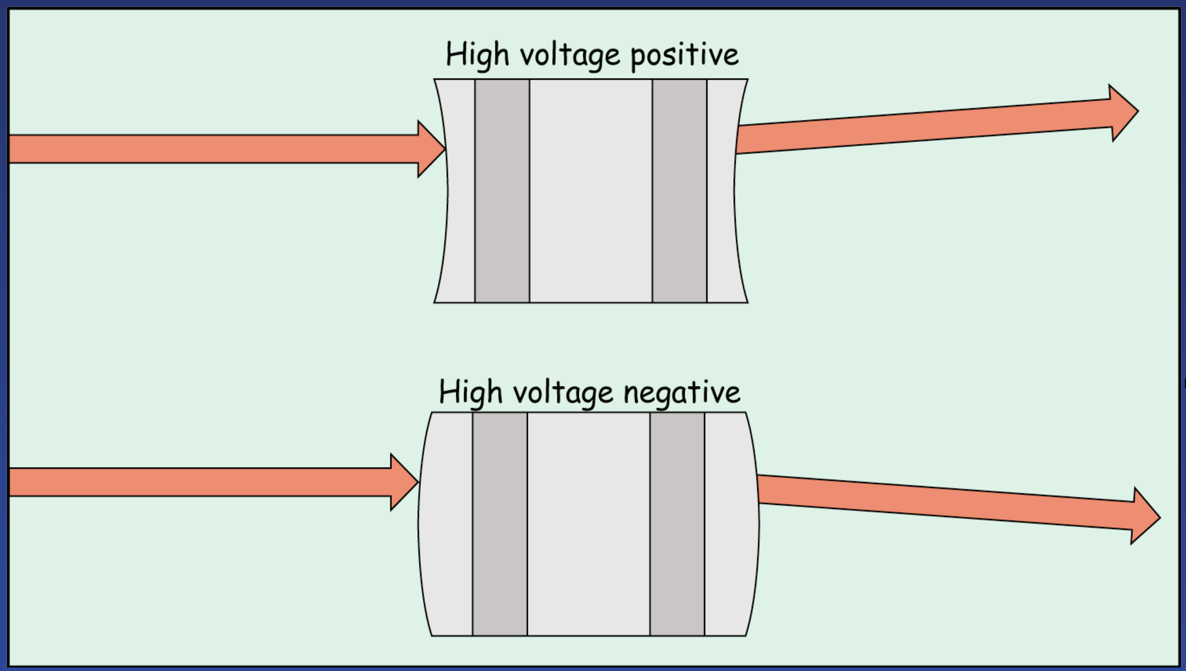
position differences in injector had maximum around 200 nanometers

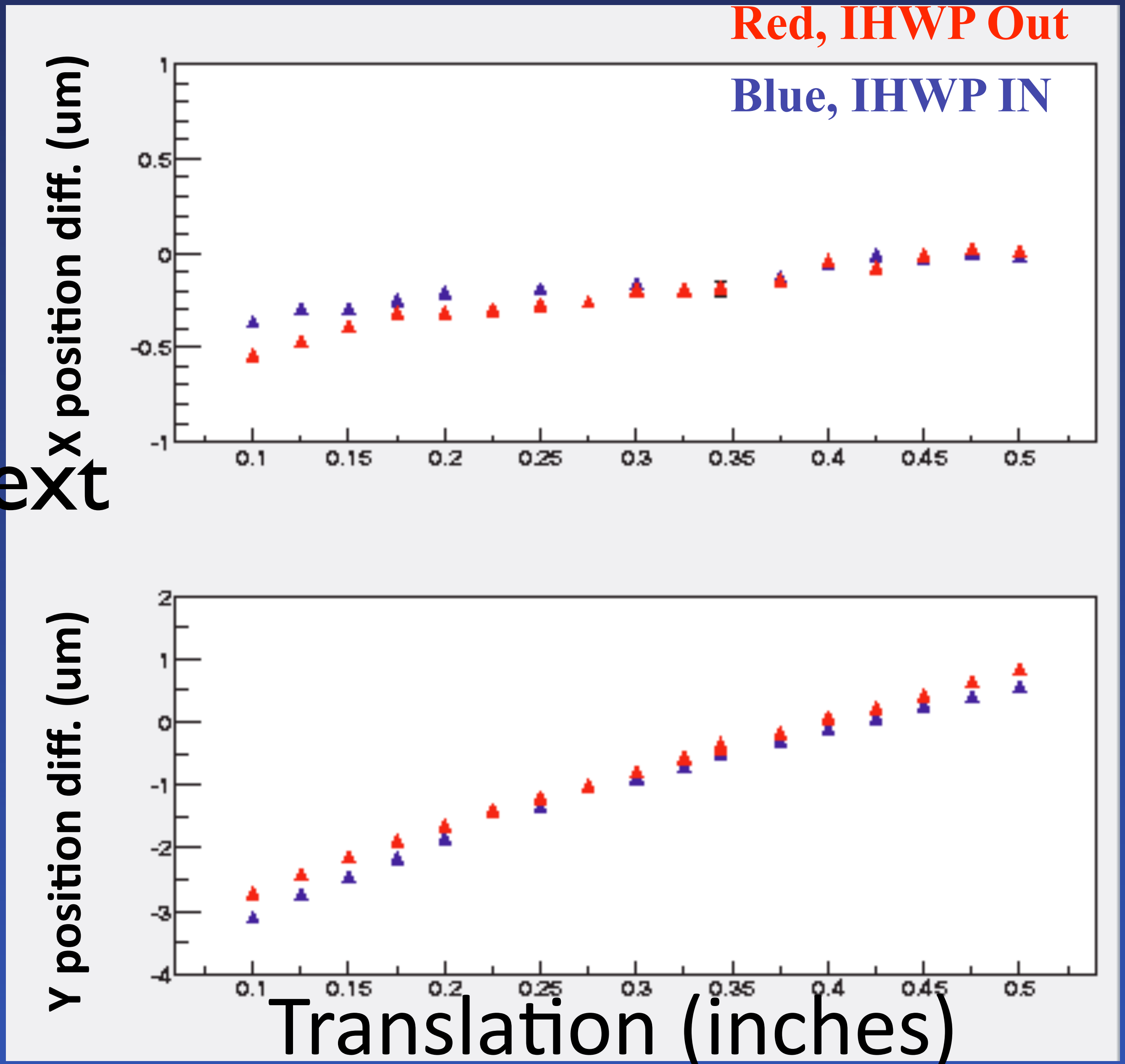


Additional suppression from slow reversal

HCBA Example: Piezoelectric Steering

The piezoelectric Pockels Cell
acts as "active" lens





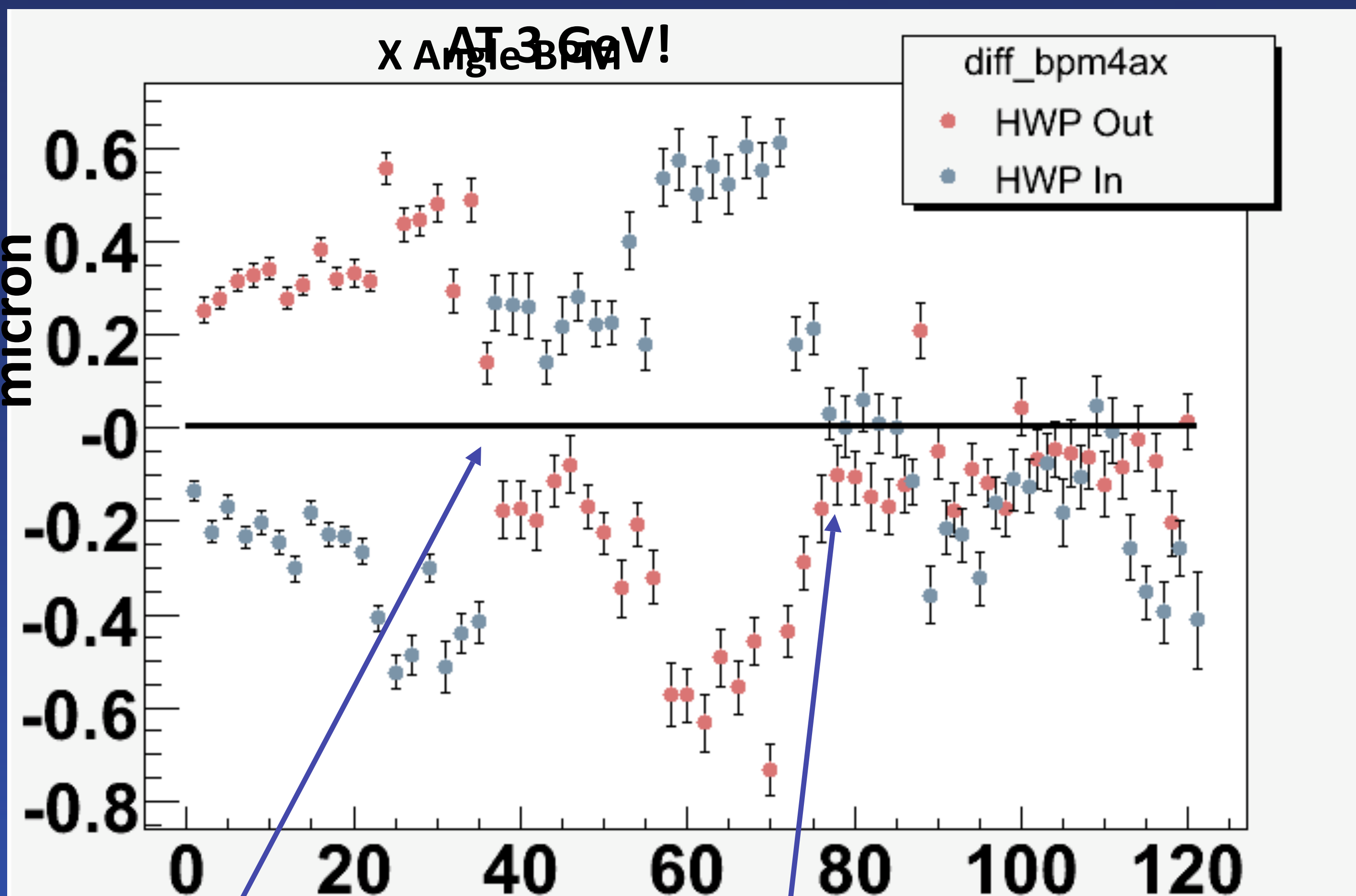
Signature of steering:

- scales with lever arm
- not related to beam polarization
- *does* cancel on slow reversal

Beam Position Differences, Helium 2005

HC beam asymmetries correspond to differences in preparation of circularly polarized laser light*.

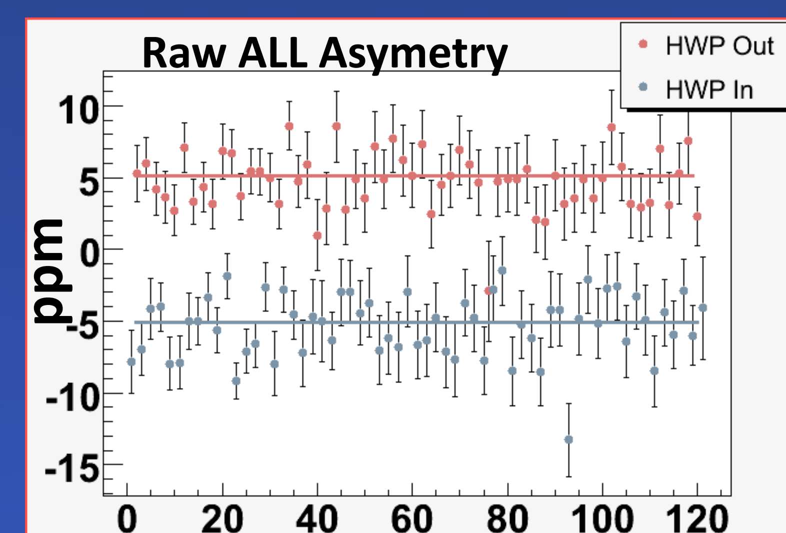
*unless you decide to add helicity information to the electron beam after it is generated from the cathode



Helicity signal to driver reversed

Helicity signal to driver removed

- Problem clearly identified as beam steering from electronic cross-talk
- Tests verify no helicity-correlated electronics noise in Hall DAQ at sub ppb level
- Large position differences mostly cancel in average over both detectors, **cancels well with slow reversal**



Problem: Helicity signal deflecting the beam through electronics "pickup"

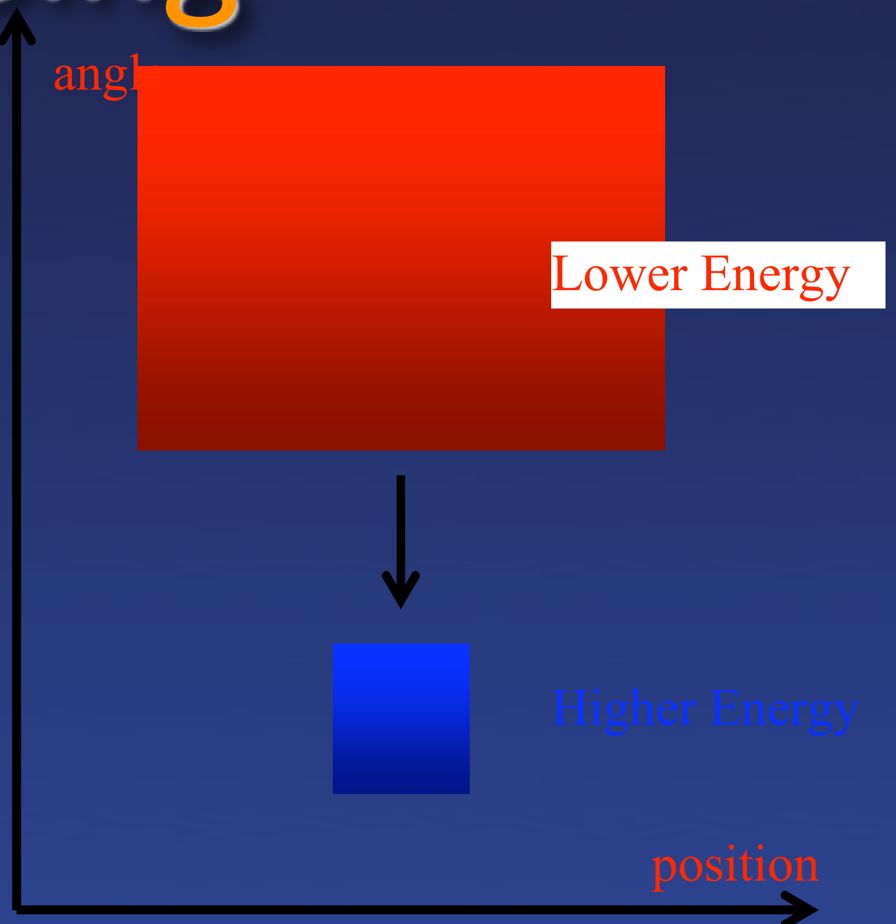
Large beam deflections even when Pockels cell is off

Adiabatic Damping

Area of beam distribution in the phase space (emittence) is inversely proportional to momentum.

From 100 keV injection energy to 3 GeV at target, one expects helicity-correlated position differences to get smaller

$$\sqrt{\frac{3\,\mathrm{GeV}}{335\,\mathrm{keV}}} \approx 95$$

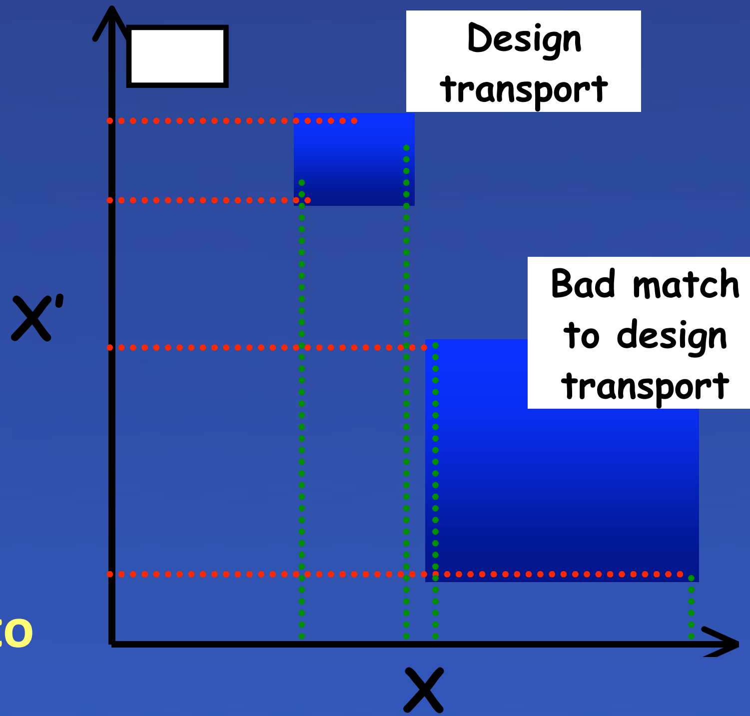


The critical parameter in position difference isn't sqrt(emittence)

The projection along each axis is sensitive to coupling.

If the coupling develops, it is difficult to remove…

To take advantage of adiabatic damping, keep machine close to design to minimize undesired correlations.

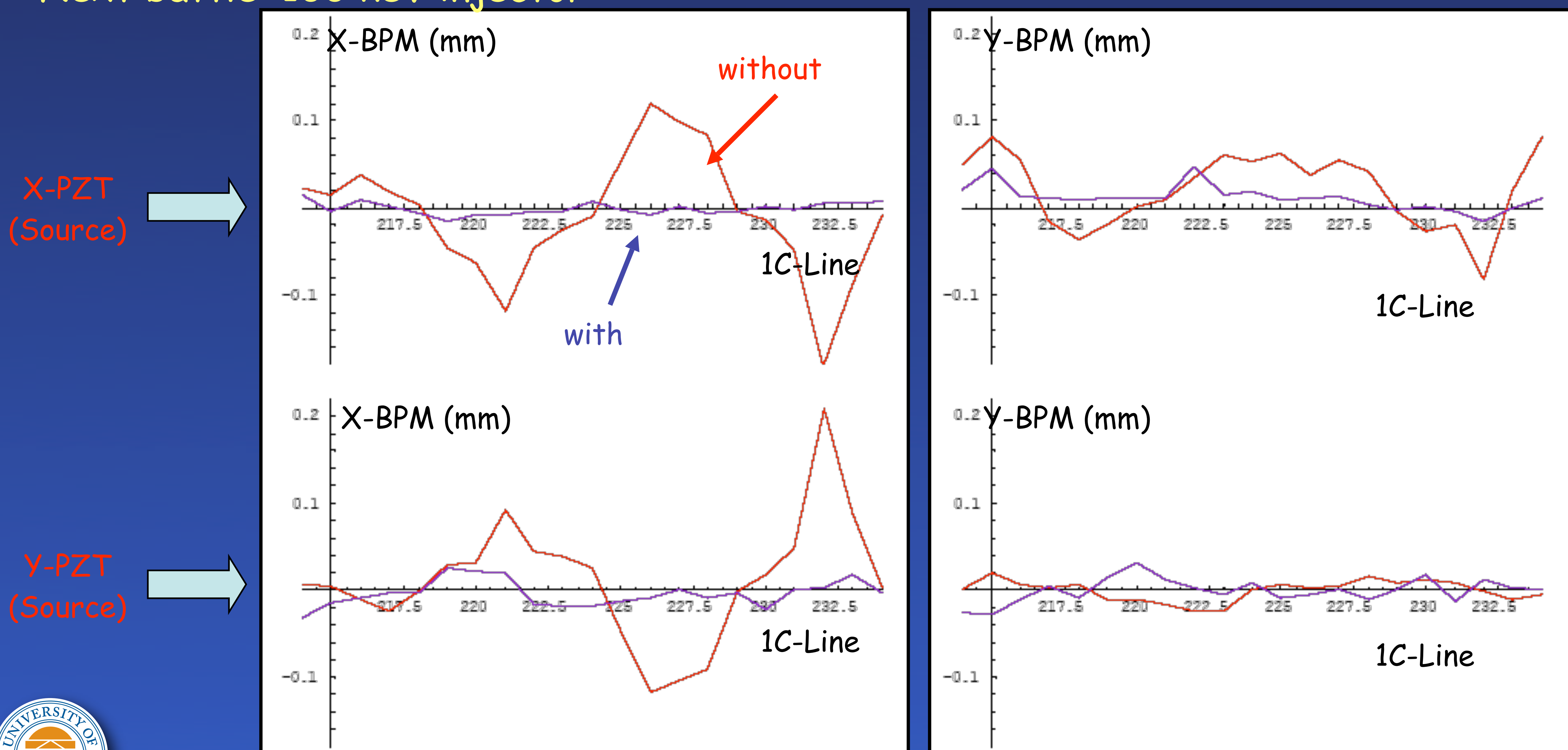


Taking Advantage of Phase Space Reduction

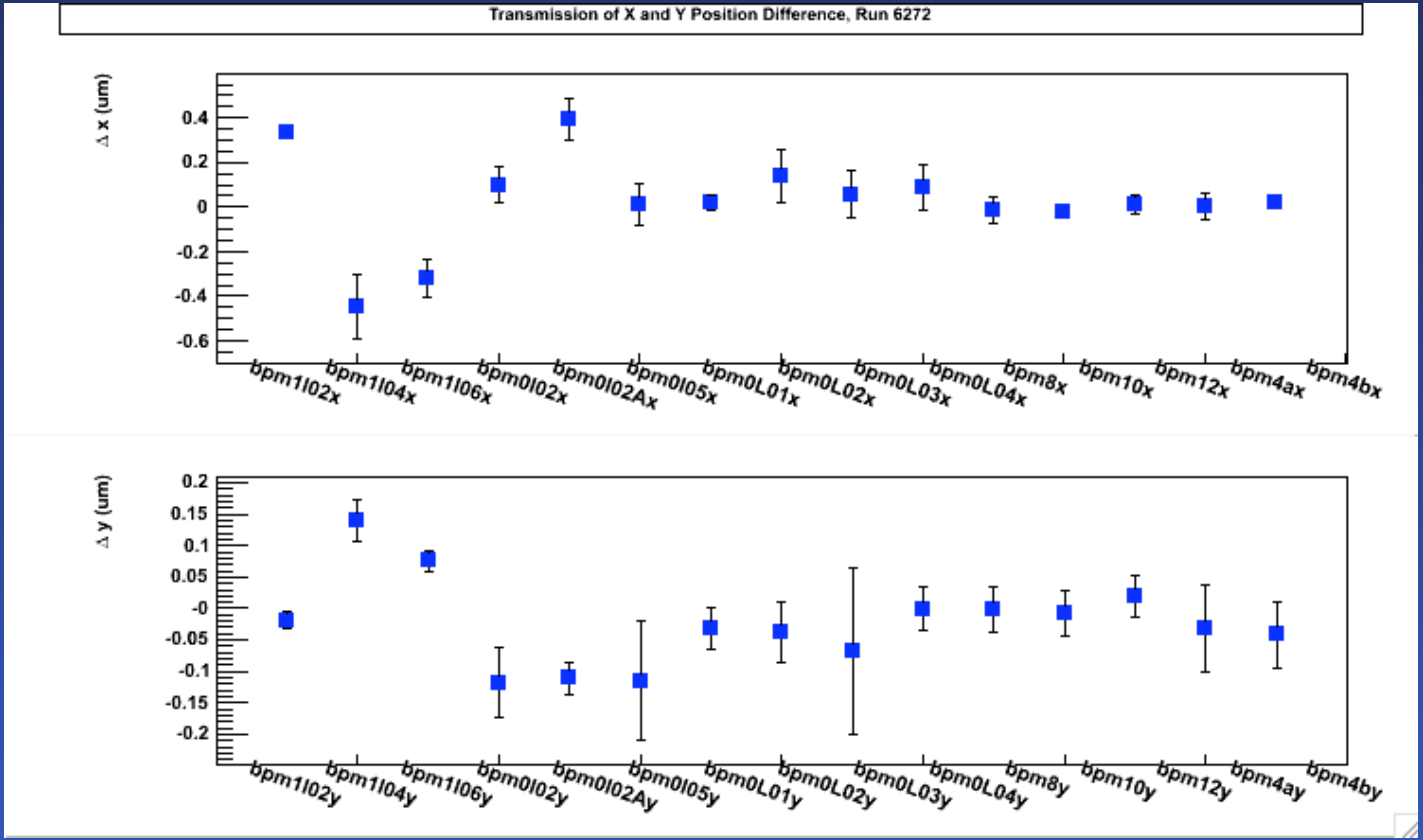
Major work invested to controlling beam transport as designed (**Yu-Chiu Chao**)

- Transport matching design (linacs & arcs) now routine.
- Improvements in the 5MeV injector major step forward
- Configuration very stable over 2+ months
- Next battle: 100 keV injector

Factor between 5-30 observed during HAPPEX-H



Position differences, End of HAPPEX-2005



Phase Trombone

Goal: vary beta phase

- implemented with eight existing quads at the beginning of the Hall A arc
- Allows for independent beta fcn phase control in horizontal and vertical planes

Uses:

- Allows one to trade off position and angle differences (10:1 scale between size in accelerator and senstivity for experiment)
- Periodic phase changes can be used to randomize or reverse the sign of position differences

Constraints:

- Preserve beam size at the location of the Compton polarimeter
- Preserve large dispersion at center of arc
- Preserve ability to independently vary spot size at target

Figures from Beck, PAVI'04

Results of Hall A Phase Trombone Test

Data from 2004 (Bogacz and Paschke):

Phase Trombone Setpoint ($\Delta\theta_x$, $\Delta\theta_y$)	Δx (μm) $\pm$0.3 μm	Δy (μm) $\pm$0.3 μm	$\Delta\theta_x$(μrad) $\pm$0.01 μrad	$\Delta\theta_y$ (μrad) $\pm$0.02 μrad
(0°,0°)	2.9	2.0	-0.08	-0.19
(30°,0°)	2.7	1.2	-0.07	-0.22
(-30°,0°)	2.8	3.2	-0.07	-0.16
(30°,30°)	1.0	1.2	-0.12	-0.21

Promising approach, but not applied in 2005

- "Local" phase trombone undone by over contraints (too few independent quads)
- "Linac" phase trombone promising, but brief test was ambiguous.
- Electronics pickup made tests uninterpretable