Parity Violation Experiments & Beam Requirements

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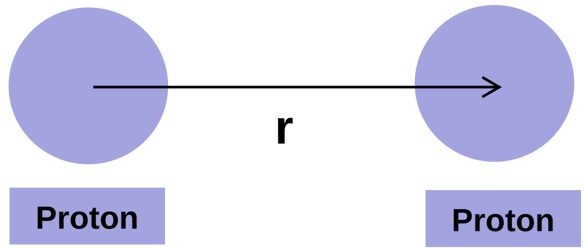
Outline

- Fundamental Interactions and Conservation Rules
- Parity Reversal and Parity Violation
- Experimental Techniques
- Beam Requirements and Physics Motivation
- Ops' and Users' Responsibilities
- Summary

Fundamental Interaction

Interaction	Source	Field Quantum	Range (m)	Coupling	Example
Gravity	Mass	Graviton	∞	0.53×10^{-38}	Solar System, Black Holes
Electromagnetic (EM)	Electric Charge	Photon	∞	1/137	Friction, Lighting
Weak	Weak Charge	Bosons ($W^{\pm}$, Z°)	10^{-18}	1.02×10^{-5}	Neutron Decay, Neutrino Interaction
Strong	Color Charge	Gluon	10^{-15}	1	Proton, Nuclei



$$F_{Gravity} = -\frac{0.53 \times 10^{-38}}{r^2}$$

$$F_{EM} = \frac{1/137}{r^2}$$

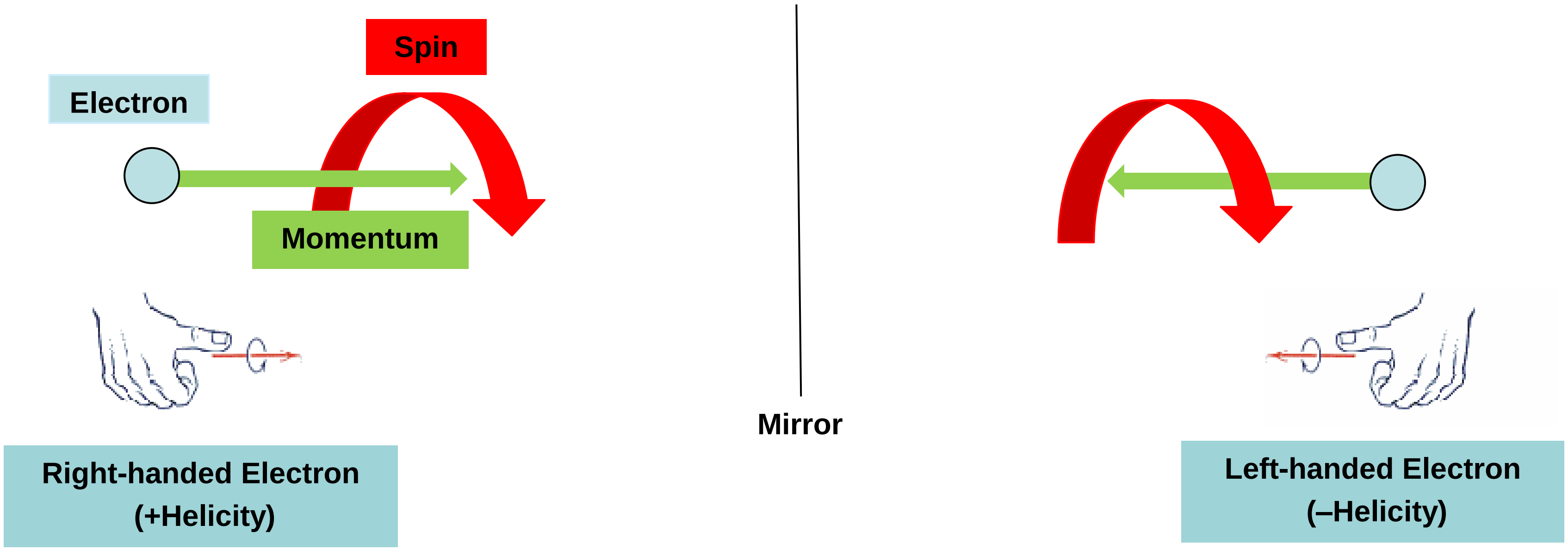
Gravity is irrelevant in elementary particle interactions

Conservation Rules

Interaction	Energy	Momentum	Electric Charge	Time Reversal	Parity Reversal* (Spatial Inversion)
Gravity	Yes	Yes	Yes	Yes	Yes
Electromagnetic (EM)	Yes	Yes	Yes	Yes	Yes
Weak	Yes	Yes	Yes	Yes	**No**
Strong	Yes	Yes	Yes	Yes	Yes

*** Do the laws of nature remain the same under Parity Reversal? Are an object and its mirror image the same?**

Parity Reversal



- Under Parity Reversal, the Right-handed electron becomes Left-handed electron (Helicity Reversal)

  - Changing the electron's spin direction (Helicity Reversal) is equivalent to Parity Reversal

Parity Violation

Particle	Electric Charge	Weak Charge	
	Right/Left	Right-handed	Left-handed
e	-1	0	-½
proton	+1	0	$1\text{-}4\sin^2\theta_W$ (=0.08)
Neutron	0	0	1

- **EM interaction is the same for Right-handed and Left-handed electrons (Parity is conserved)**
- **Weak interaction is not the same for Right-handed and Left-handed electrons: Left-handed electrons interact weakly but Right-handed do not (Parity is violated)**
- **Electrons do not interact strongly**

Experimental Techniques

- **How to carry out a parity violation experiment:**
  - **Scatter longitudinally polarized electrons off un-polarized target (*i.e.*, Hydrogen, Deuterium, Helium, Lead)**
  - **Reverse the beam helicity (±) with Pockels Cell, measure detected signals ($D^{\pm}$) and currents ($I^{\pm}$), calculate physics asymmetry ($A_{physics}$):**

$$A_{physics} = \frac{\frac{D^+}{I^+} - \frac{D^-}{I^-}}{\frac{D^+}{I^-} + \frac{D^-}{I^+}} \approx \frac{Weak}{EM}$$

1/15th of a second

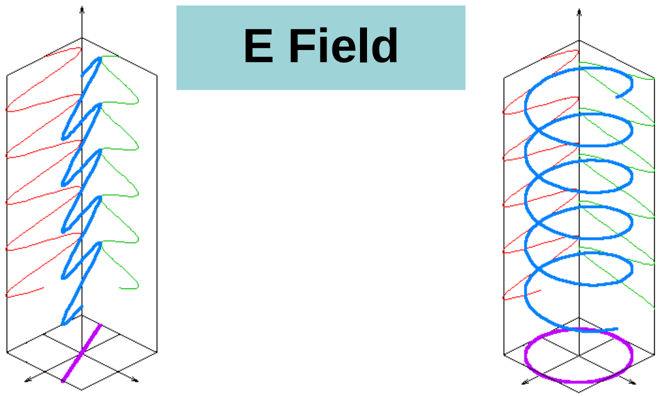
  - **Repeat the whole experiment: Millions of measurements**
  - **Statistical distribution of these measurements is Gaussian: Mean is average asymmetry and error is width of Gaussian divided by square root of number of asymmetry measurements**
  - **Average asymmetry is very small (1-50 ppm)**

(1 drop of ink in 50 liters of water would produce an "ink concentration" of 1 ppm)

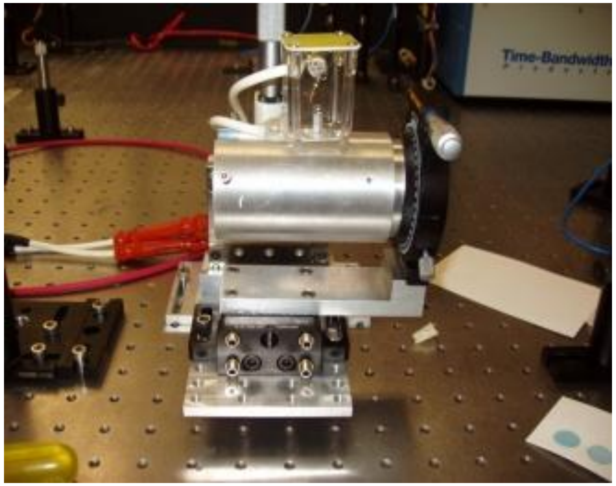
Pockels Cell

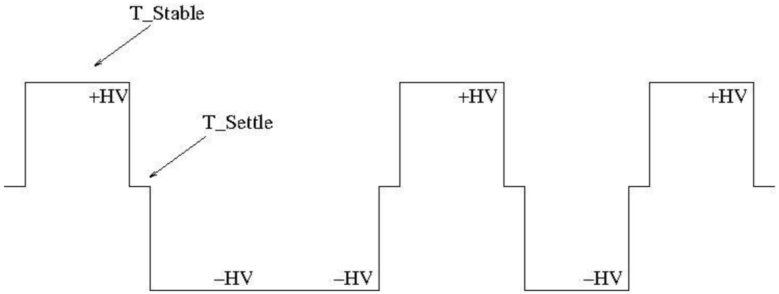
- Pockels Cell is voltage controlled quarter wave plate
- Changes polarization of laser from linearly-polarized light to circularly polarized light

Linearly Polarized Light



Circularly Polarized Light



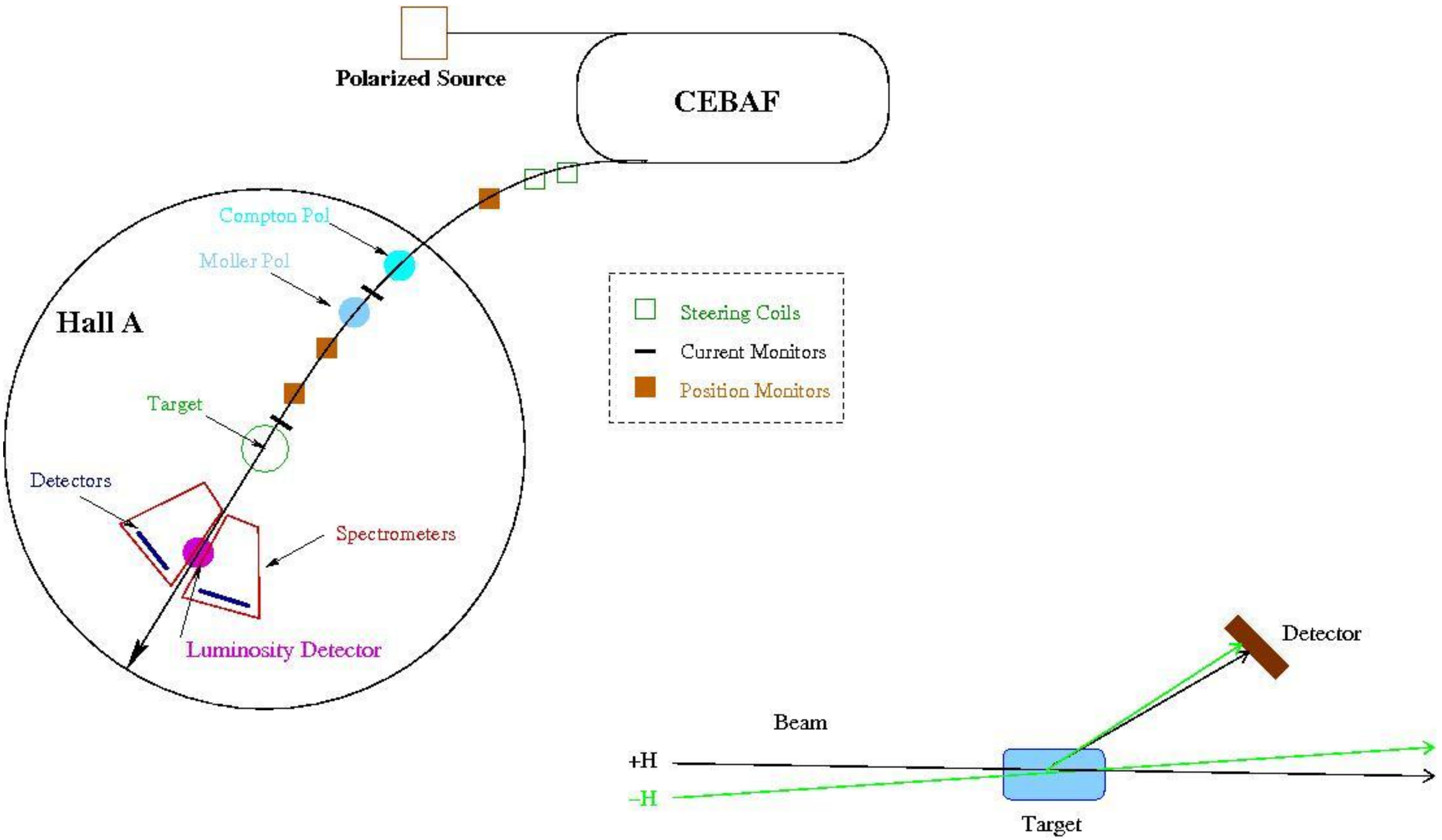


Pockels Cell HV

+HV: Right-handed circularly polarized light → +Helicity electron

-HV: Left-handed circularly polarized light → -Helicity electron

Experiment Layout



Charge Asymmetry and Position Difference

- **Charge Asymmetry: When the average current of the electron beam corresponding to one helicity state is different from the other state,**

$$A_I = \frac{I^+ - I^-}{I^+ + I^-}$$

  - ❑ **We measure charge asymmetry of order 1-50 ppm**

- **Position Difference: When the average position of the electron beam corresponding to one helicity state is different from the other state,**

$$\Delta x = x^+ - x^-$$

$$\Delta y = y^+ - y^-$$

  - ❑ **We measure position differences of order 1-40 nm**

(1 nm is one-billionth of a meter. The width of human hair is 50,000 nm)

Parity-Quality Beam (PQB)

- **Goal: Use the Pockels Cell at Fast Helicity Reversal to reverse only the spin direction, nothing else: All other properties of the electron beam (*i.e.*, position, current, energy, size) must stay the same**

- **Techniques to achieve "PQB":**
  I. **(users) Careful alignment of the Pockels Cell to minimize un-wanted changes**
  II. **(ops) Slow Helicity Reversal using Insertable Half Wave Plate (IHWP) and the Two Wien to cancel un-wanted changes on the electron beam**
  III. **(Reza, Yves) Injector and Accelerator Matching to achieve Adiabatic Damping of beam orbits**
  IV. **(users) Charge Feedback to reduce beam's current changes using either Pockels Cell or Intensity Attenuator (IA) without or with the option to correct for Pockels Cell hysteresis**
  V. **(users) Position Feedback can also be done using the helicity magnets**

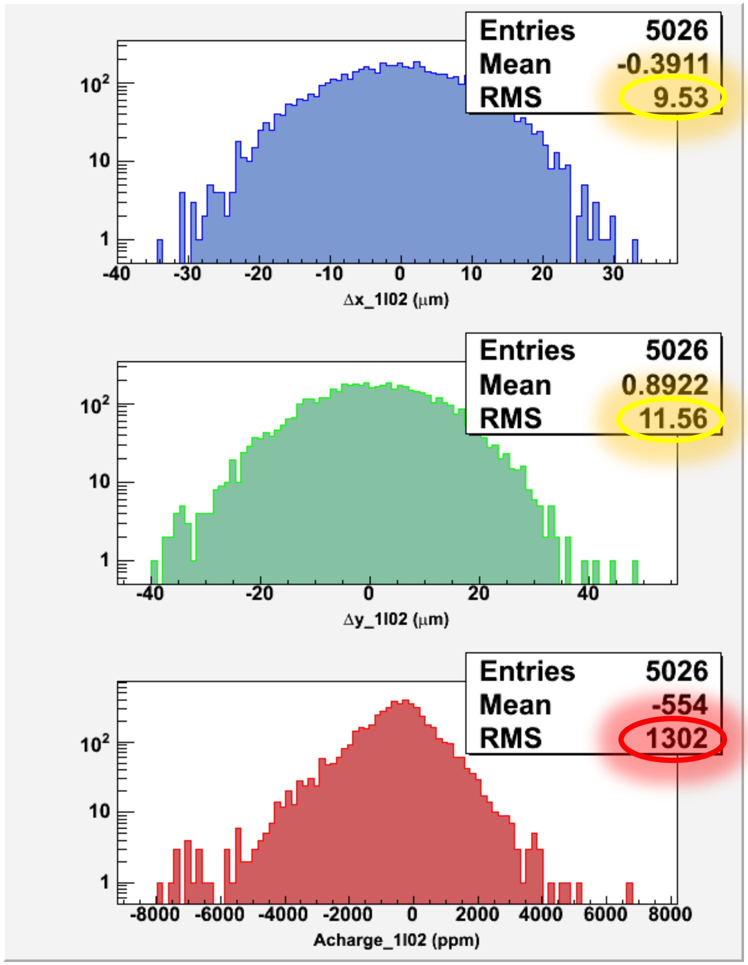
Pockels Cell Fast Helicity Reversal

- **We have been using 30 Hz helicity reversal:**
  I. **Power line 60 Hz frequency is major source of noise in parity experiments**
  II. **For 30 Hz reversal, T_Stable (= 33.333 ms) contains exactly two cycles of 60 Hz line noise → this reversal cancels line noise**

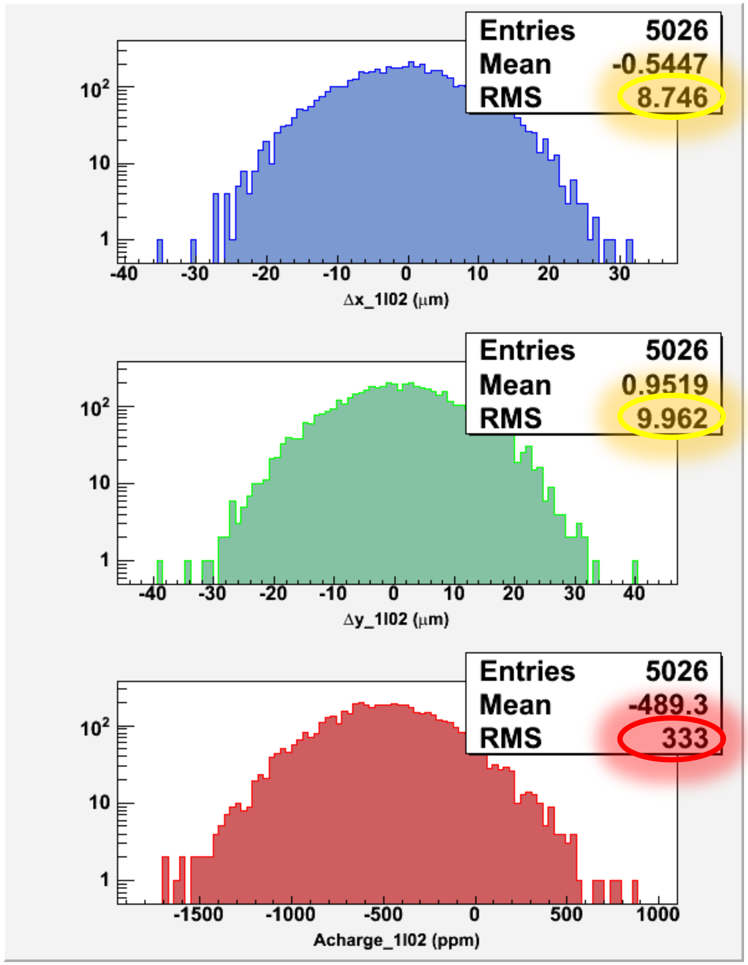
- **However:**
  - **There are other sources of noise at low frequencies, *i.e.*, target density fluctuations, beam current fluctuations**

    → Cause larger widths of helicity correlated distributions, double-horned distributions

- **Solution: Use faster helicity reversal (faster than 30 Hz)**



30 Hz, T_Stable = 33.333 ms, T_Settle = 500 μs



1 kHz, T_Stable = 0.980 ms, T_Settle = 60 μs

- **Summary of Fast Helicity Reversal Studies (Spring 09)**

  - **Faster Helicity Reversal is needed:**
    I. **Reasonable reduction in beam position noise**
    II. **Reduces noise on beam current by factor of 4**
    III. **Huge reduction of noise from target density fluctuations**

  - **Achieved Pockels Cell T_Settle of 60 µs**
  - **Future Parity Experiment:**

Experiment	Frequency	Clock	Pattern
HAPPEx III & PVDIS	30 Hz	Line-Locked	Quartet
PREx	240 Hz	Line-Locked	Octet
QWeak	1 kHz	Free	Quartet

  - **New Helicity Board to be installed in August 2009**

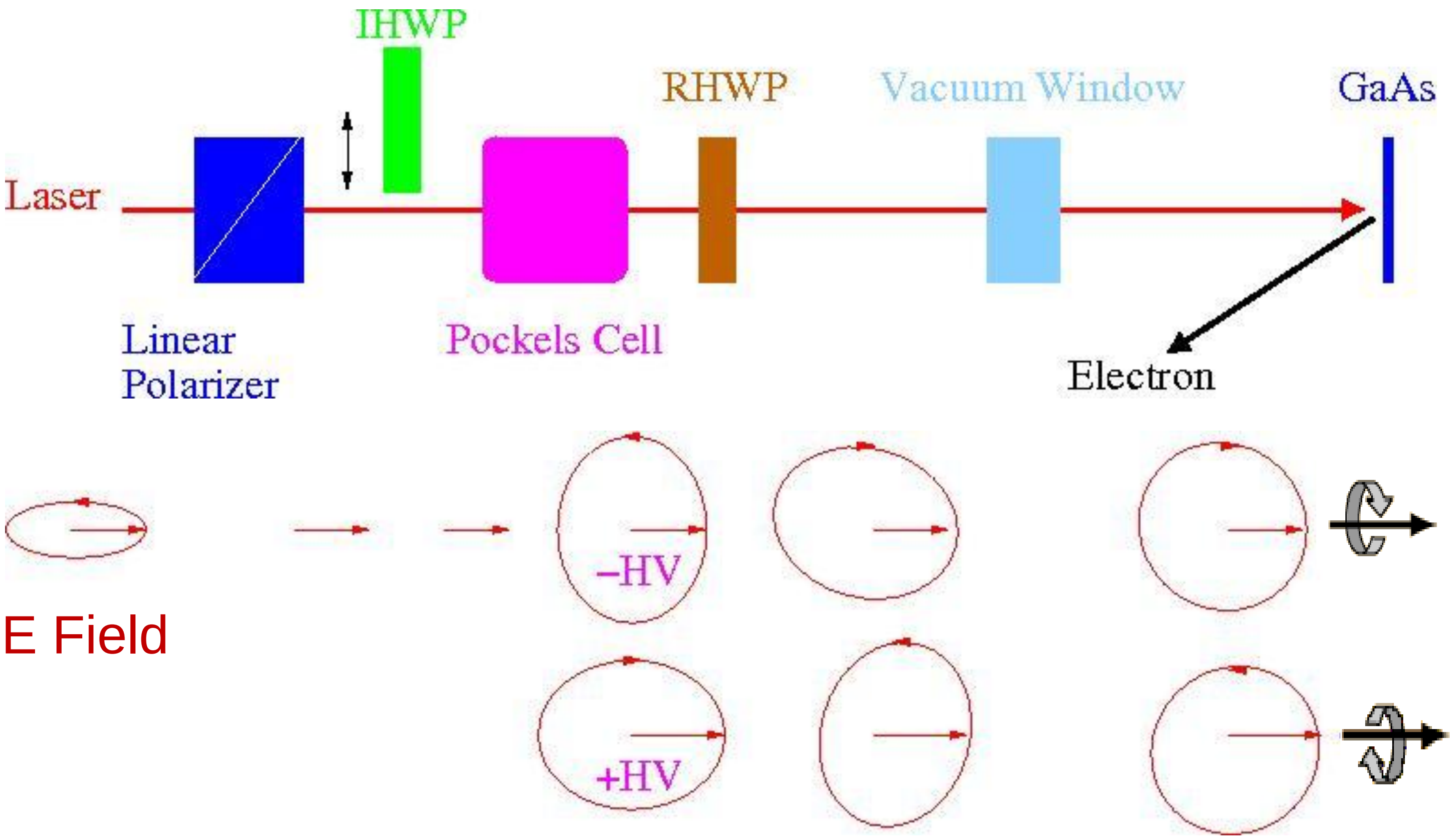
Slow Helicity Reversal

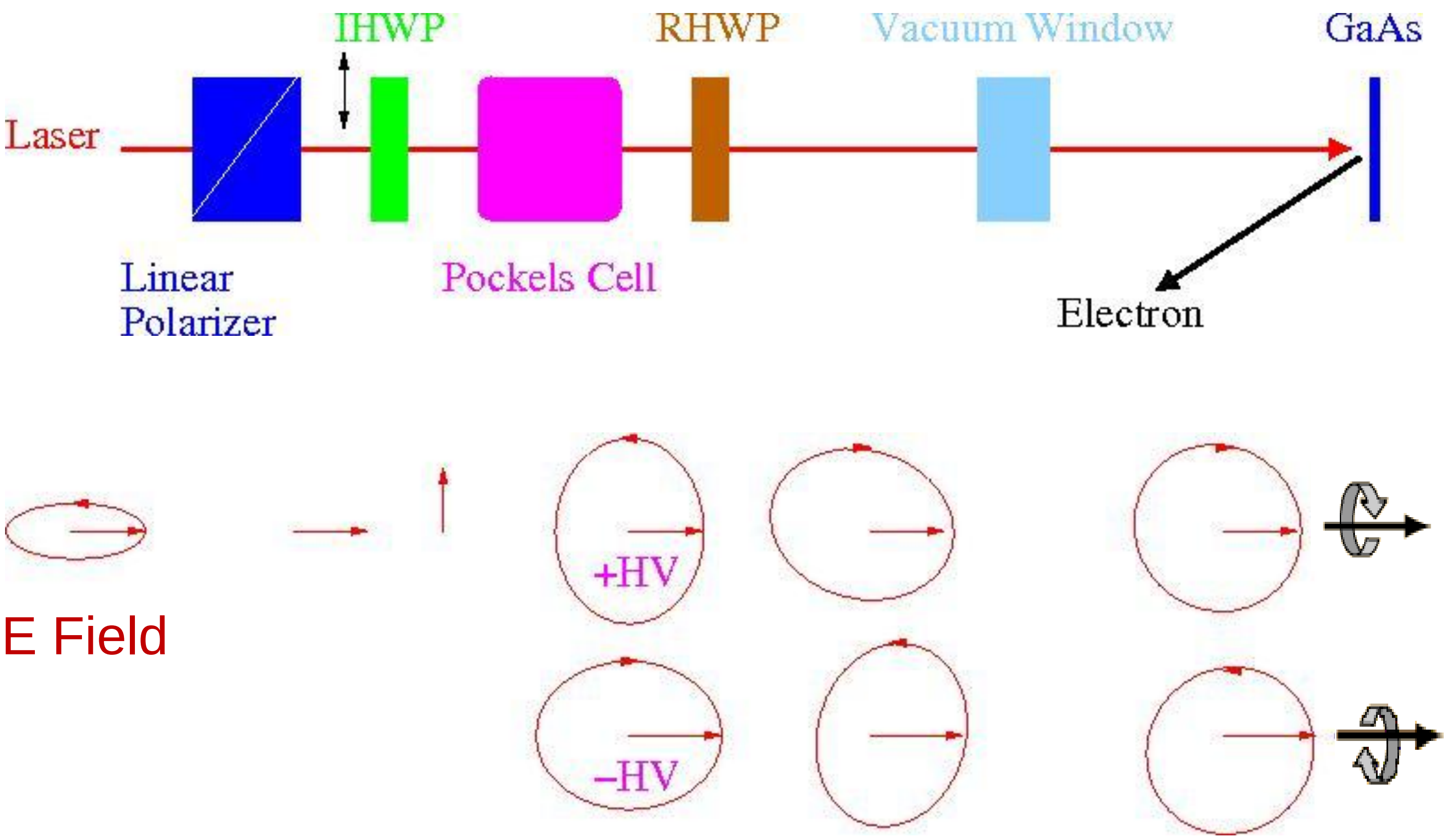
- Slow Helicity Reversal (once a day) reverses the sign of the physics asymmetry. Some false asymmetries do not change sign, thus cancel when combining the data

I. Insertable Half Wave Plate (IHWP) provides slow helicity reversal of laser polarization:
   - ❑ Cancels electronic cross talk and Pockels Cell steering
   - ❑ Residual linear polarization effects do not cancel
   - ❑ Spot size asymmetry, which we cannot measure, does not cancel

II. New: Slow helicity reversal of electron polarization using two Wien Filters and Solenoid:
   - ❑ Cancels all helicity-correlated beam asymmetries from Injector including spot size
   - ❑ Will be installed in Winter SAD, modify beamline from Gun to Chopper

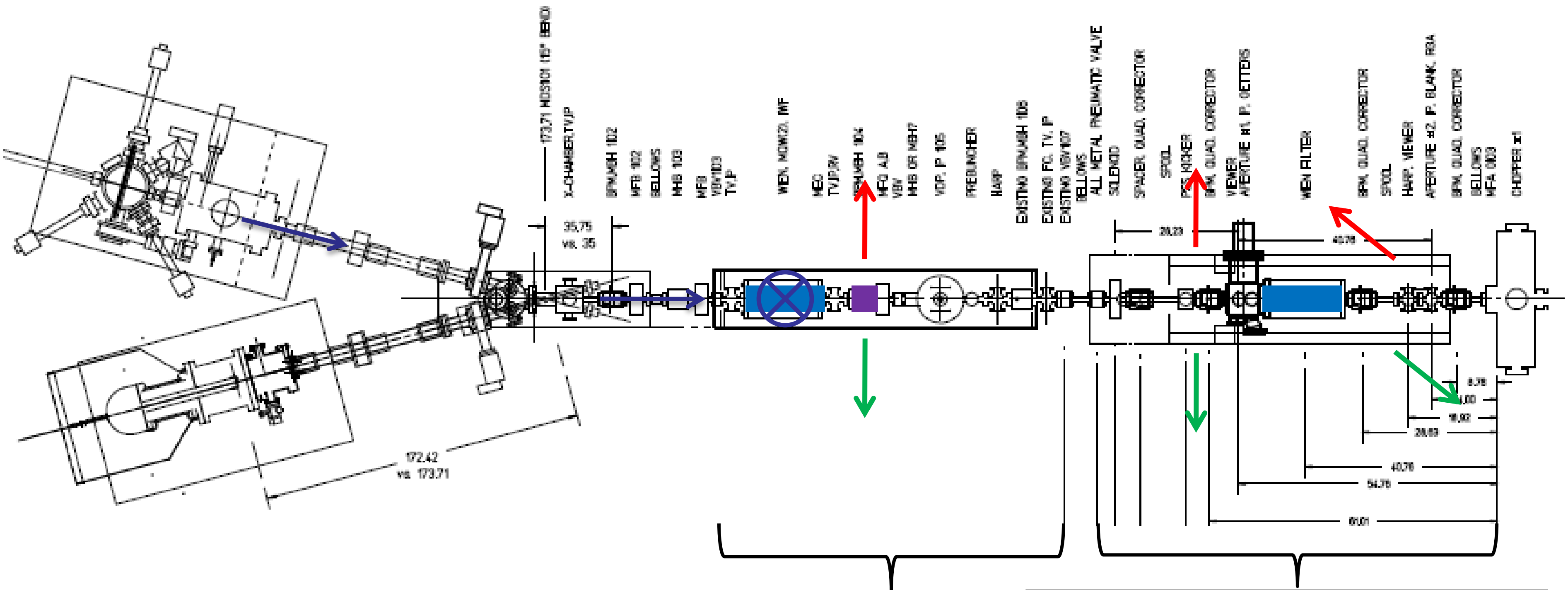
IHWP Slow Helicity Reversal




IHWP
RHWP
Vacuum Window
GaAs
Laser
Linear
Polarizer
Pockels Cell
Electron
E Field
+HV
–HV

Two Wien Slow Helicity Reversal

- Wien settings constant
- Solenoid rotates spin by 90 with B but focuses beam as B^2
  - ➢ Maintain constant Injector and Accelerator configuration



→ (green)	+ Solenoid current
→ (red)	- Solenoid current

"Spin Flipper"
Vertical Wien = 90°
Azimuthal Solenoid = ± 90°

"Long. Pol. for Halls"
Horizontal Wien = -90° → +90°

Parity Beam Requirements

Experiment	Hall	Start	Energy (GeV)	Current (μA)	Target	$A_{physics}$ (ppm)	Maximum Charge Asym (ppm)	Maximum Position Diff (nm)
HAPPEx-III	A	Aug 09	3.484	85	^{1}H (25 cm)	16.9±0.4	1	10
PVDIS	A	Oct 09	6.068	85	^{2}H (25 cm)	63±3	1	10
PREx	A	March 10	1.056	50	^{208}Pb (0.5 mm)	0.500±0.015	0.100±0.010	2
QWeak	C	May 10	1.162	180	^{1}H (35 cm)	0.234±0.005	0.100±0.010	2
Achieved							0.4	1

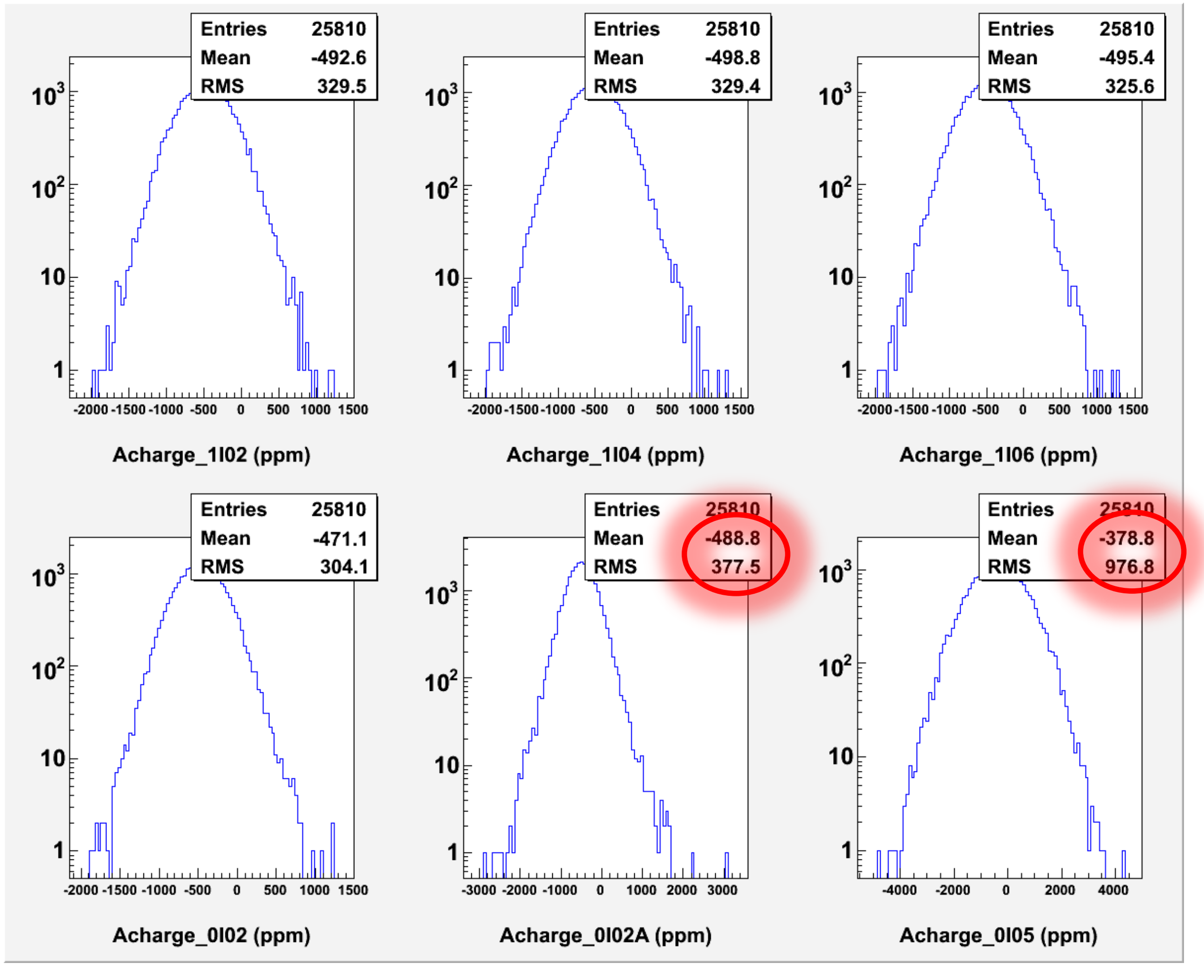
Physics Motivation

- HAPPEx-III: Measure weak charge distribution of strange-quark sea in proton
- PVDIS: Measure weak charges of quarks
- PREx: Measure weak charge distribution of neutrons in Lead (82 protons, 126 neutrons)
- QWeak: Measure weak charge of proton ($1-4\sin^2\theta_W$)

Ops' Responsibilities

- Good transmission in Injector through A1, A2, and MS. Watch the widths of charge asymmetries (will be displayed on Wall)
- Low beam halo in Compton Polarimeter
- Alarm Handler:
  - I. Pockels Cell ON
  - II. Helicity Board settings
  - III. IHWP IN/OUT

• Example of bad transmission through Master Slit



Users' Responsibilities

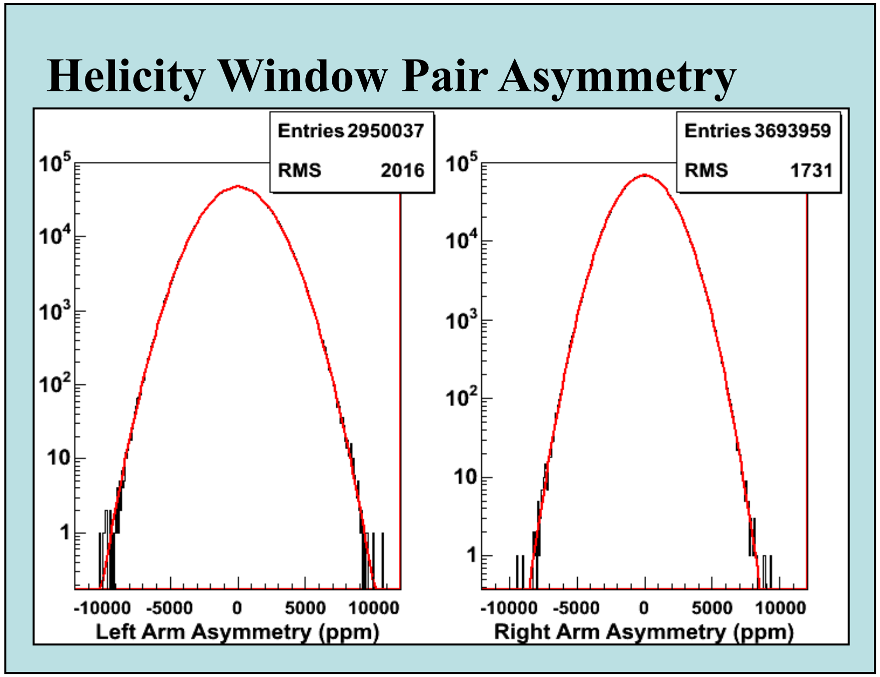
- Pockels Cell alignment
- Charge Feedback: Channel Access to IA or Pockels Cell Voltages. Note: Each Hall has its own IA but the Pockels Cell is common to three Halls. Hall A will also do charge feedback on Hall's C charge asymmetry and vise versa.
- Position Feedback (if needed)
- Will turn off Fast Feedback (FFB) when doing Coil Modulation

Summary

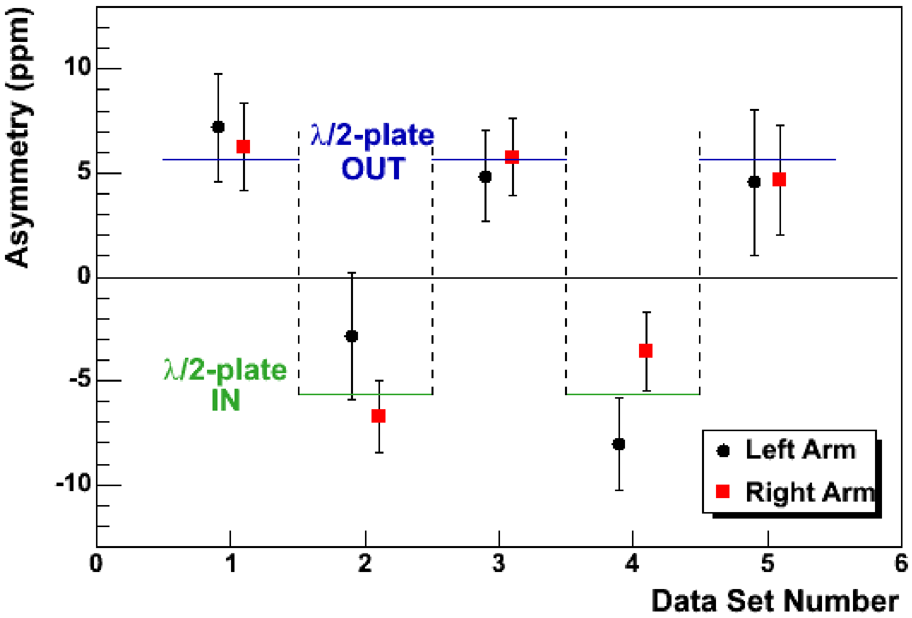
- The success of parity violation experiments depends mainly on achieving "PQB"
- Jefferson Lab is an ideal place for parity violation experiments
- We are getting better with many improvements in "PQB"
- Looking forward for even more demanding parity violation experiments at 12 GeV

Backup Slides

^{4}He Results



Helicity Window Pair Asymmetry
Entries 2950037
RMS 2016
Entries 3693959
RMS 1731
Left Arm Asymmetry (ppm)
Right Arm Asymmetry (ppm)



Asymmetry (ppm)
λ/2-plate OUT
λ/2-plate IN
Left Arm
Right Arm
Data Set Number