Parity Violation Experiments

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thanks to the HAPPEX, G0 and Qweak Collaborations,
D. Armstrong, E. Beise, G. Cates, E. Chudakov, D. Gaskell, C. Furget, J. Grames,
B. Humensky, D. Lhuillier, R. Michaels, K. Paschke, M. Pitt, P. Souder, R. Suleiman

User Group Symposium and Annual Meeting

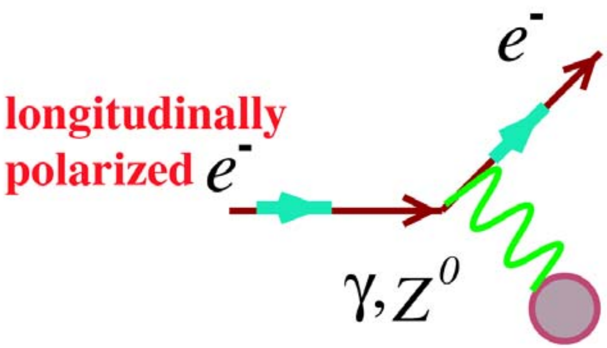
A Celebration of CEBAF Physics:
Highlights of the First Seven Years

June 12 2003

Outline

- Experimental Program
- Measuring Small Asymmetries
- Technical Highlights
- HAPPEX Result
- Recent Progress
- Outlook

Weak-Electromagnetic Interference



$$\sigma \;\alpha\; |A_\gamma + A_{weak}|^2$$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}$$

$$Q^2 \sim 0.01 - 1\ \text{GeV}^2 \longrightarrow A_{PV} \lesssim 10^{-7} - 10^{-4}$$

Historical Perspective

$\delta A \sim 10^{-6}$ → $\sim 10^{12}$ events → 100 kHz

SLAC
C.Y. Prescott et.al.
1978

SLAC E122 pioneered techniques:

* Rapid helicity flips (optical pumping)
* Integrate scattered flux
* monitoring, calibration, control of electron beam fluctuations

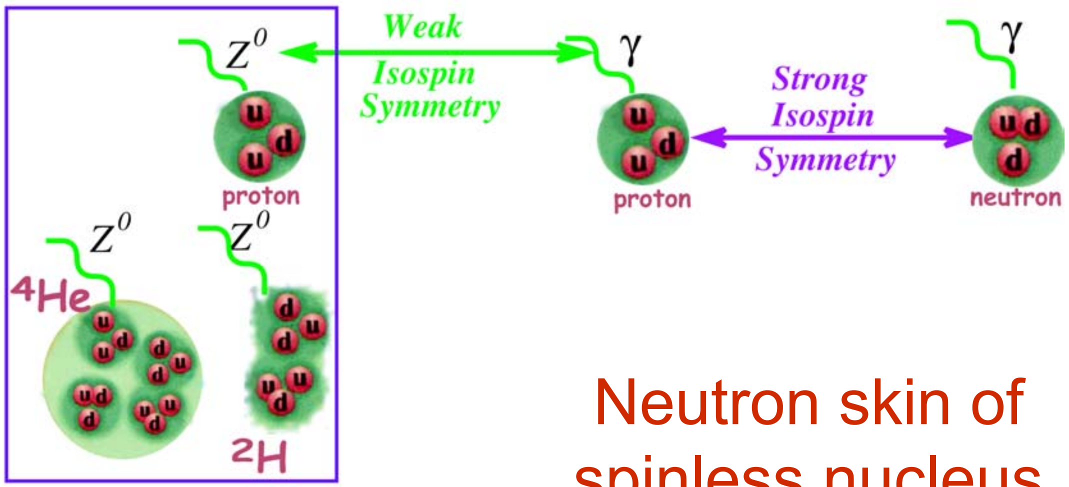
C. Sinclair et. al.

$\delta A \sim 10^{-7}$

Mainz
W. Heil et.al.
1989

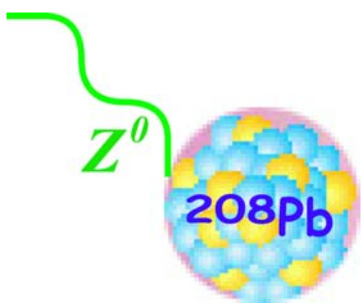
MIT-Bates
P.A. Souder et.al.
1990

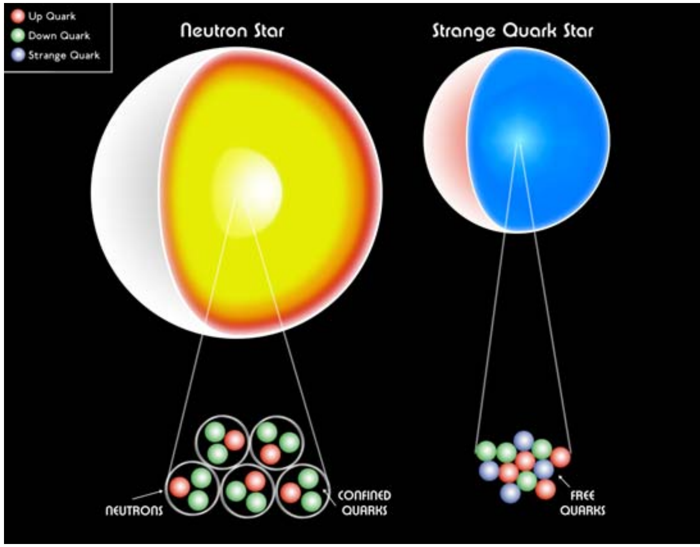
Physics Overview

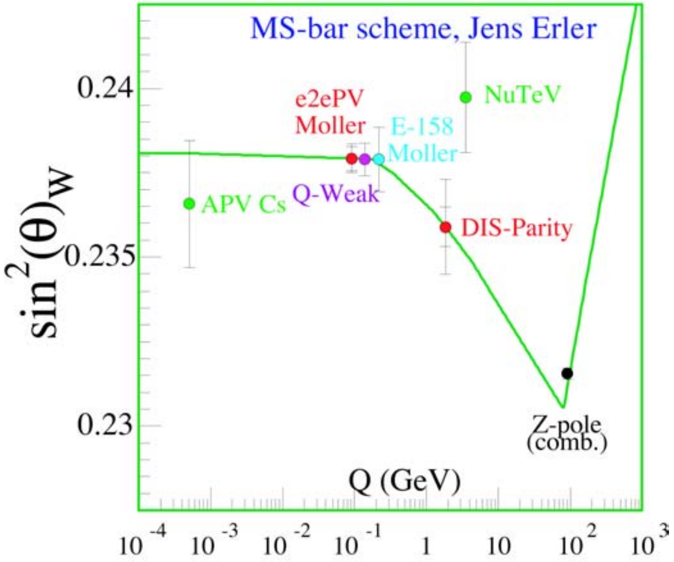


Strangeness content of the nucleon

Neutron skin of spinless nucleus







New physics at the TeV Scale

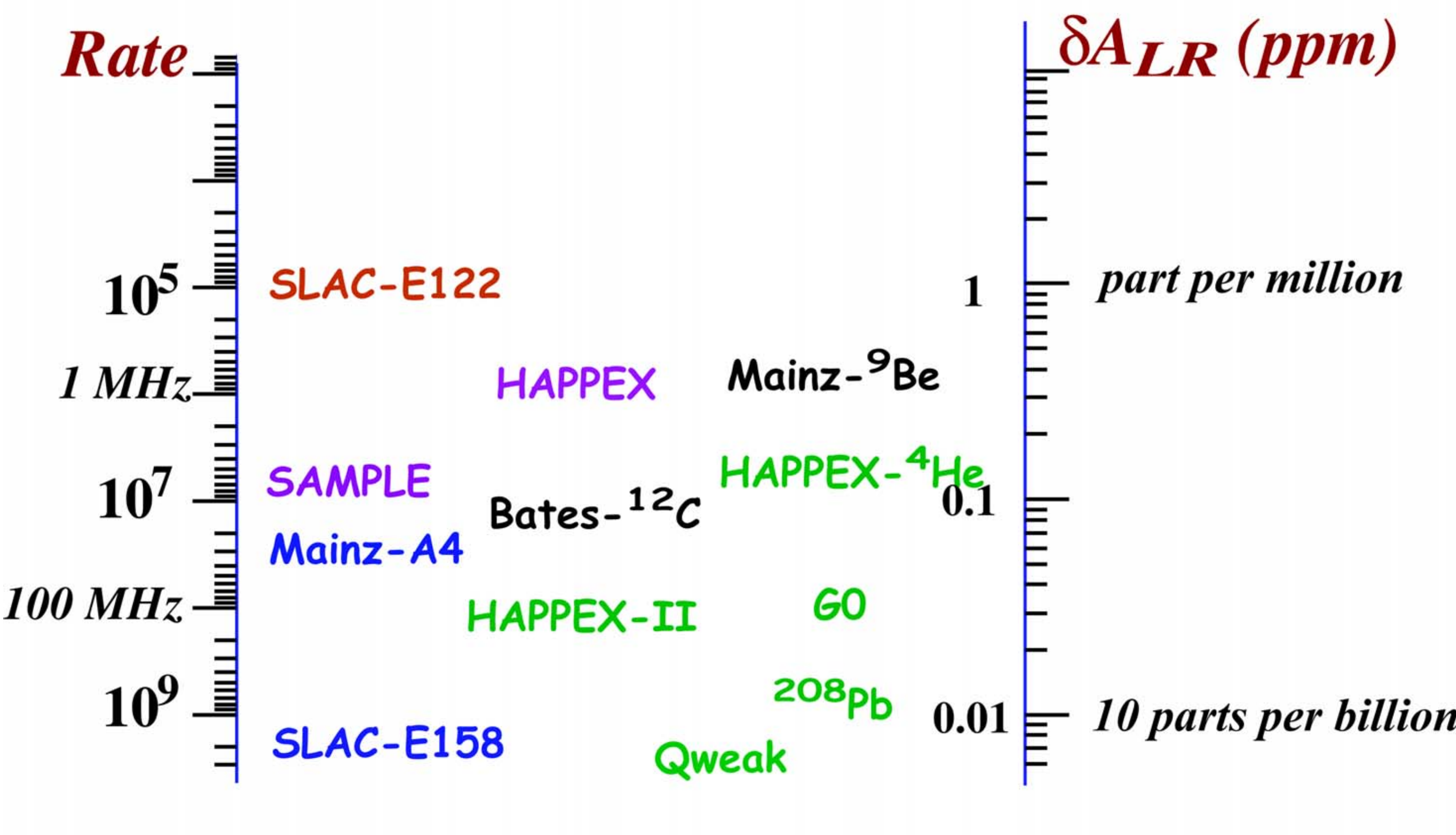
World Program

Lab/Expt	target	Q^2 GeV^2	A_{phys} ppm	Sensitivity	Status
MIT-Bates					
- SAMPLE	H_2	0.10	8.0	$\mu_s + 0.4 G_A^Z$	published
- SAMPLE-II	D_2	0.10	8.0	$\mu_s + 2.0 G_A^Z$	published
- SAMPLE-III	D_2	0.04	3.0	$\mu_s + 3.0 G_A^Z$	completed
JLab Hall A					
-HAPPEX	H_2	0.47	15.0	$G_E^s + 0.39 G_M^s$	published
-HAPPEXII	H_2	0.11	1.5	$\rho_s + \mu_p \mu_s$	2004
-Helium-4	^4He	0.11	10.0	ρ_s	2004
-Helium-4	^4He	0.60	50.0	G_E^s	unscheduled
-Lead-208	^{208}Pb	0.01	0.5	neutron skin	2005
Mainz					
- A4	H_2,D_2	0.1-0.25	1.0-10.0	G_E^s, G_M^s	running
Jlab Hall C					
- G0	H_2,D_2	0.1-1.0	1.0-30.0	G_E^s, G_M^s	2003
- Qweak	H_2	0.03	0.3	Qw	2007
SLAC					
- E158	H_2	0.02	0.2	Qw	running

Jefferson Lab Program

- Hall A
  - **HAPPEX**
    - *$Q^2 = 0.5$ GeV^2, published*
  - **HAPPEX-H & HAPPEX-He**
    - *$Q^2 = 0.1$ GeV^2, separate G_E and G_M, 2004*
  - **HAPPEX-Pb**
    - *$Q^2 = 0.01$ GeV^2, neutron skin, ~2005*
- Hall C
  - **G0**
    - *$Q^2 = 0.2$ - 1.0 GeV^2, separate G_E and G_M, 2003-2006*
    - *Axial and transition form factors*
  - **Qweak**
    - *$Q^2 = 0.03$ GeV^2, search for TeV physics, ~2007*

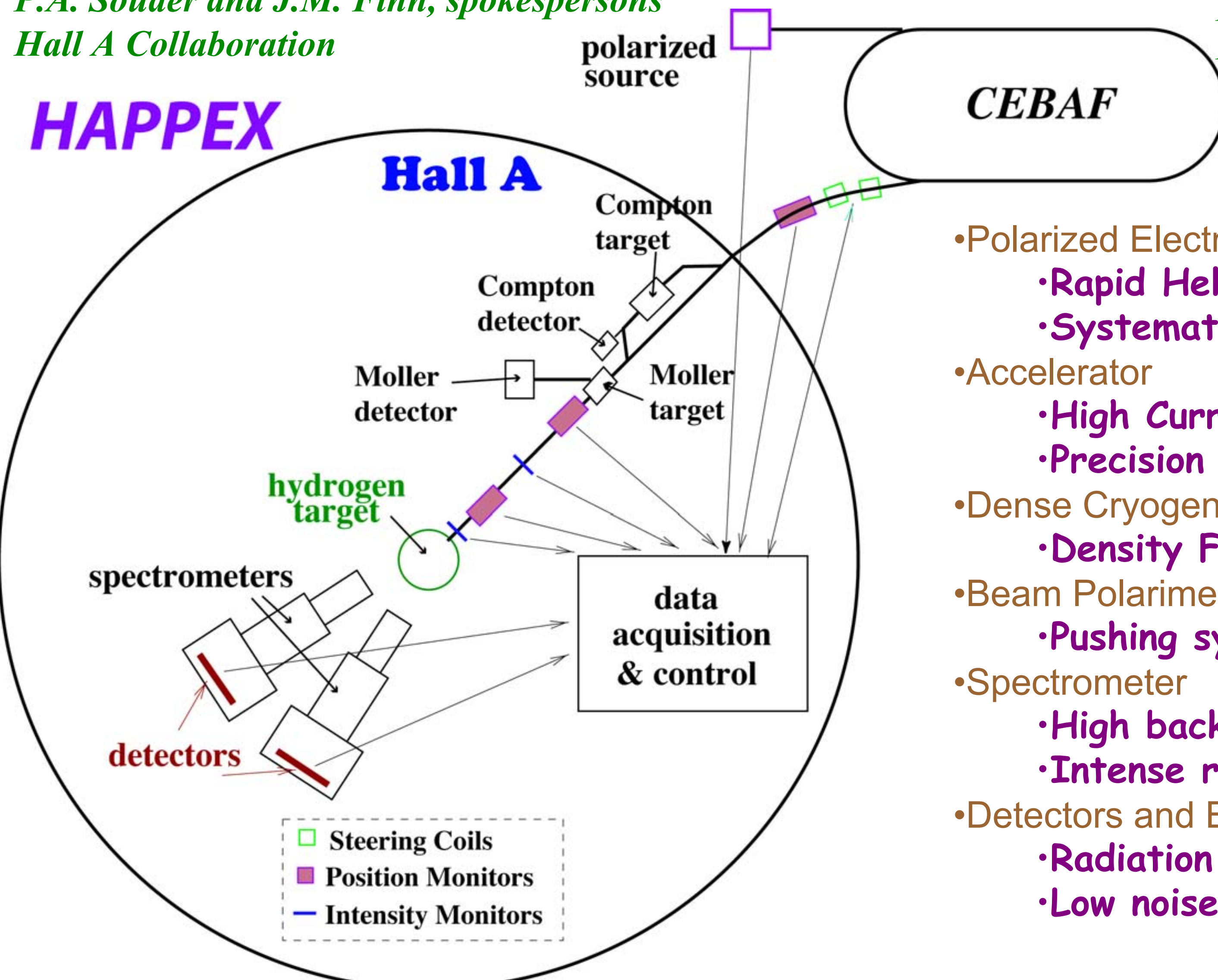
Faster, Smaller….



Experimental Overview

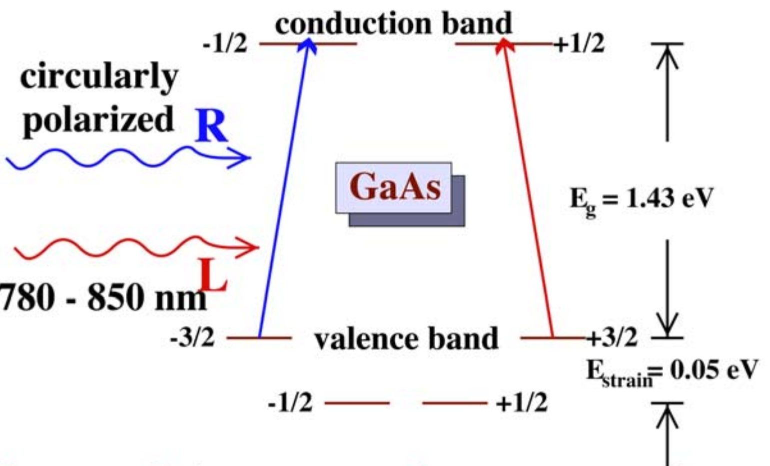
P.A. Souder and J.M. Finn, spokespersons
Hall A Collaboration

Phys. Rev. Lett. 82, 1999 (1096)
Phys. Lett. B. 509, 2001, (211)



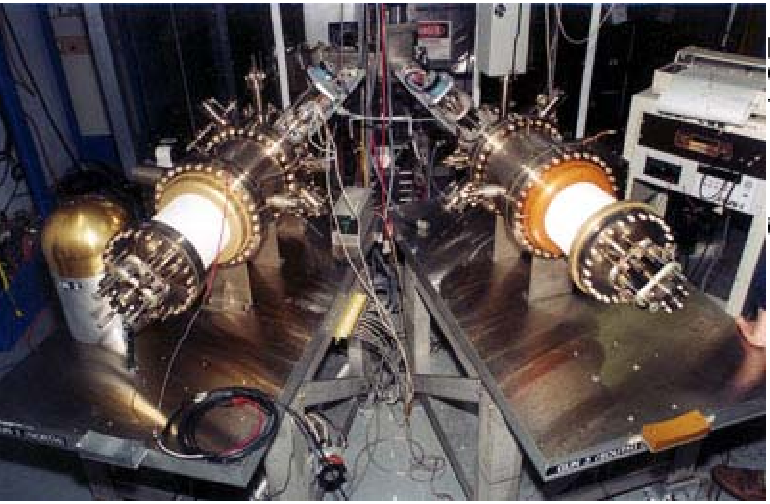
- Polarized Electron Source
  - Rapid Helicity Flips
  - Systematic Control
- Accelerator
  - High Current & Low Jitter
  - Precision Monitoring
- Dense Cryogenic Target
  - Density Fluctuations
- Beam Polarimetry
  - Pushing systematic limits
- Spectrometer
  - High background rejection
  - Intense radiation environment
- Detectors and Electronics
  - Radiation Hardness
  - Low noise and high speed

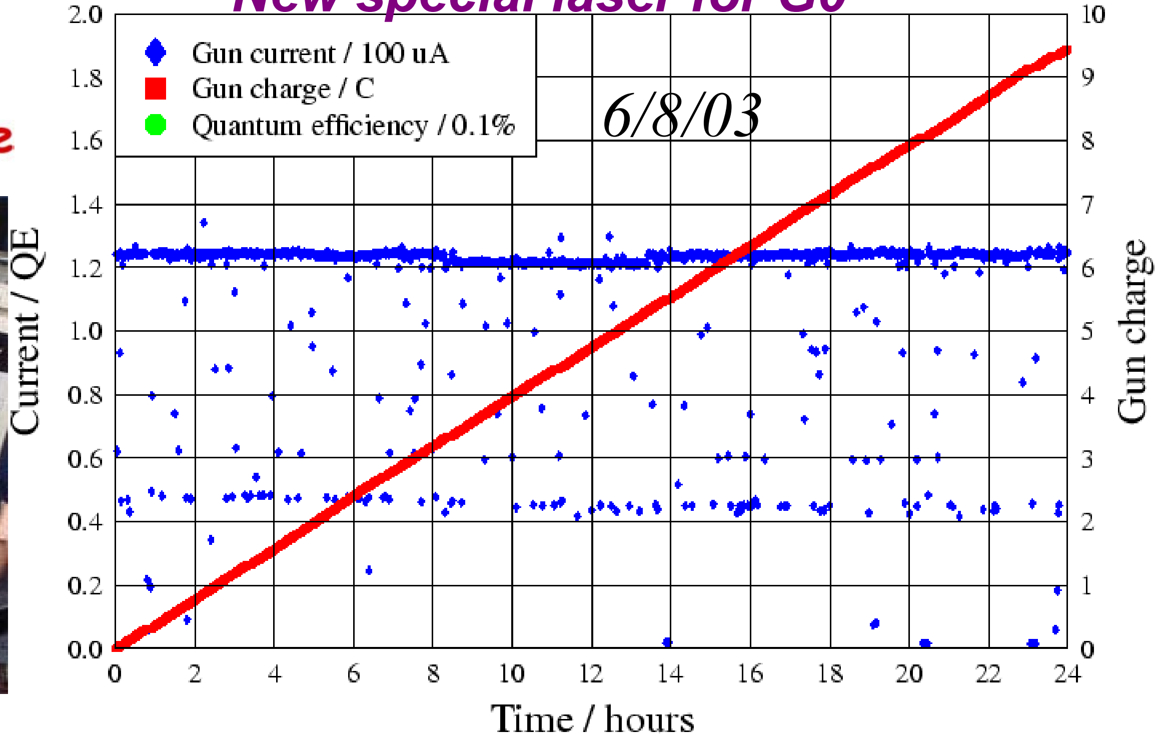
Polarized Electrons



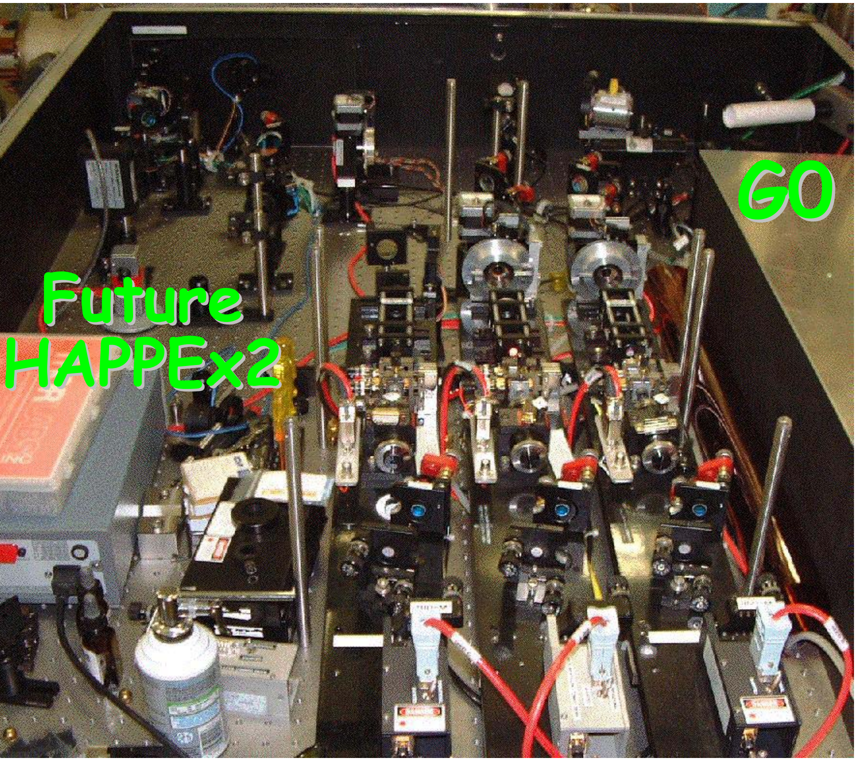
"strain" boosts polarization, but introduces anisotropy in response

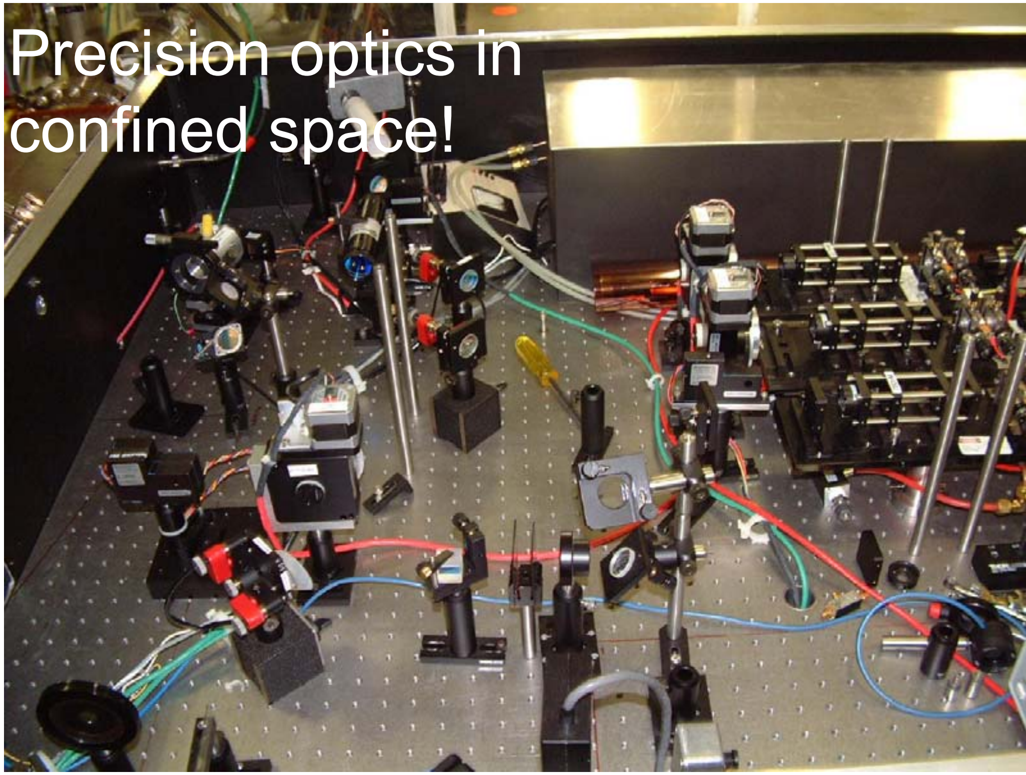
- Polarization ~ 75-80%
- Lifetime ~ 200 C
- Uninterrupted ~ 5 days
- 230 μA max, 120 μA typical
- 40 μA at Pe ~70% to HAPPEX
- New laser to provide ~ 100 μA
- New special laser for G0





Lasers and Optics

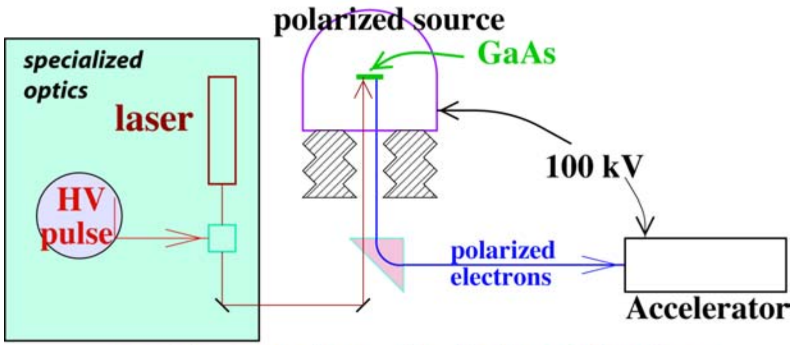




Parity Violation Experiments present special challenges:

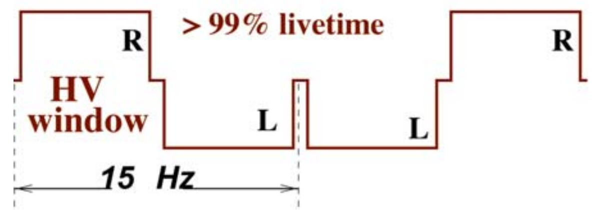
- *High Current AND High Polarization*
- *Pulsed to match beam requirements: 499 MHz, 31 MHz*
- *"Parity Considerations": close collaboration with Source Group*

The Raw Asymmetry



rapid, random, helicity flipping

Rapid, Random Helicity Flips

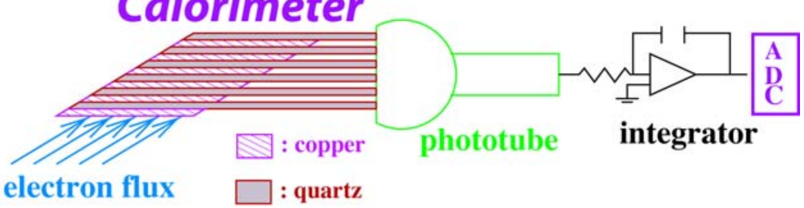


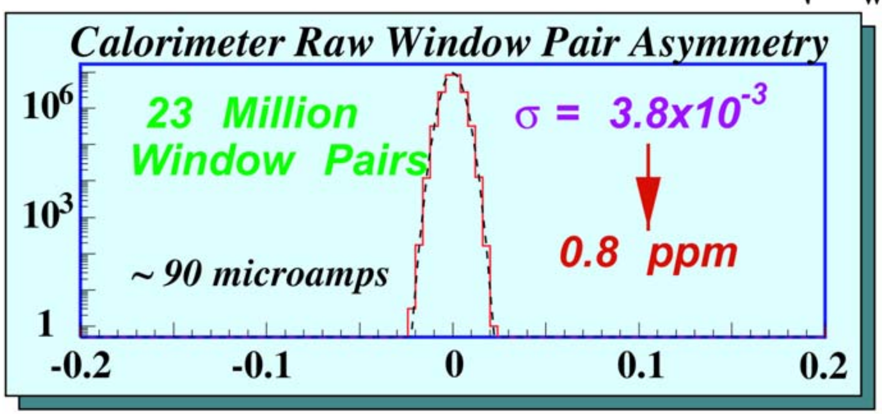
Measure flux F for each window

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

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

Flux Integration Technique:
HAPPEX: 2 MHz
Qweak: 6 GHz





No non-gaussian tails to +/- 5σ

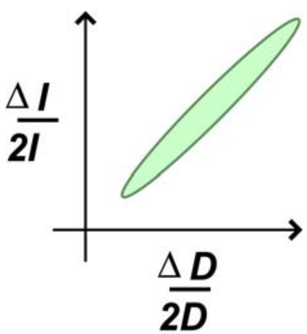
Random Fluctuations

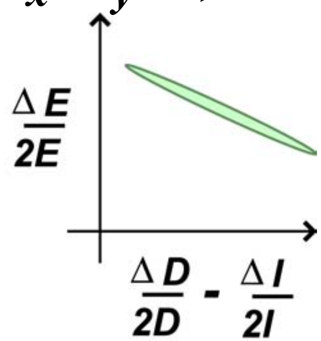
D: PMT response

I: Intensity

***F**: Scattered Flux = D/I*

$$F = f\,(X, Y, \theta_x, \theta_y, E)$$





Expt	σ(ppm) at 15 Hz
HAPPEX	3800
HAPPEX-He	1100
HAPPEX-H	350
HAPPEX-Pb	100
Qweak	50

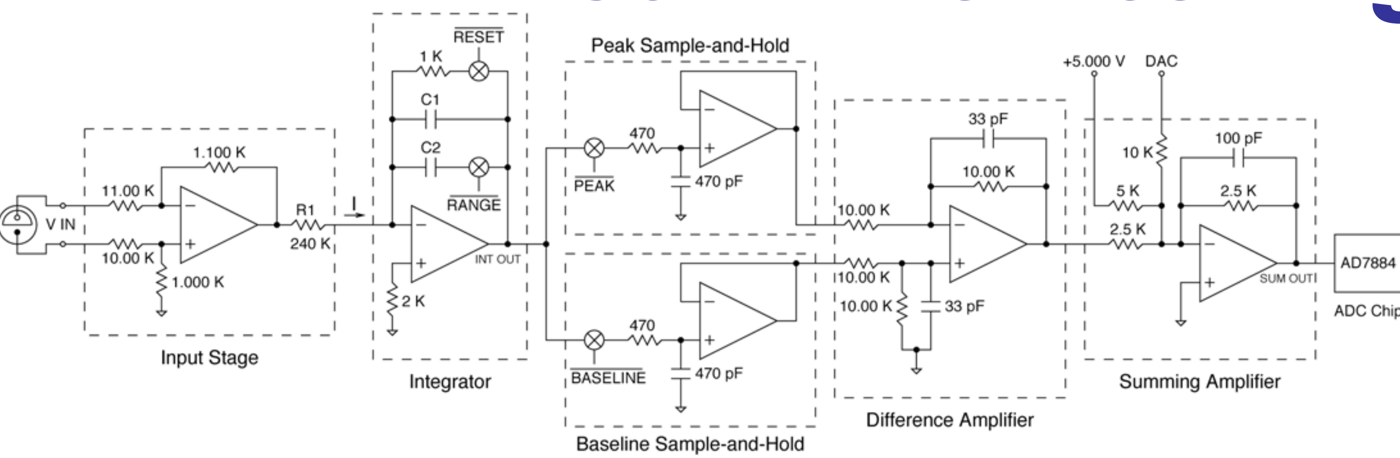
$$A_{\substack{window\\pair}} \equiv \frac{F_R - F_L}{F_R + F_L} \cong \frac{\Delta D}{2D} - \frac{\Delta I}{2I} + \sum_i \alpha_i \cdot \Delta X_i$$

Jitter (ppm)	**1000**	**400**
Accuracy	**40**	**150**

Jlab beam characteristics naturally leads to small jitter!

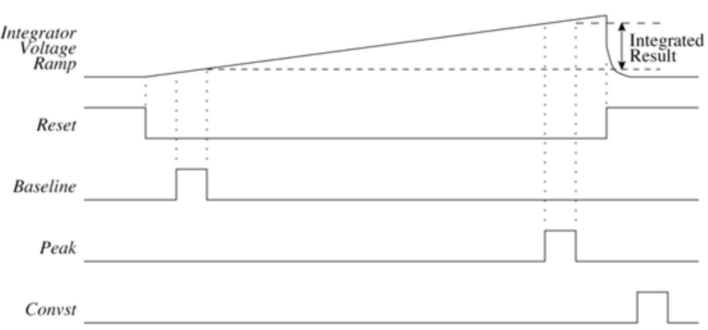
low noise instrumentation

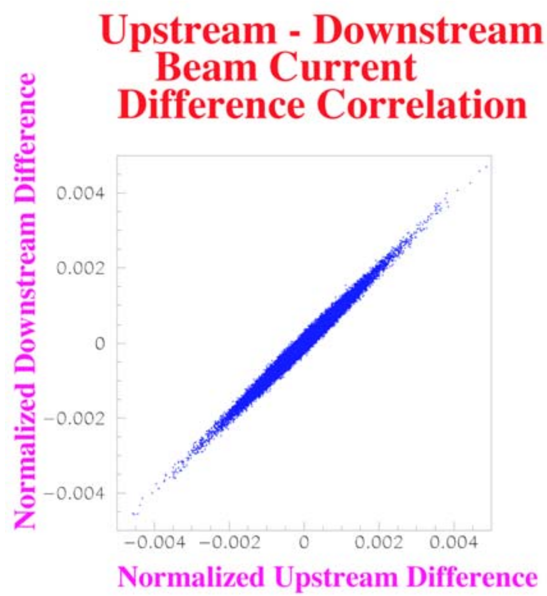
Beam Monitoring

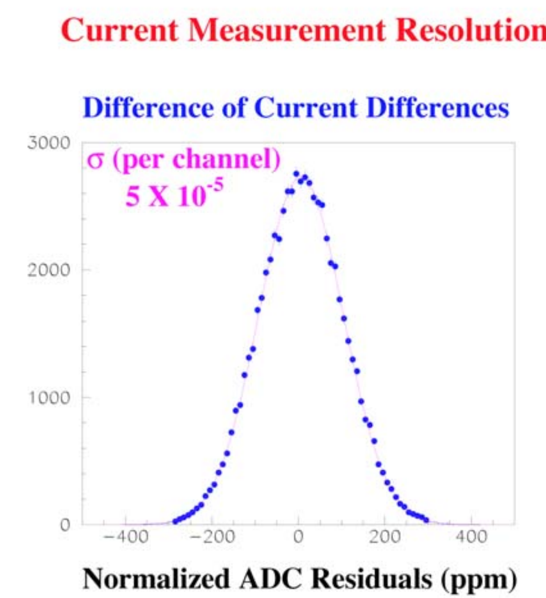


HAPPEX
16 bit ADC:
≤ 200 μV noise

Analog input → **integrator** → **Sample/hold** → **Difference** → **ADC chip**

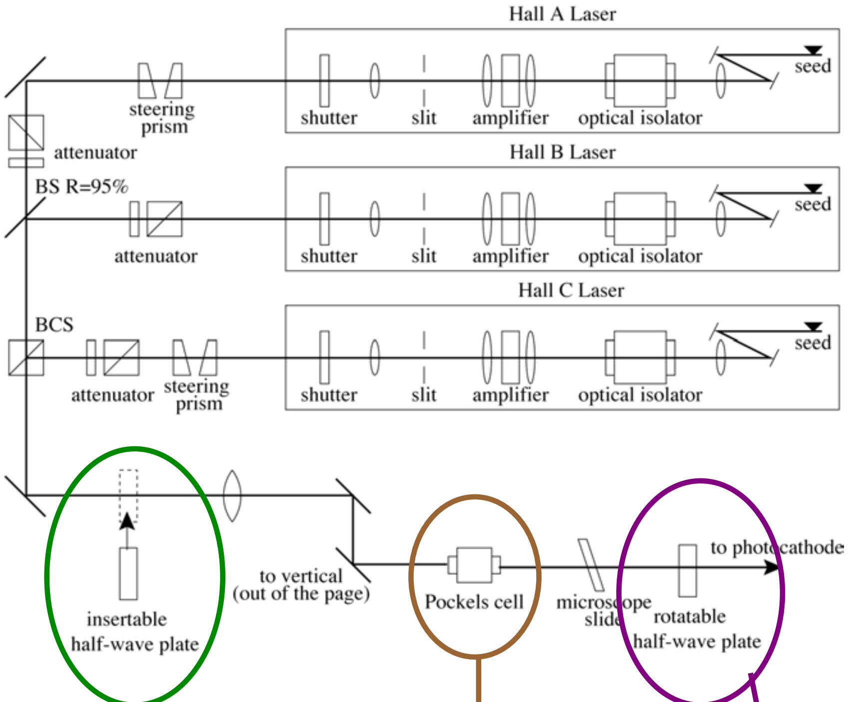




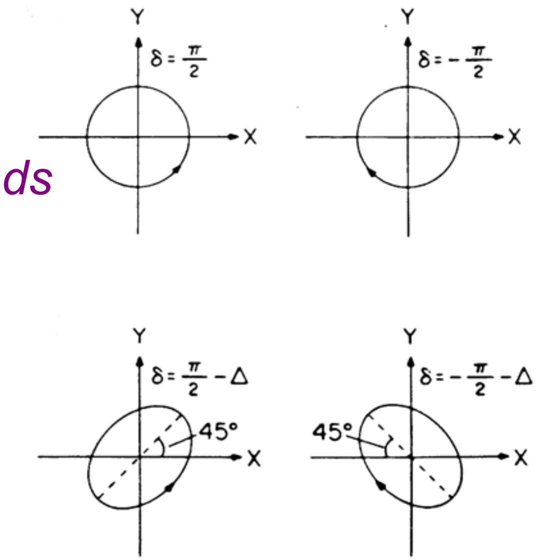


Early tests ~ 1996-97

Systematic Fluctuations



Small imperfections in laser light properties: Extracted charge depends on helicity at level of 0.01 % (100 ppm)



Subtler effects responsible for beam centroid differences ~ 0.00001 m (10 μm)

$$A_{window} \equiv \frac{F_R - F_L}{F_R + F_L} \cong \frac{\Delta D}{2D} - \frac{\Delta I}{2I} + \sum_i \alpha_i \cdot \Delta X_i$$

Circular polarization

Flip circular polarization

Rotate linear polarization

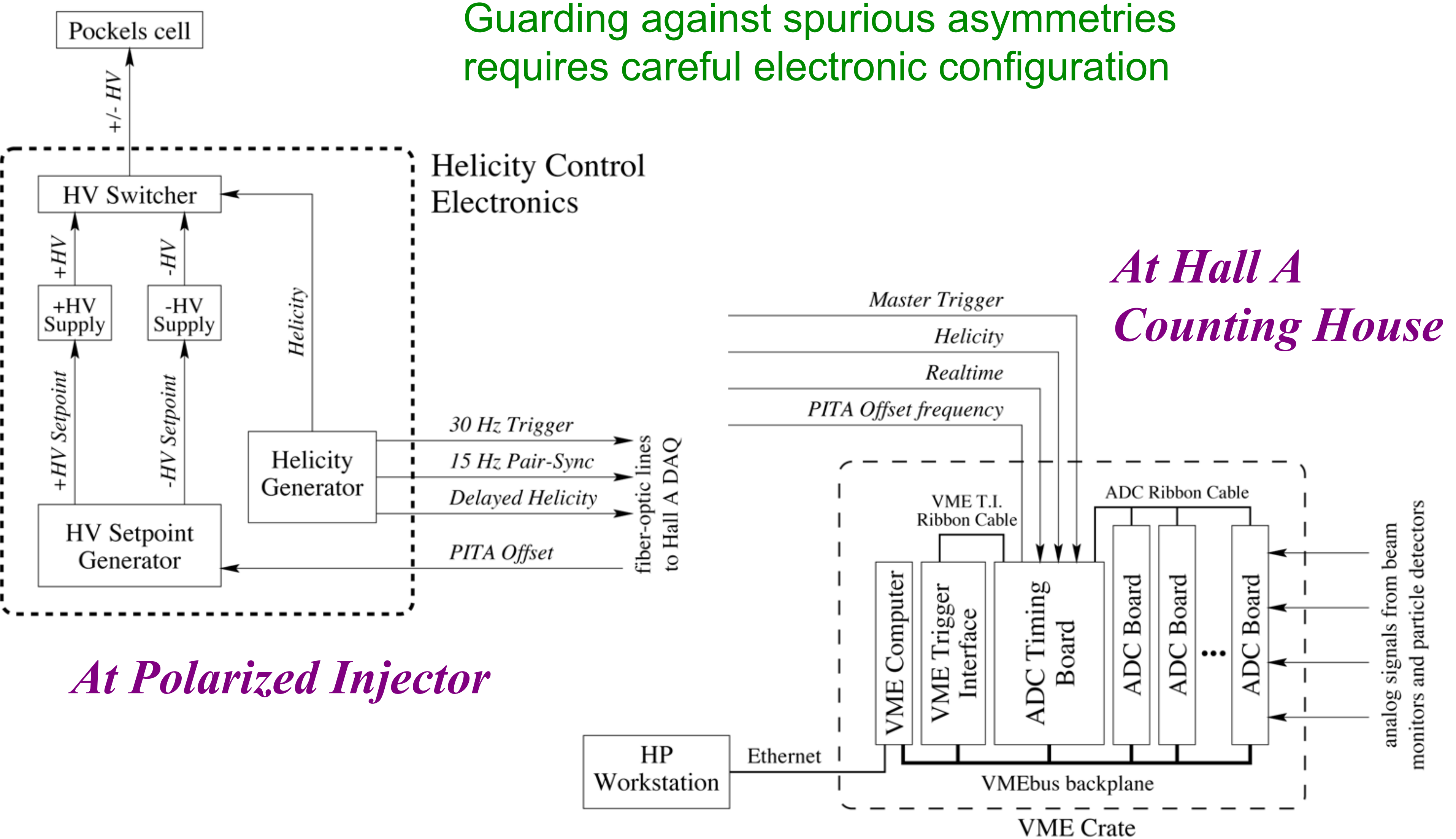
Correction (ppm)	***1.0***	***0.1***
Accuracy	***<0.05***	***<0.1***

Happex achieved ~ 20 nm

Future experiments need ~ 1 nm!

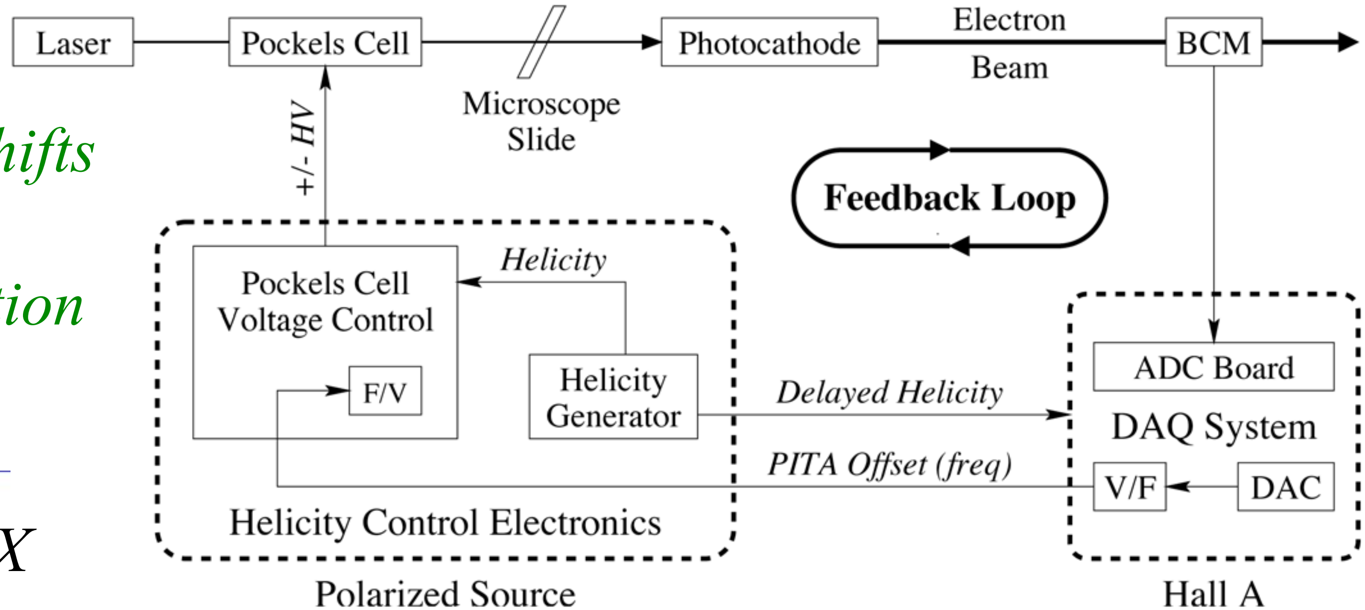
HAPPEX Electronics

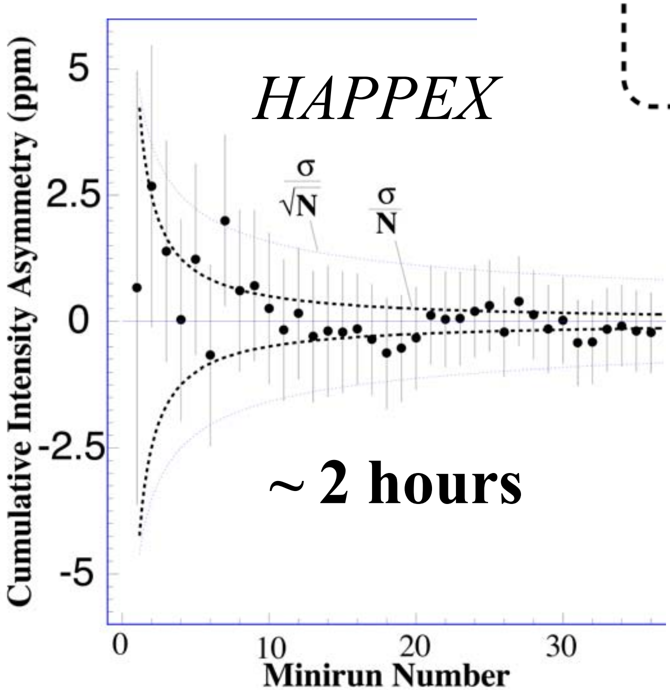
Guarding against spurious asymmetries requires careful electronic configuration



Intensity Feedback

Adjustments for small phase shifts to make close to circular polarization





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

In practice, aim for 0.1 ppm over duration of data-taking.

Systematic Position Fluctuations

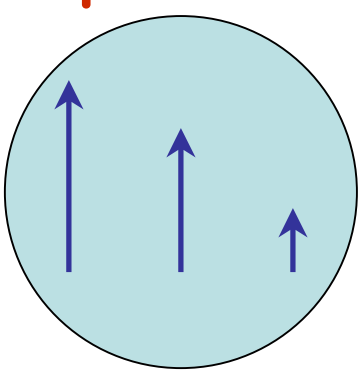
Strained GaAs has 10% analyzing power for linearly polarized light

Careful optics alignment:
1 μm centroid differences

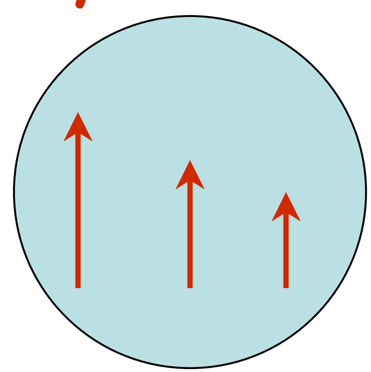
1% linear component x
10% analyzing power:
1000 ppm charge asymmetry

"Brute force" position feedback would rely on over 3 orders of magnitude suppression

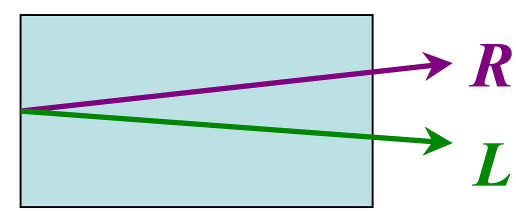
3 important sources of systematic position differences:



photocathode analyzing power



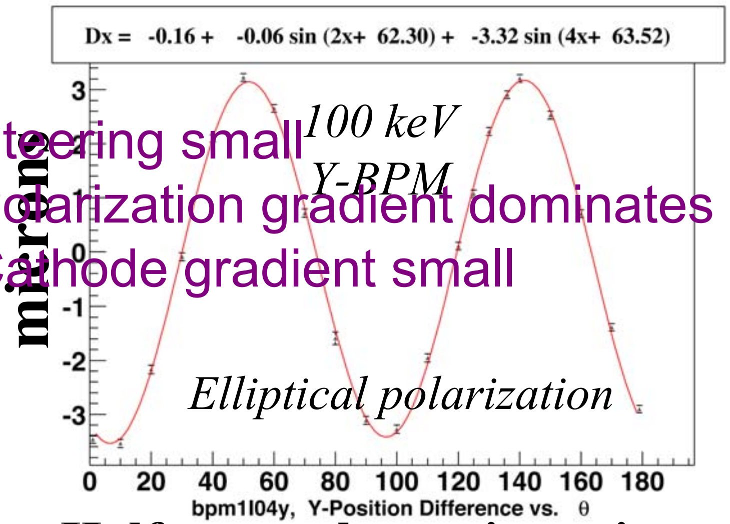
Laser beam linear polarization



Pockels Cell steering

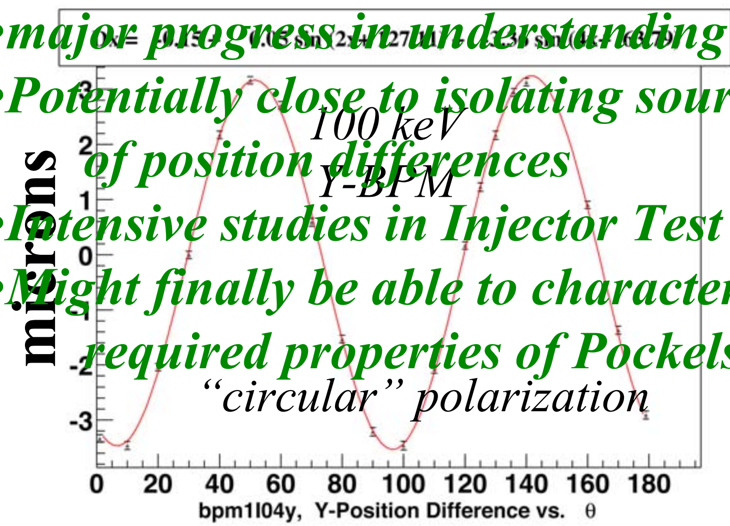
Recent Progress

Data taken during MD, 4/25/03

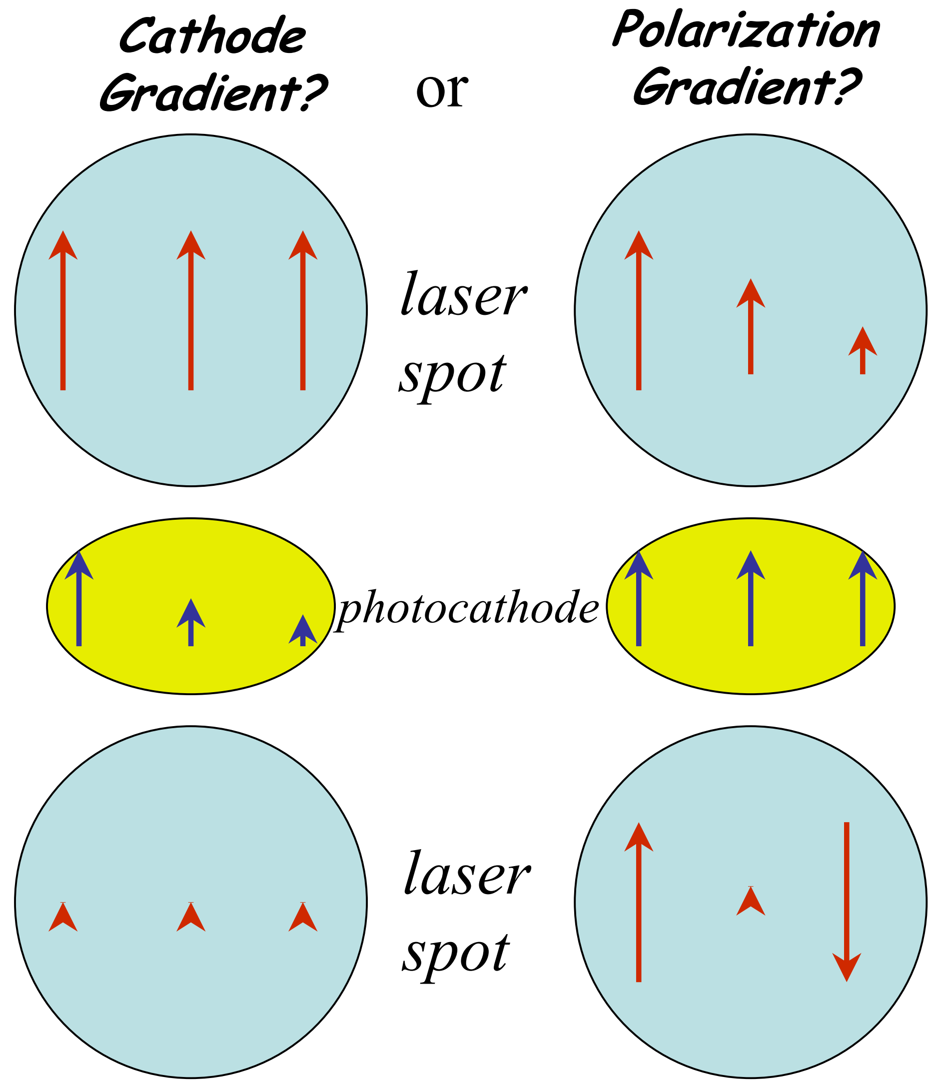


- Steering small
- Polarization gradient dominates
- Cathode gradient small

Half-wave plate orientation

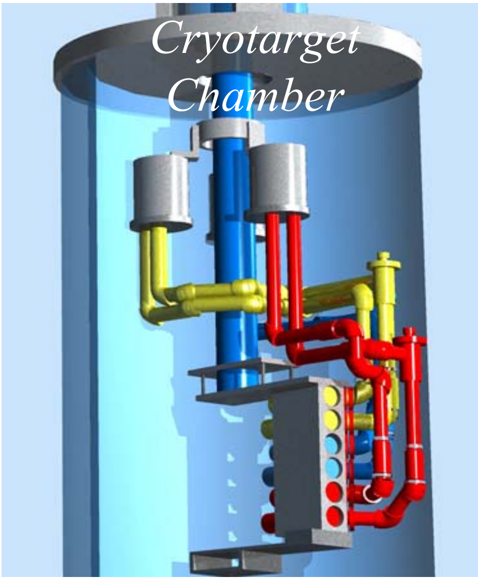


- ***major progress in understanding***
- ***Potentially close to isolating sources of position differences***
- ***Intensive studies in Injector Test Lab***
- ***Might finally be able to characterize required properties of Pockels cell***



Cryogenic Targets

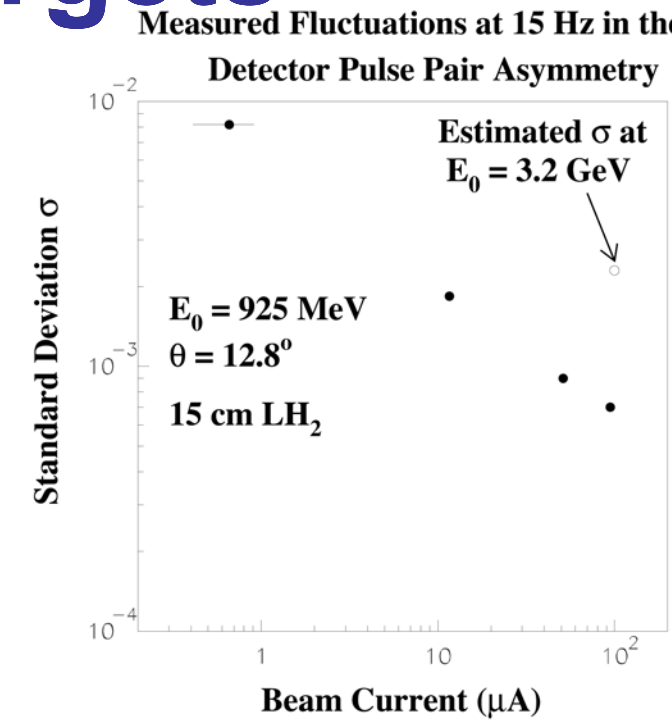
Hall A Cryotarget Chamber

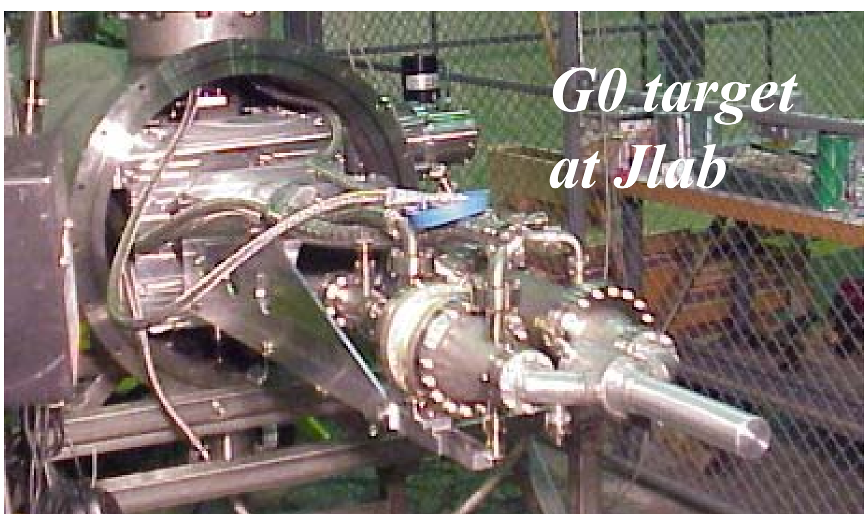


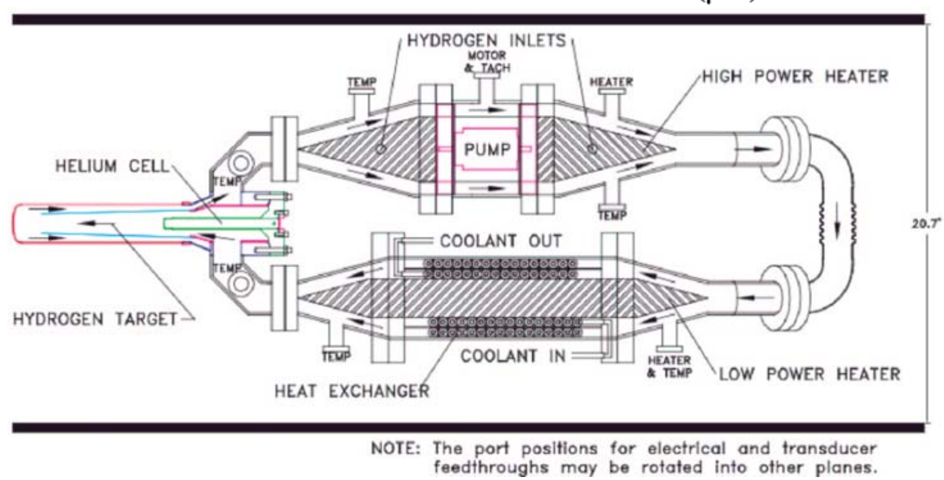
HAPPEX:
15 cm "beer can"

Density fluctuations: less than 200 ppm at 15 Hz

Statistics: 3800 ppm

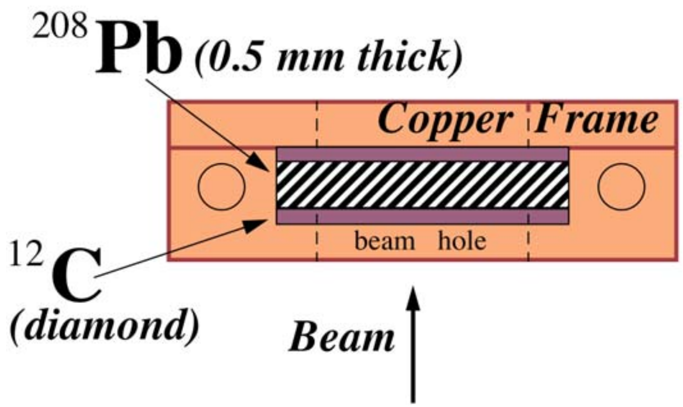






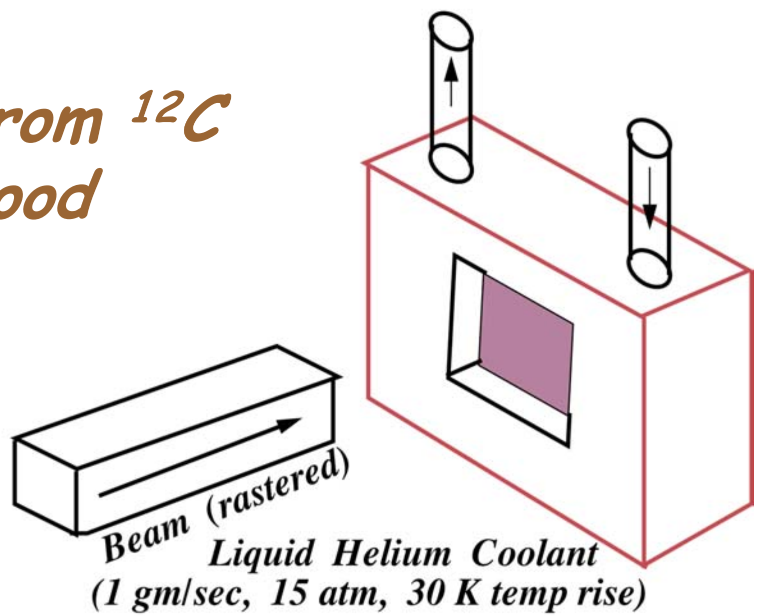
High Power Lead Target

40 Watts dissipated by 50 μA



Diamond has high thermal conductivity

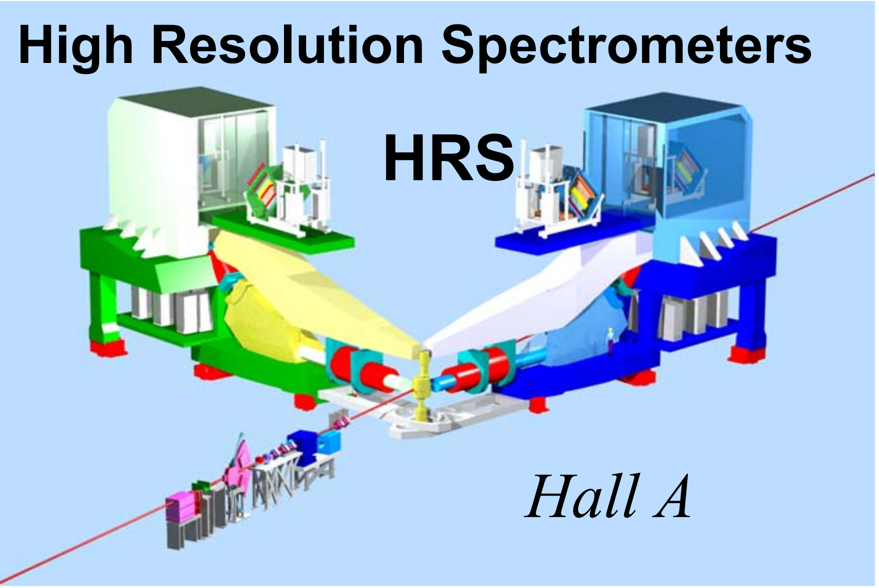
Scattering from ^{12}C well-understood

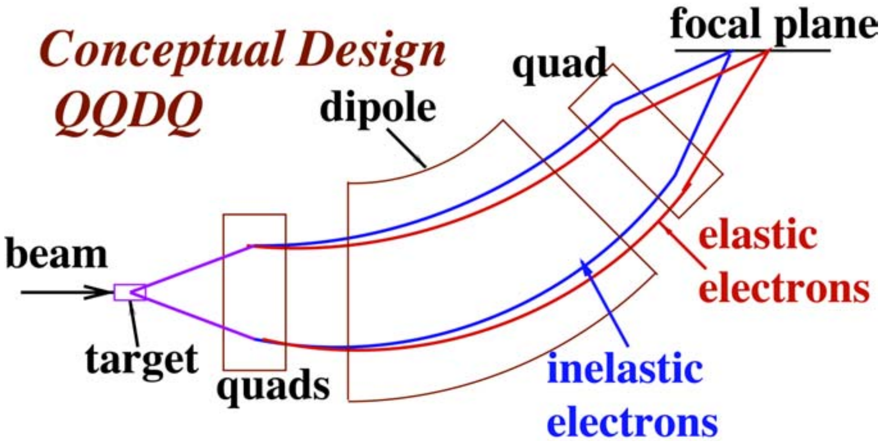


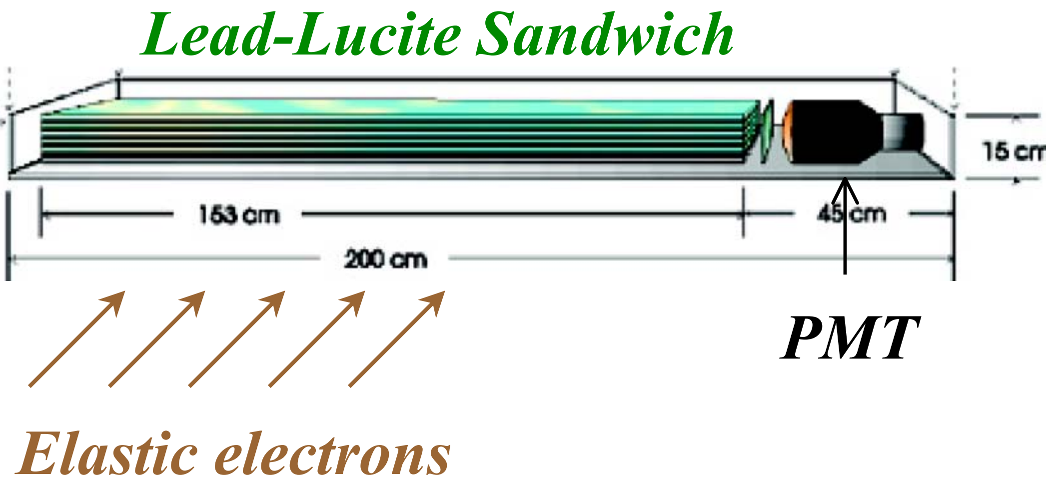
Active cooling by liquid Helium

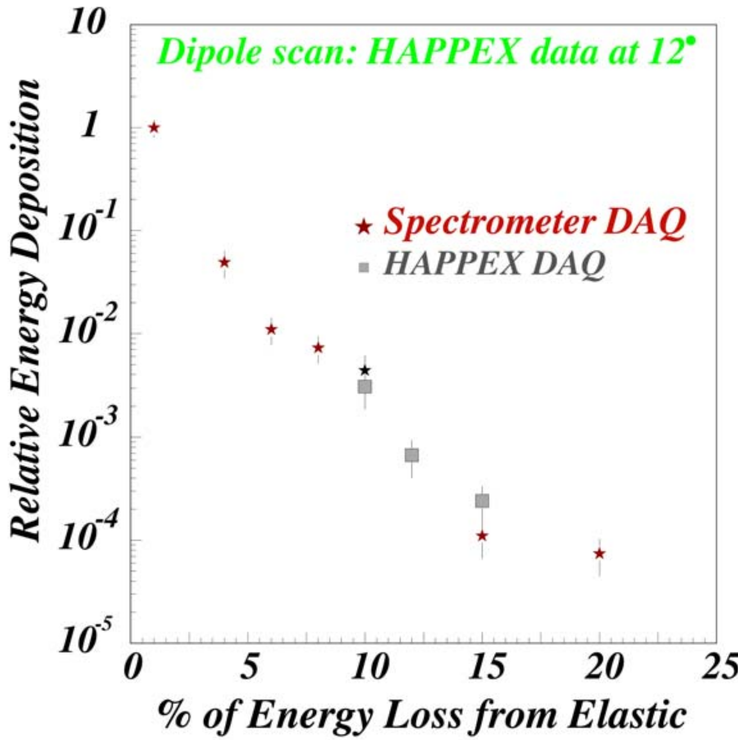
Successfully tested in Hall A

HRS for HAPPEX









HAPPEX Raw Asymmetry

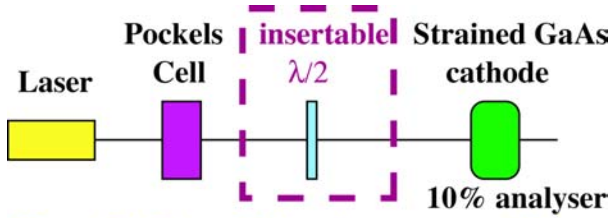
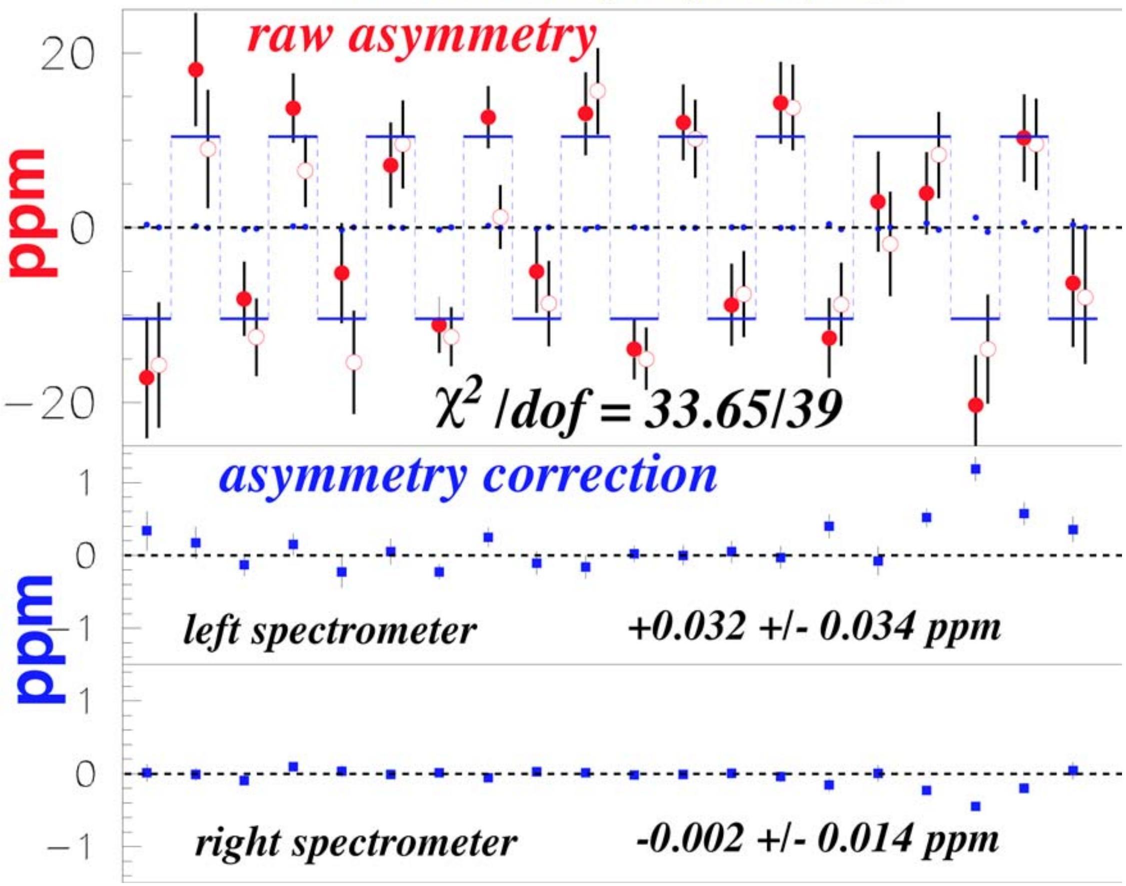


Plate In/Out: Flips Asymmetry Sign



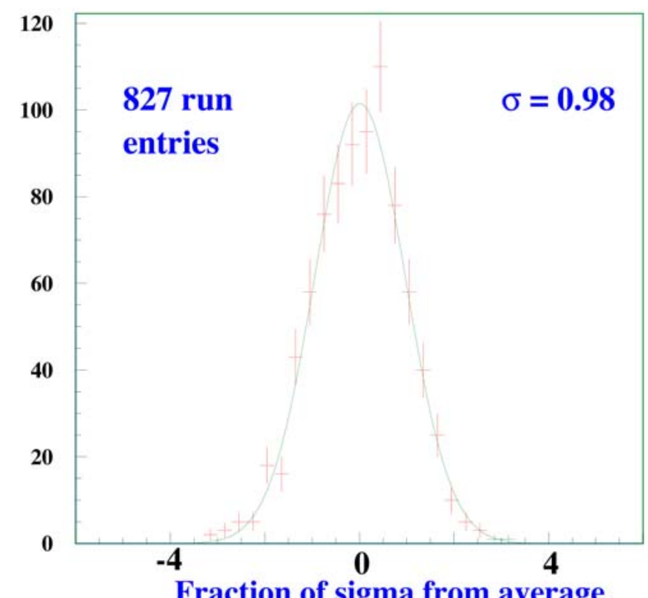
98 Data A_{raw} = -5.64 ± 0.75 (ppm)

~ 95 uA, ~ 38% polarization

99 Data A_{raw} = -10.45 ± 0.75 (ppm)

~ 40 uA, ~ 70% polarization

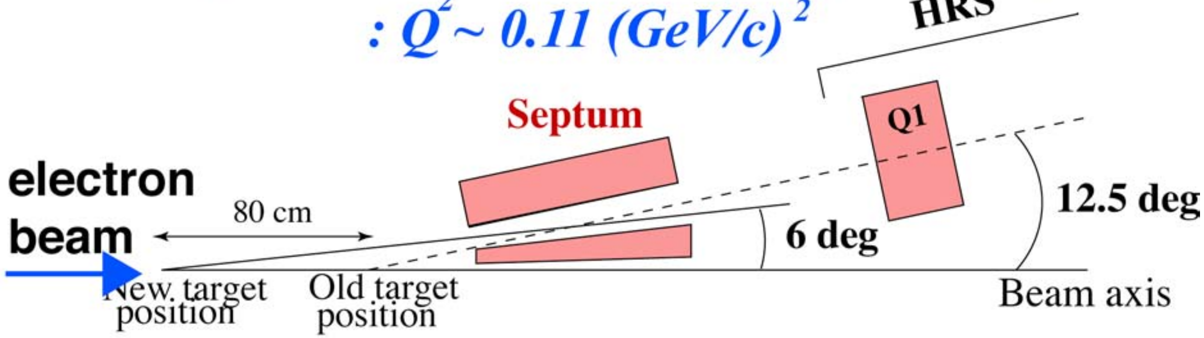
Run asymmetry residuals (normalized to error)

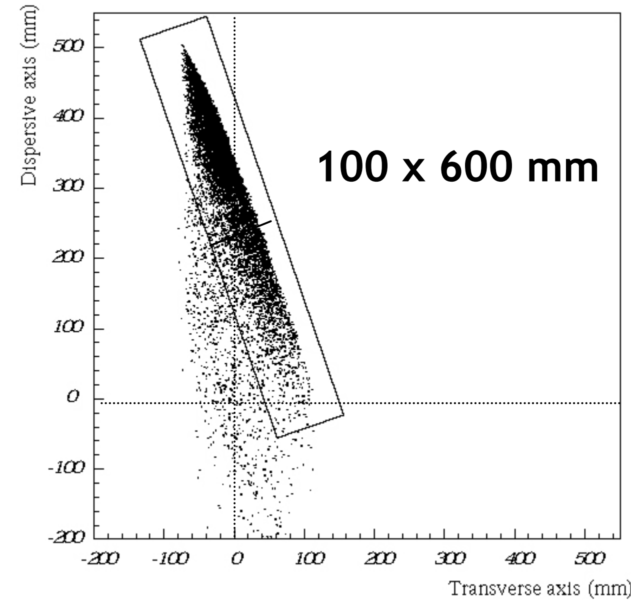


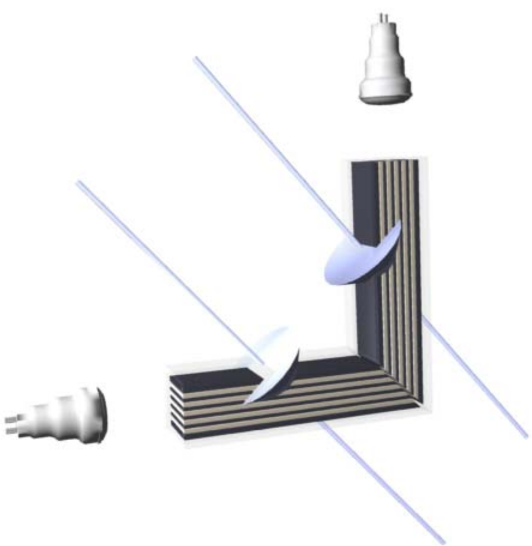
HAPPEX-^{1}H, ^{4}He & ^{208}Pb

Beam Energy ~ 3.2 GeV, scattering angle ~ 6 degrees

: $Q^2 \sim 0.11\ (GeV/c)^2$





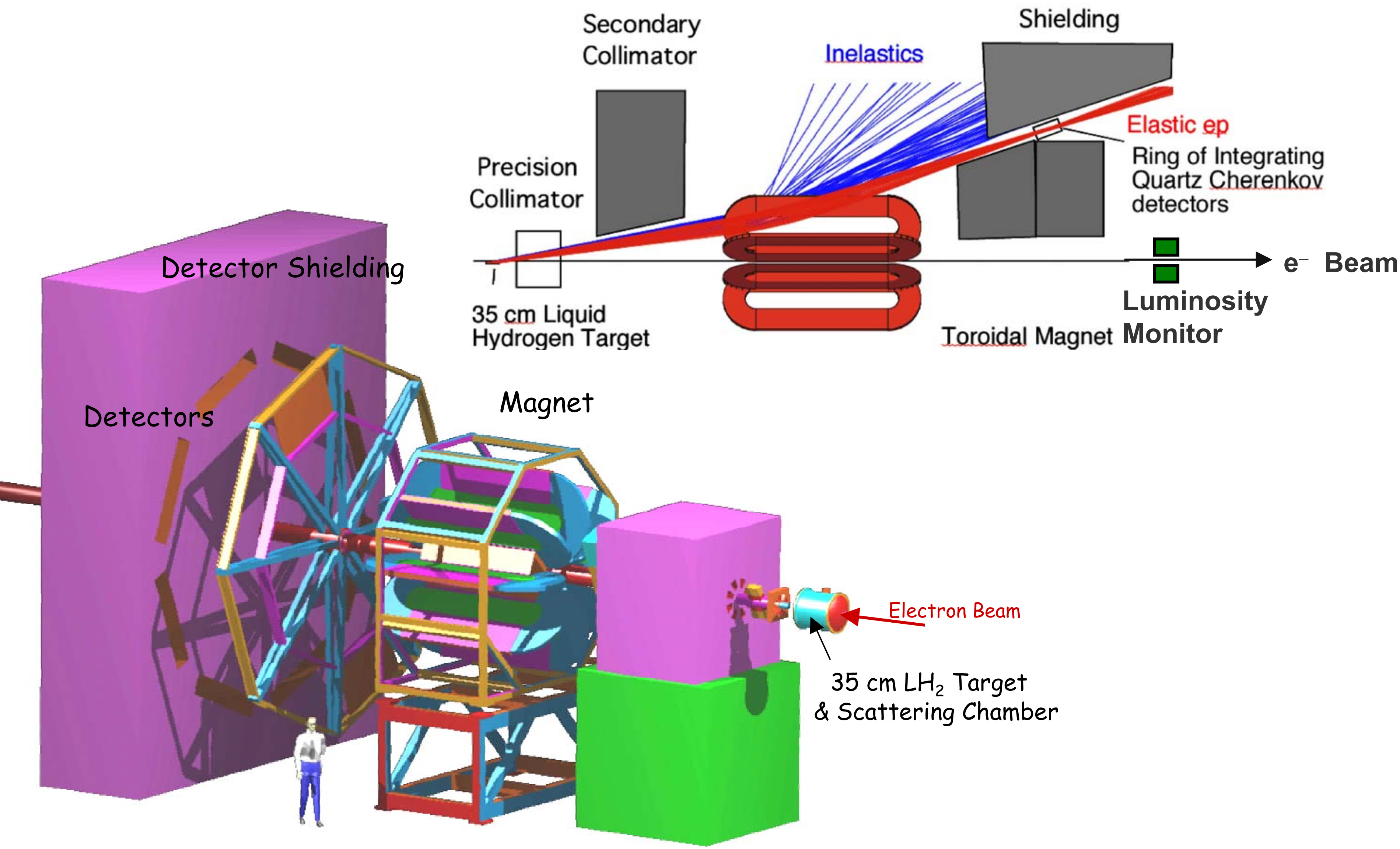


Brass-Quartz Sandwich

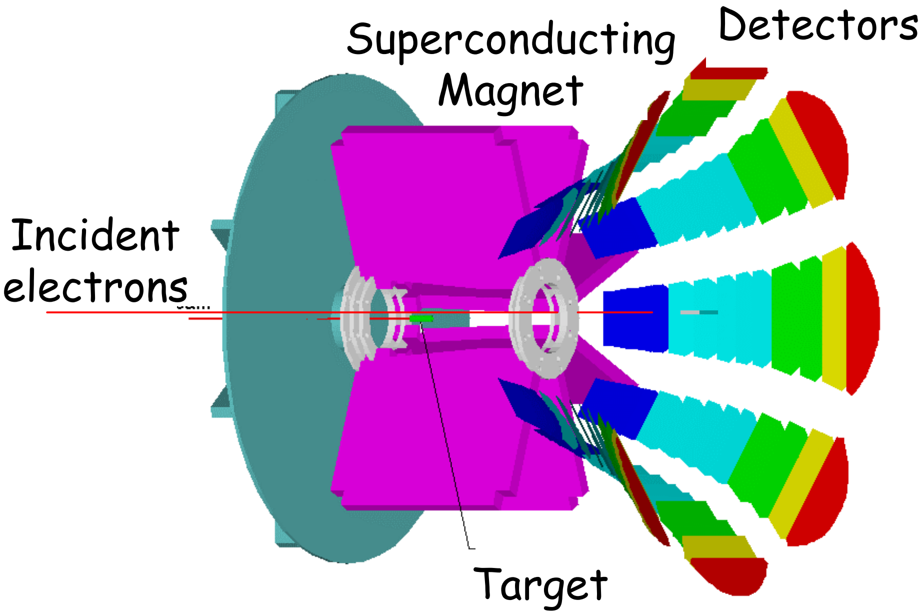
Radiation Hard

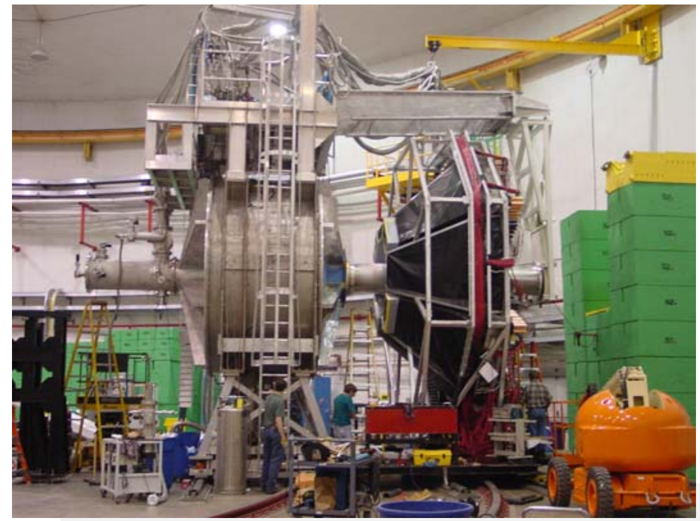
L-shaped for ^{1}H
1 Module for ^{4}He

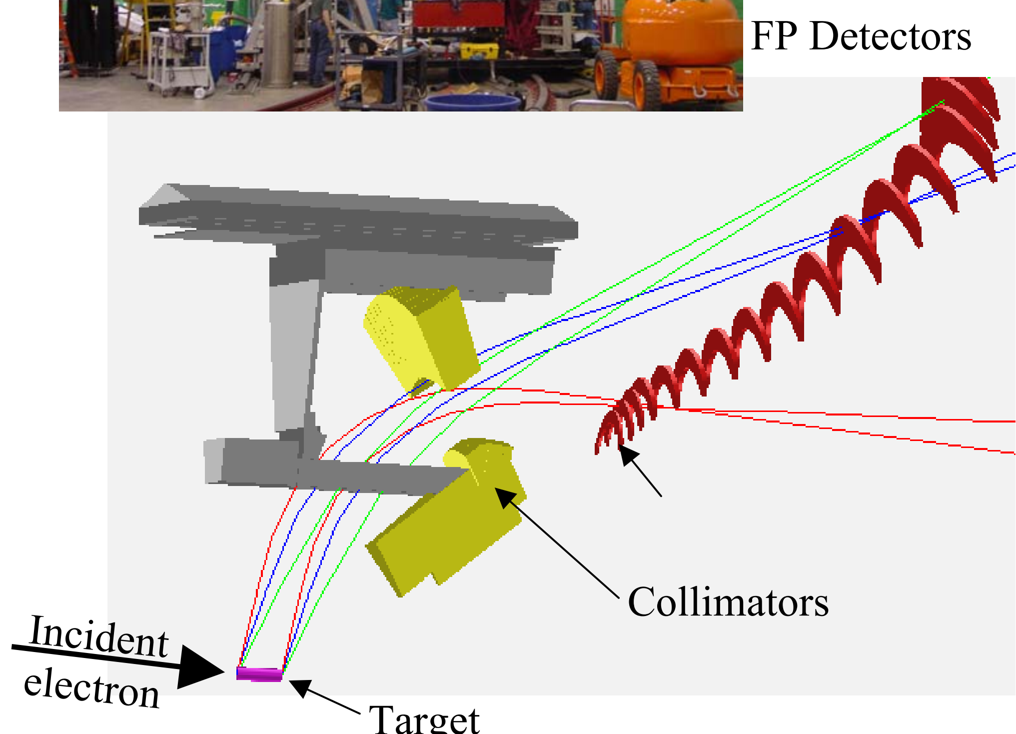
Qweak Spectrometer



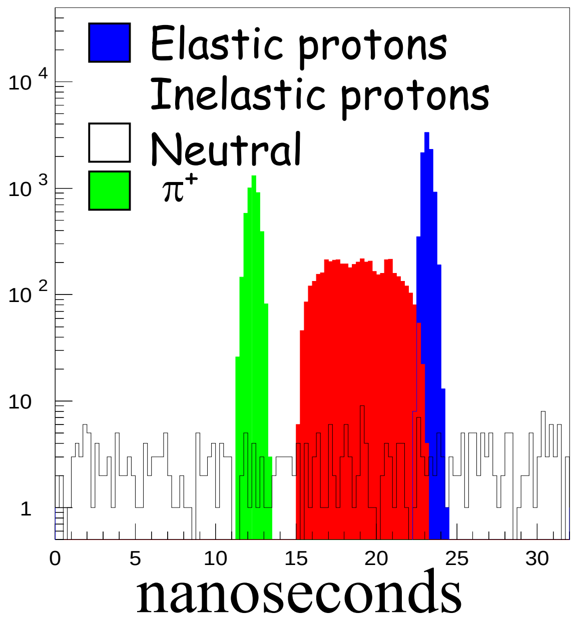
G0 Spectrometer



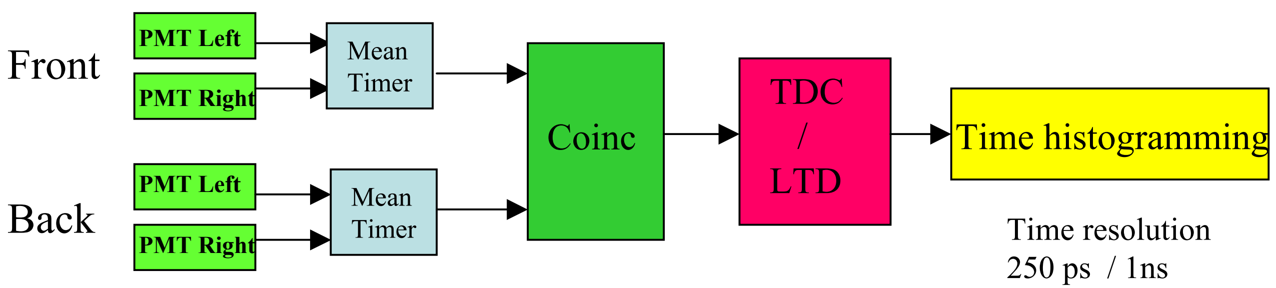




G0 Electronics



Time of Flight measurement



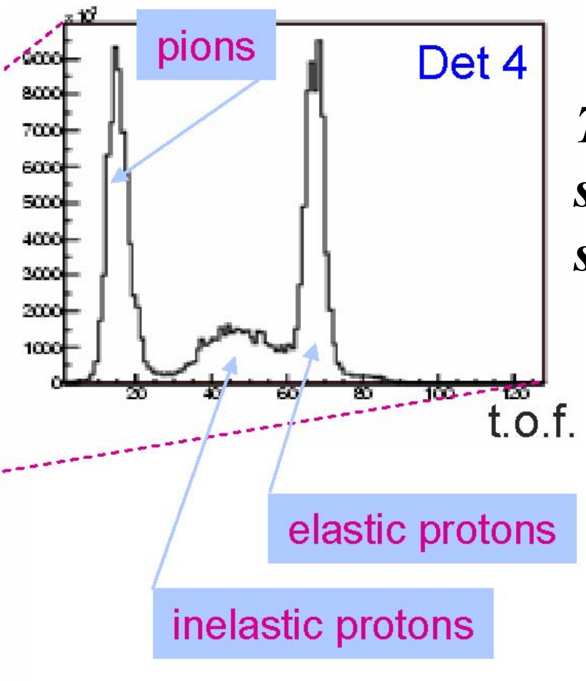
Beam structure: 32 ns between pulses

FR octants: flash TDCs (0.25 ns over 32 ns range)

NA octants: Latching Time Digitizer (500 MHz)
$\rightarrow$ scalers (1 ns over 24 ns range)

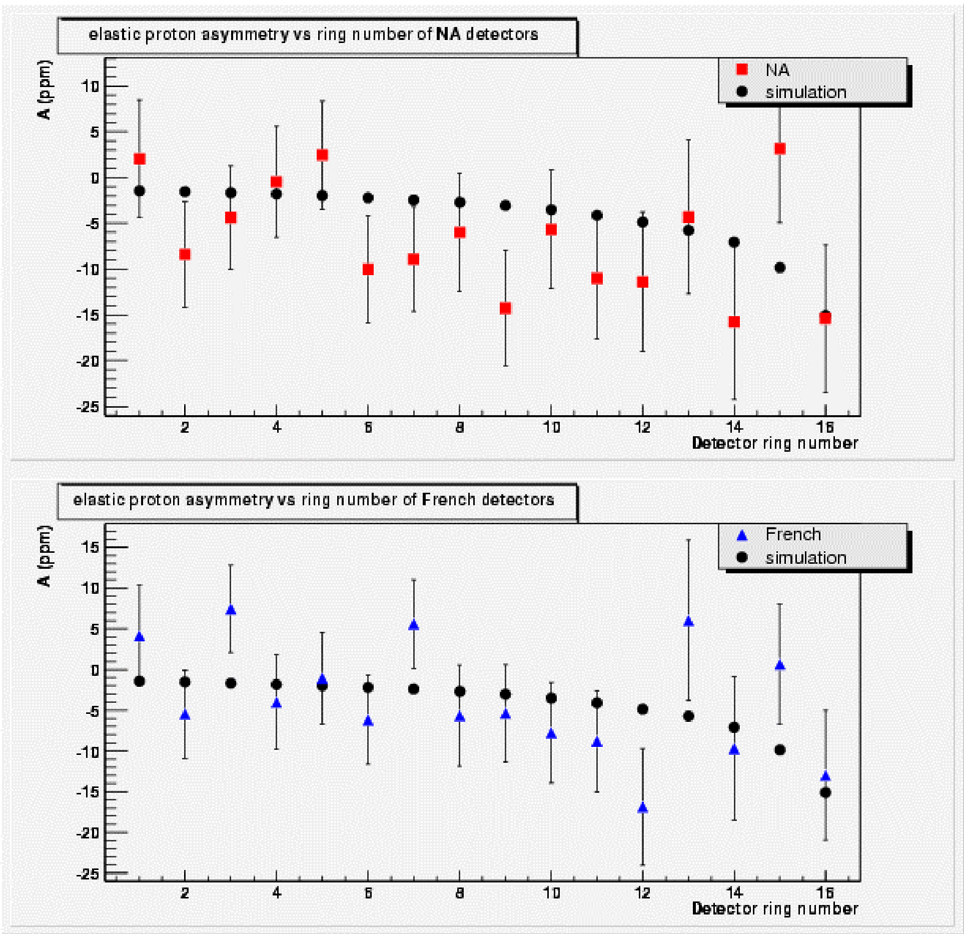
Time histogramming read out at 30 Hz (polar. reversal)

G0 Commissioning



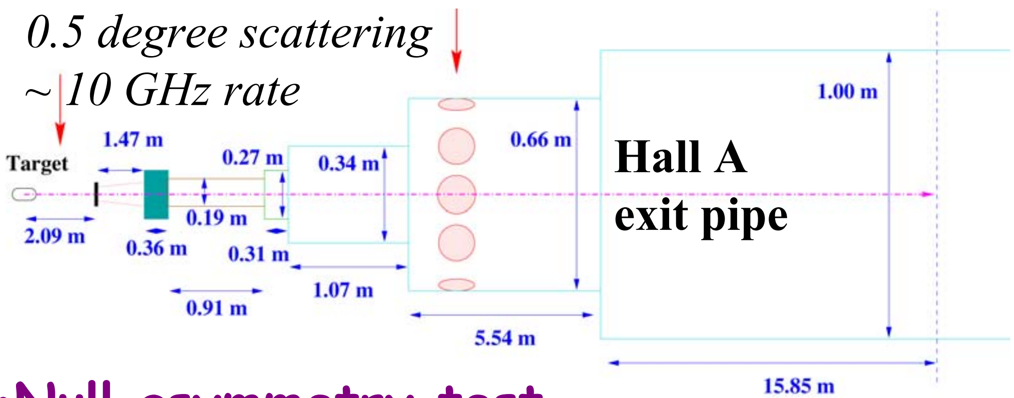
Time-of-flight spectrum from single detector

Online Asymmetries

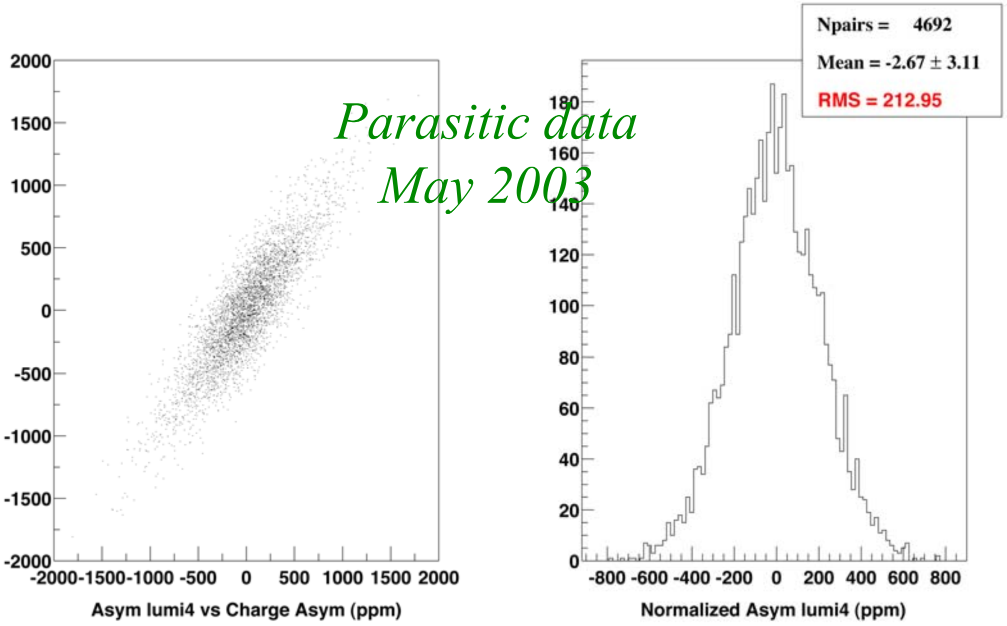


- ***Complete apparatus checkout***
- ***Beam checkout***
- ***Final commissioning: Fall 03***
- ***Forward angle run: Spring 04***

Hall A Luminosity Monitor



- Null asymmetry test
- Target density fluctuations



- *First tests show 200 ppm resolution*
- *50 ppm would be awesome*

(SLAC E158 monitor limits density fluctuations at 40 ppm with 100 ppm resolution)

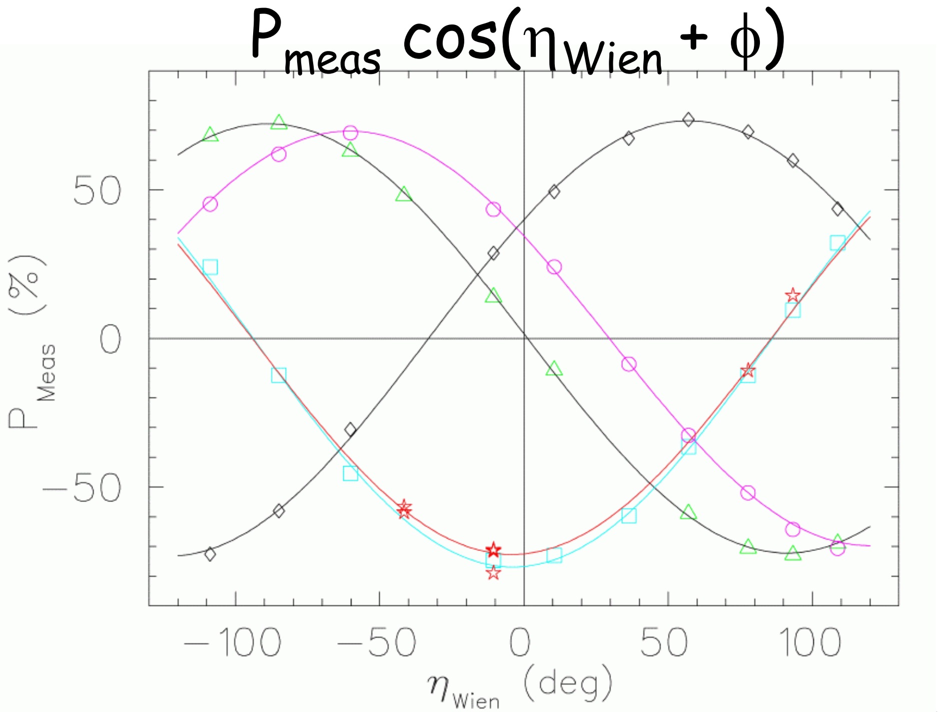
Normalization

The track record in parity violation experiments in electron scattering: Normalization errors limit ultimate sensitivity

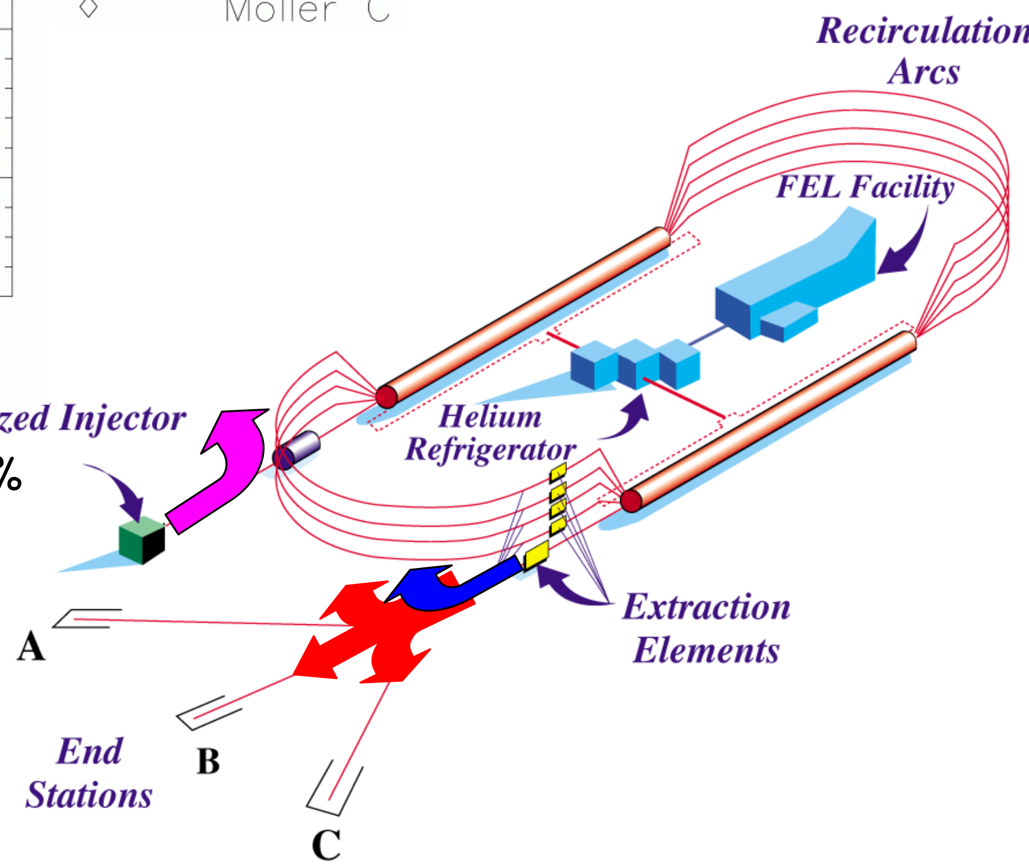
- ***10% measurements of asymmetry have been typical***
- ***Jlab will enter a new era of ~ few % measurements***

- Electron Beam Polarization
- Experimental Determination of Q^2
- Physics backgrounds
- Dilution factors
- …

Electron Beam Polarimetry



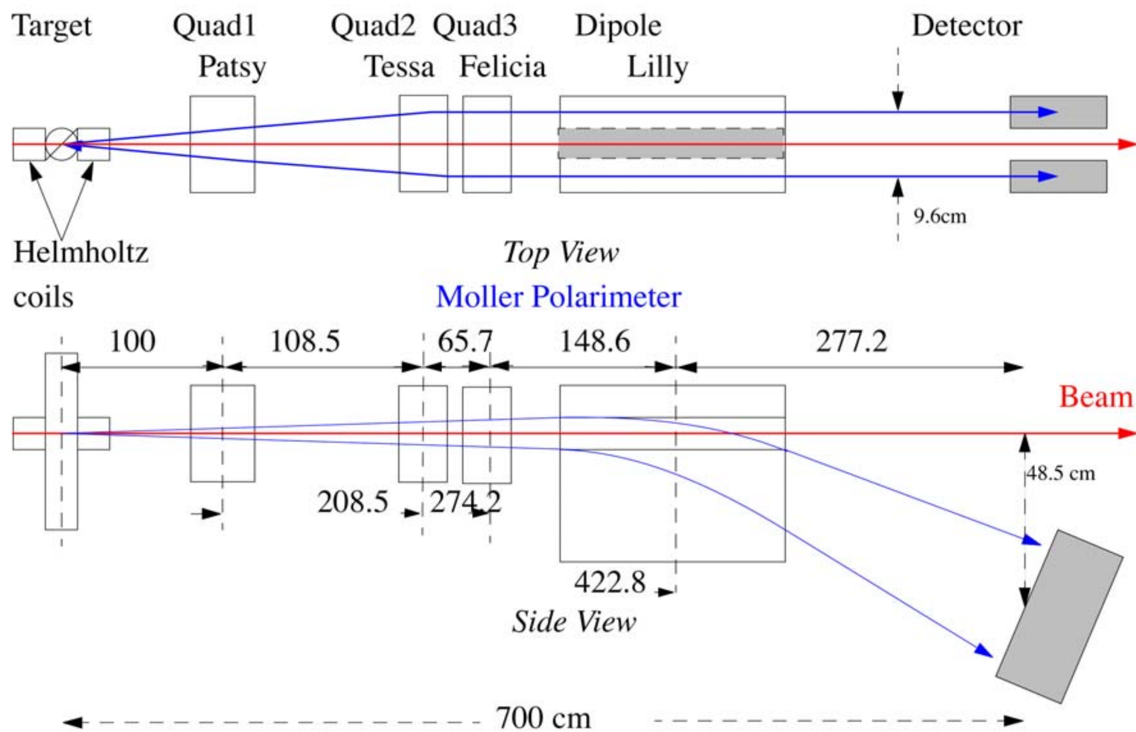
- •Mott
- •Møller
- •Compton



- •Polarimeter systematics range from 1 to 3%
- •Upcoming experiments require a concentrated effort to develop robust and redundant polarization measurements with 1% error
- •"Spin Dance" measurements crucial!
- •By product: energy scale to 10^{-4}!

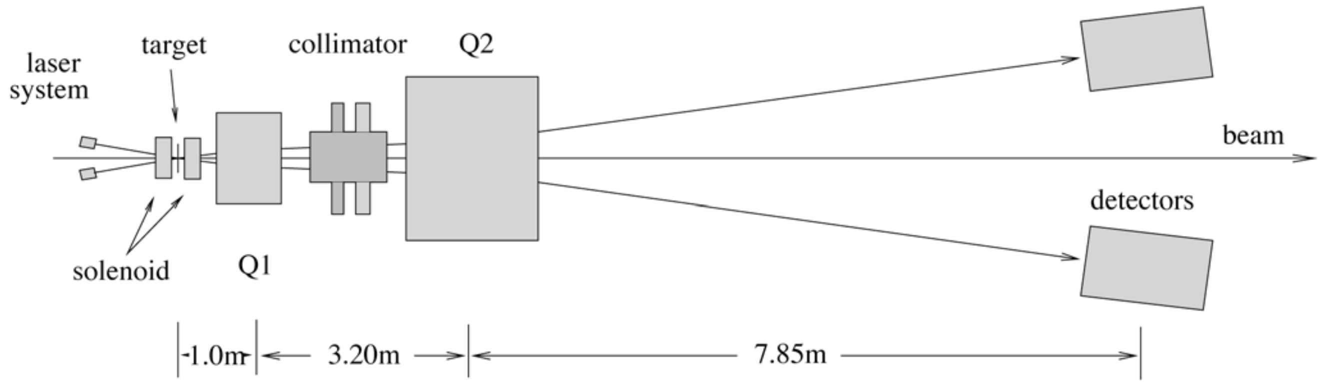
Hall A Møller Polarimeter

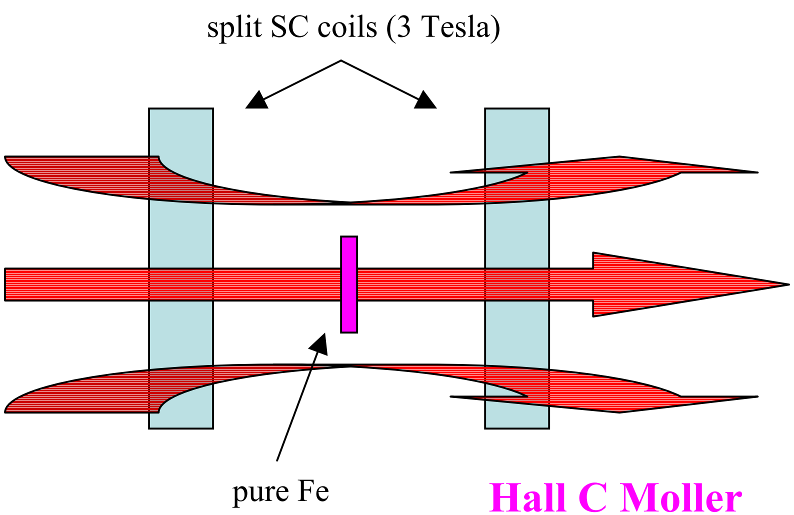
Double-Spin Asymmetry in polarized electron-electron scattering



Hardware robust and well-tested
Systematic error ~ 3.4%
Dominant contribution: foil ~ 3%
Unstable extrapolation from low to high current

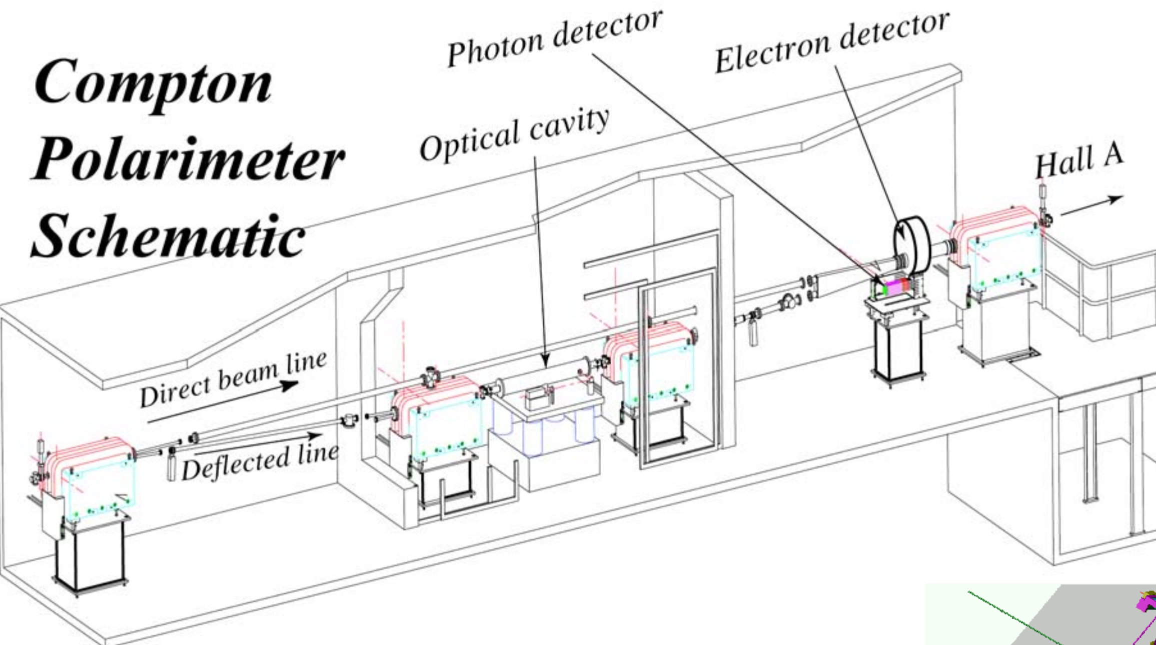
Hall C Møller Polarimeter





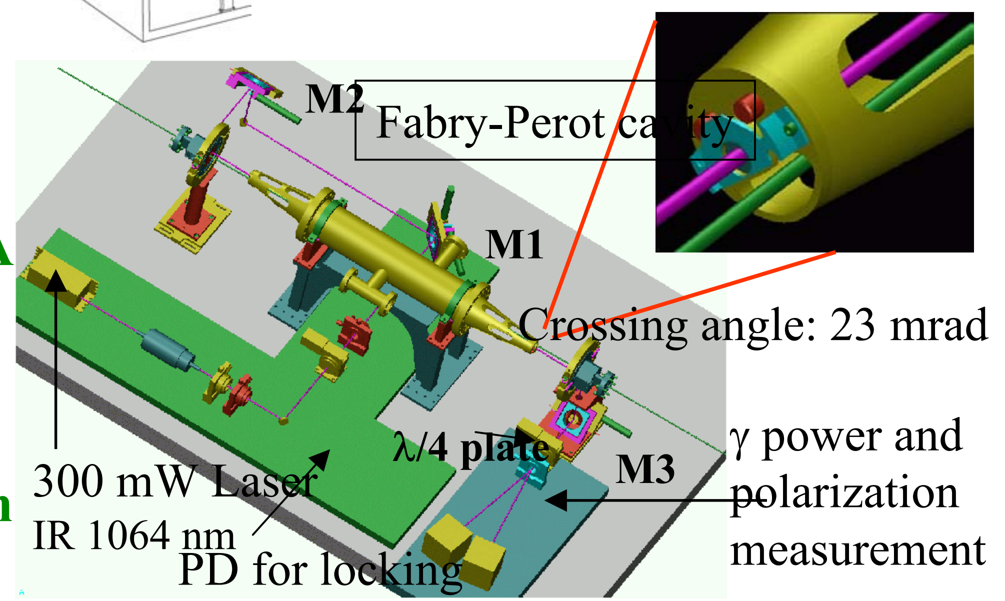
- ***spin-polarization versus magnetization known for pure iron ~ 0.25%***
- ***High field saturation ~ 3 Tesla***
- ***Greatly reduces target polarization error***
- ***Other errors potentially less than 1%***
- ***Extrapolation studies to high current under way***
- ***G0 commissioning included several tests***

Hall A Compton Polarimeter



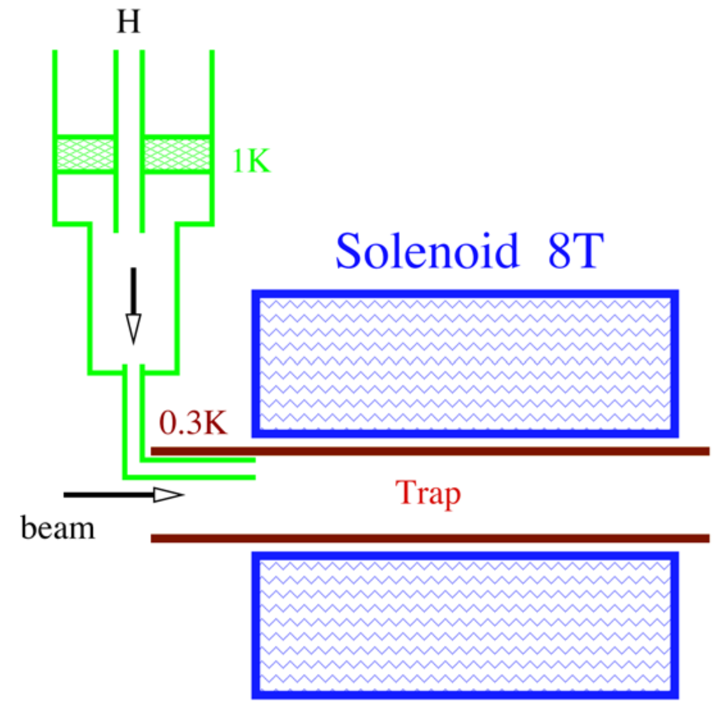
Double spin asymmetry in polarized photon-electron scattering

- 1.4% total error at 4.5 GeV
- 0.8% stat. error in 40 minutes at 40 μA
- electron & photon detection
- 1.5 kW laser power
- Stable operation over 1 year
- High accuracy at 1 GeV requires green laser and detector upgrade



Atomic Hydrogen Polarimetry

- *300 mK atom trap*
- *100% electron polarization*
- *Density ~ $3x10^{15}/cm^3$*
- *Contamination < 10^{-4}*



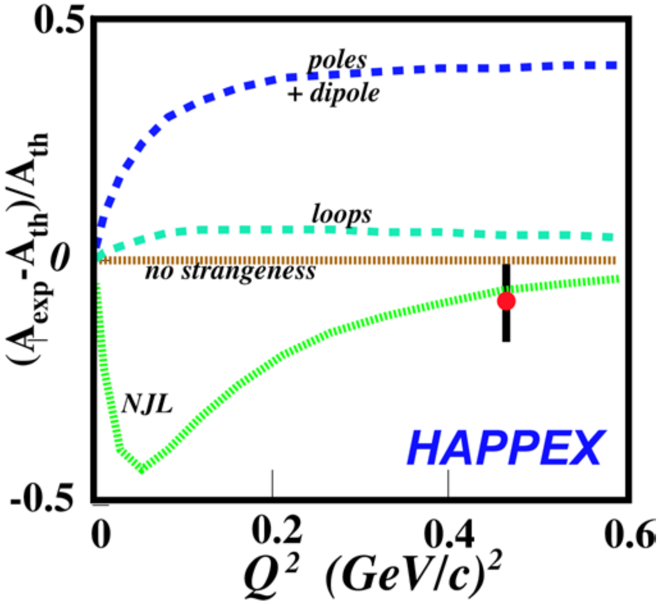
Potentially,

- **Statistical error ~ 1% in ~ 0.5 hr**
- **Calculations show that the gas is stable and not depolarized in 100 µA Jlab beam**
- **No Levchuk effect**
- **Low background**
- **Systematic error better than 0.5%**

Assuming availability of resources,
Jlab can break into uncharted territory

HAPPEX Physics Result

Source of Error	$\Delta A/A$ (%)
Statistics	6.4
Beam Polarization	3.2
Average Q	1.8
Backgrounds	0.6
Total Systematic	3.7
Electromagnetic Form Factors	4.9
Axial Form Factor	1.4



$Q^2 = 0.477$ $(GeV/c)^2$

$$\frac{G_E^s + 0.39\, G_M^s}{G_{Mp}^{\gamma}/\mu_p} = 0.070 \pm 0.056 \pm 0.041$$

HAPPEX Physics Asymmetry (final, 98 + 99 data)

$$A_{phy} = -15.05 \pm 0.98 \pm 0.56 \ \text{(ppm)}$$

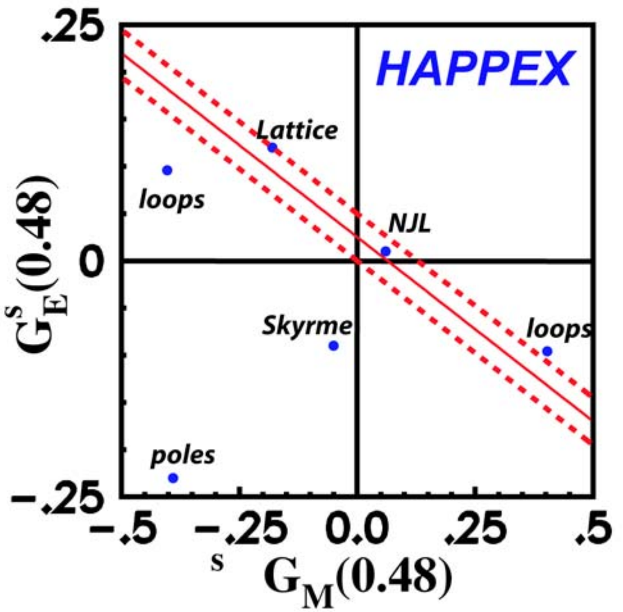
Standard Model (w/o nucleon strangeness): -16.45 ppm

Axial Form Factor Contribution: 0.56 ± 0.23

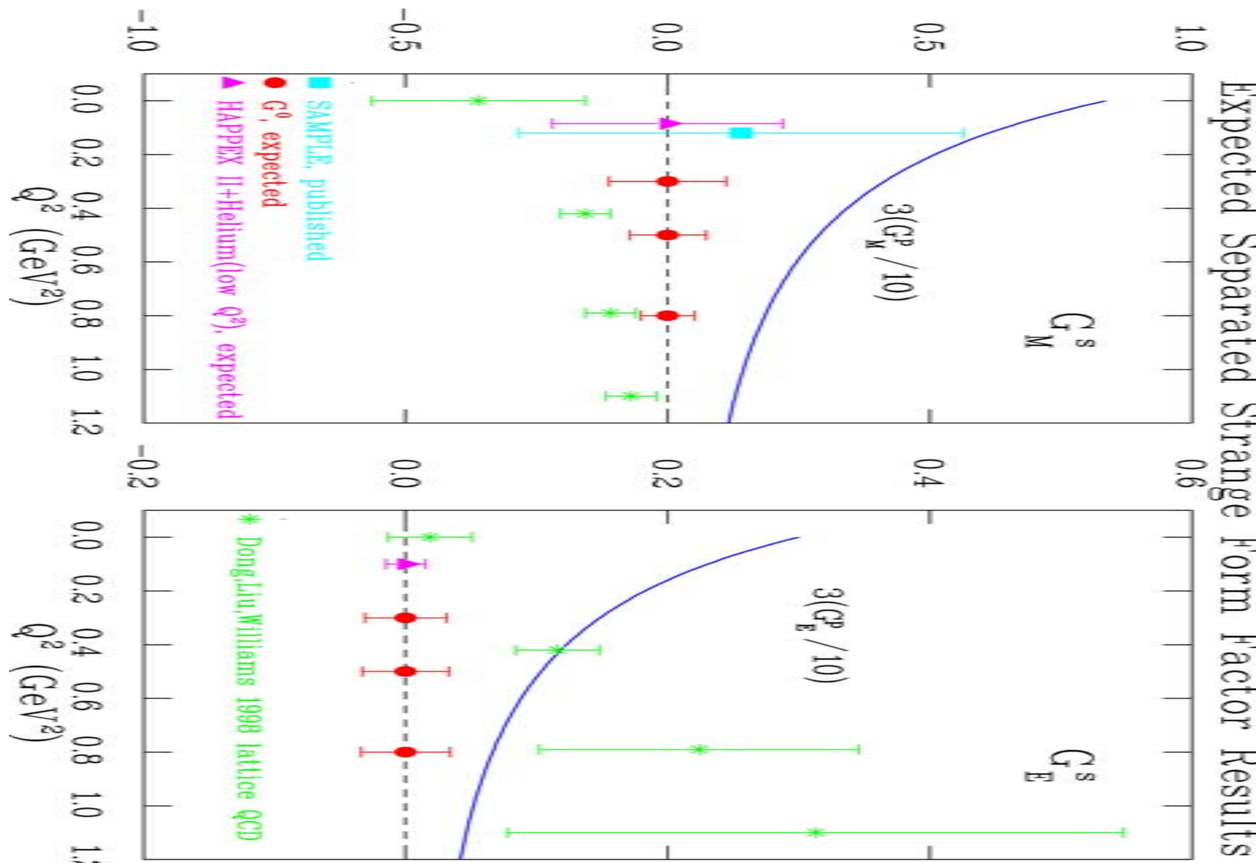
published result

$$\frac{A_{phy} - A_{theo}}{A_{theo}} = -0.085 \pm 0.060 \pm 0.034$$

Implications and Outlook



From an experimentalist's point of view: the turf is still wide open for a discovery



- G0 will provide separation over Q^2
- HAPPEXII will provide high precision anchor points

Mainz PVA4 is taking data like there is no tomorrow!

Back to Physics…..

- Strange Form Factors
  - **Firm foundation in place**
  - **Poised for more measurements**
- Neutron Skin
  - **Unique measurement exploiting Jlab capabilities**
- Beyond the Standard Model
  - **E158 has made the inroads into new era**
  - **Qweak and 12 GeV experiments go deeper into discovery space**
- Transverse Asymmetry
  - **As is typical in science, perhaps sensitivity to 2-photon diagrams might eventually be as interesting as the above topics, and these experiments could have major impact on this question.**

A Look Back

- Parity violation experiments exploit all aspects of Jlab capabilities
- Extraordinarily fruitful partnership between accelerator physicists and physics collaborations
- Excellent training for graduate and undergraduate students
- Expanding, rich physics program

Conclusion

Parity experiments are here to stay

So

Let's get some barbecue!