Lead (^{208}Pb) Radius Experiment: PREX

Elastic Scattering Parity Violating Asymmetry

$\Rightarrow$ measure neutron radius in Pb

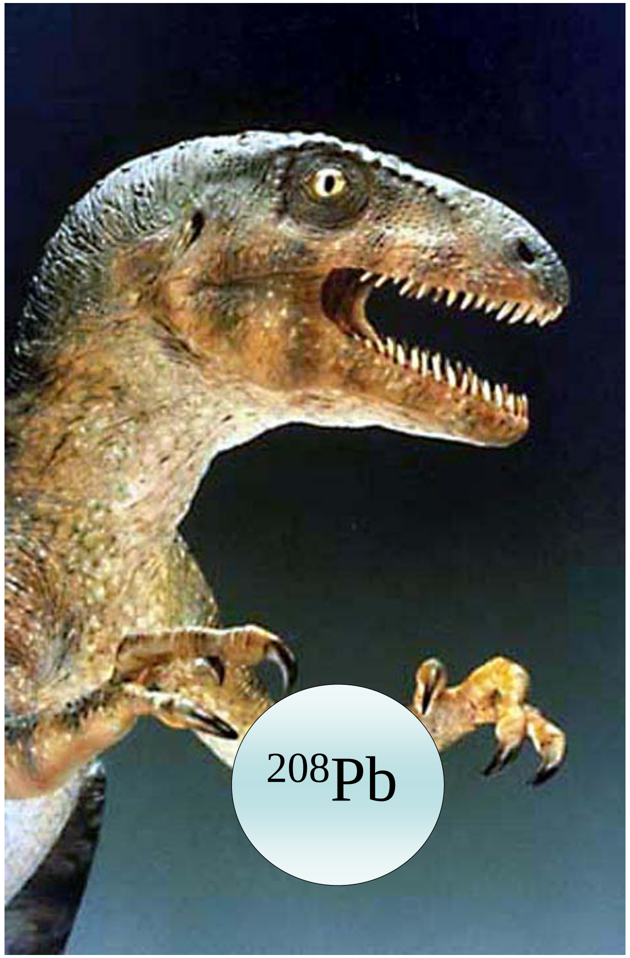
E = 1 GeV, ϑ=5° electrons on lead

Spokespersons

- Paul Souder
- Krishna Kumar
- Robert Michaels
- Guido Urciuoli

Hall A Collaboration Experiment

Presa dati: primavera 2010



Gran parte delle trasparenze da: G.M. Urciuoli

Electron - Nucleus Potential

$$\hat{V}(r) = V(r) + \gamma_5 A(r)$$

electromagnetic

$$V(r) = \int d^3r' \; Z \; \rho(r') / |\vec{r} - \vec{r}'|$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott} |F_P(Q^2)|^2$$

Proton form factor

$$F_P(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_P(r)$$

axial

$$A(r) = \frac{G_F}{2\sqrt{2}} \left[(1 - 4\sin^2\theta_W) Z \rho_P(r) - N \rho_N(r) \right]$$

⇒ $A(r)$ is small, best observed by parity violation

⇒ $1 - 4\sin^2\theta_W << 1$ neutron weak charge >> proton weak charge

Neutron form factor

$$F_N(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_N(r)$$

Parity Violating Asymmetry

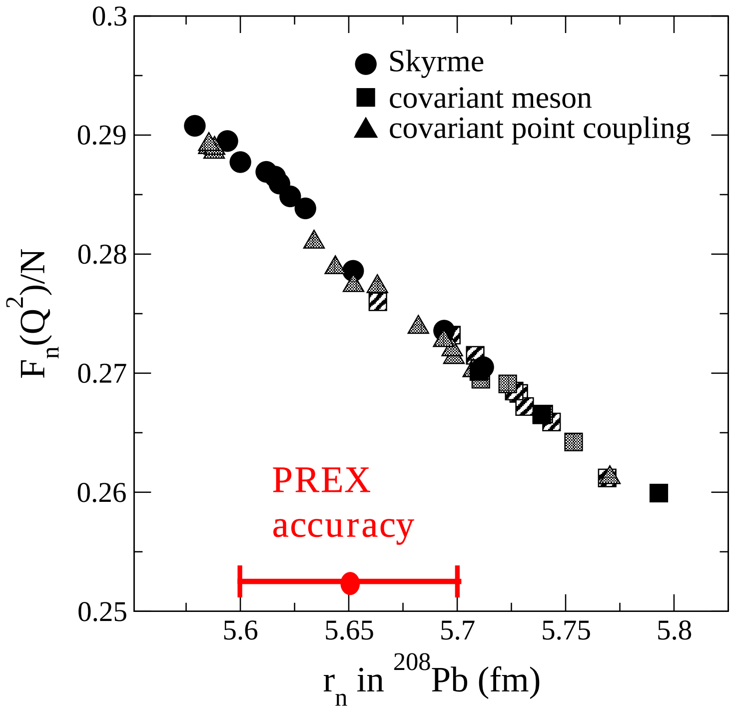
$$A = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_N(Q^2)}{F_P(Q^2)} \right]$$

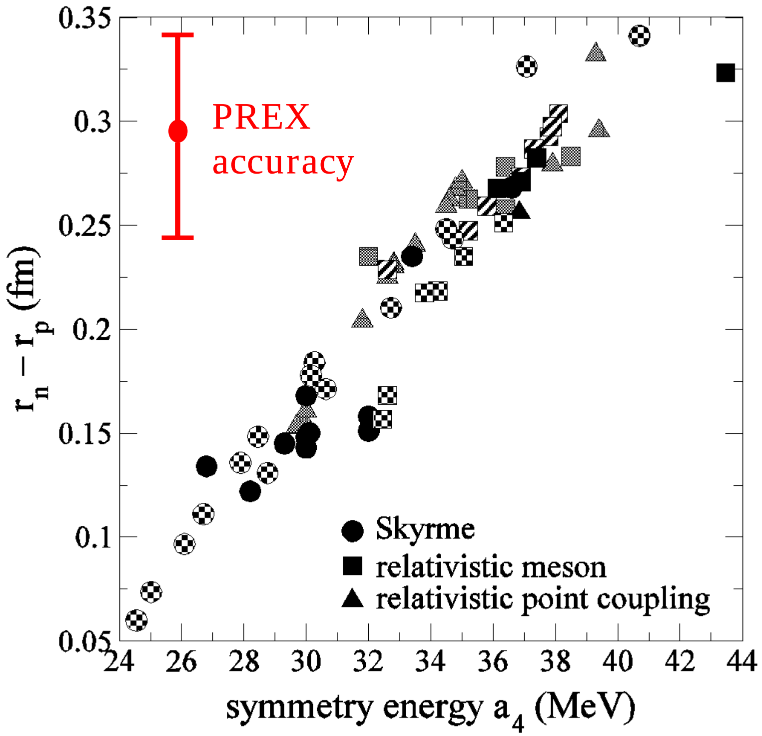
$A_{PV} \sim 500 \pm 15$ ppb, $Q^2 \sim 0.01$ GeV^2

$$\frac{dA}{A} = 3\% \quad \rightarrow \quad \frac{dR_n}{R_n} = 1\%$$

Measurement at one Q^2 is sufficient to measure R_N

Pins down the symmetry energy (1 parameter)





(R.J. Furnstahl)

$$E(n,x) = E(n,x=1/2) + S_\upsilon(n)(1-2x^2)$$

n = n.m. density $\quad x$ = ratio proton/neutrons

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PREX impatto su

- Misura della densità nucleonica $\Rightarrow$ migliore conoscenza della energia di simmetria
- Miglioramento modelli su Neutron Stars Equation of State (e Heavy Ions)
- Atomic Parity Violation

PREX & Neutron Stars

(C.J. Horowitz, J. Piekarweicz)

Crab Pulsar

R_N calibrates EOS of Neutron Rich Matter

→ Crust Thickness

→ Explain Glitches in Pulsar Frequency ?

Combine PREX R_N with Observable Neutron Star Radii

→ Phase Transition to "Exotic" Core ?

→ **Strange star ? Quark Star ?**

Some Neutron Stars seem too Cold

→ Cooling by neutrino emission (URCA)

→ $R_n - R_p > 0.2$ fm → URCA probable, else not

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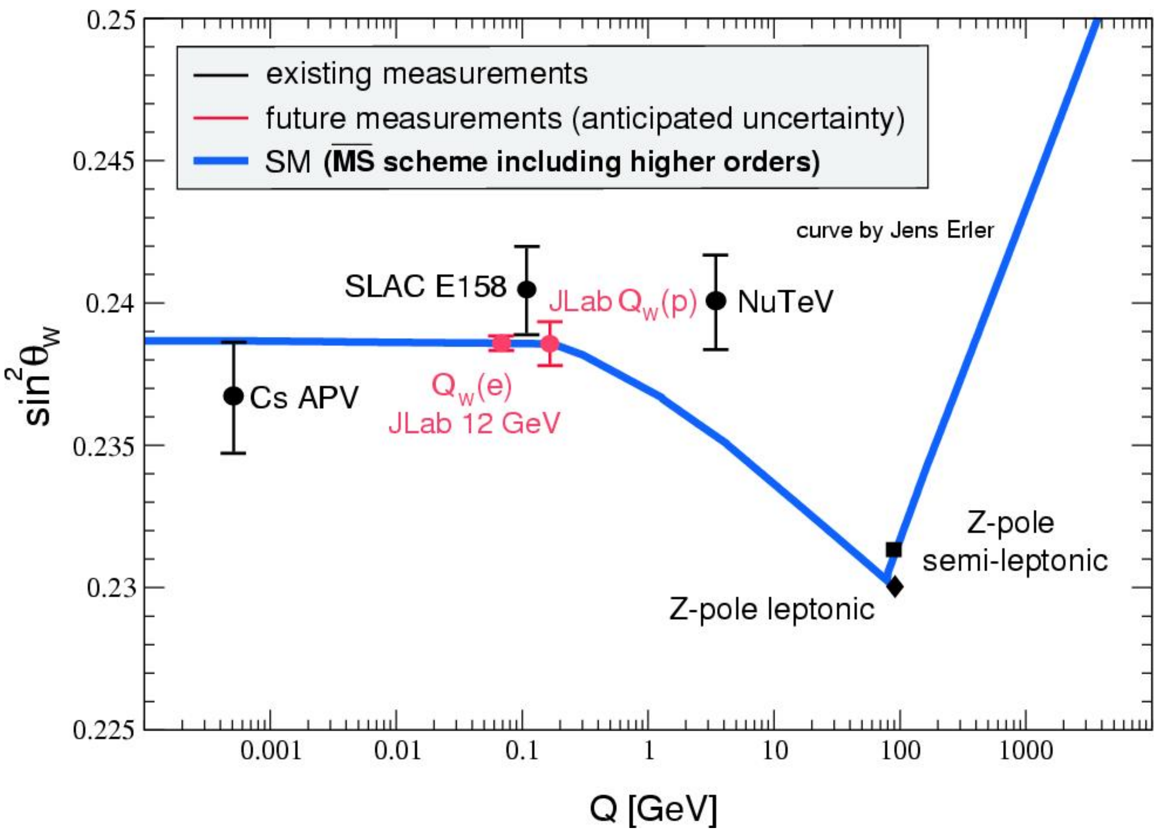
Atomic Parity Violation

- Low Q^2 test of Standard Model
- Needs R_N to make further progress.

Isotope Chain Experiments
e.g. Berkeley Yb

$$H_{PNC} \approx \frac{G_F}{2\sqrt{2}} \int \left[-N \rho_N(\vec{r}) + Z \underbrace{(1-4\sin^2\theta_W)}_{\approx 0} \rho_P(\vec{r}) \right] \psi_e^{\dagger} \gamma^5 \psi_e \, d^3 r$$



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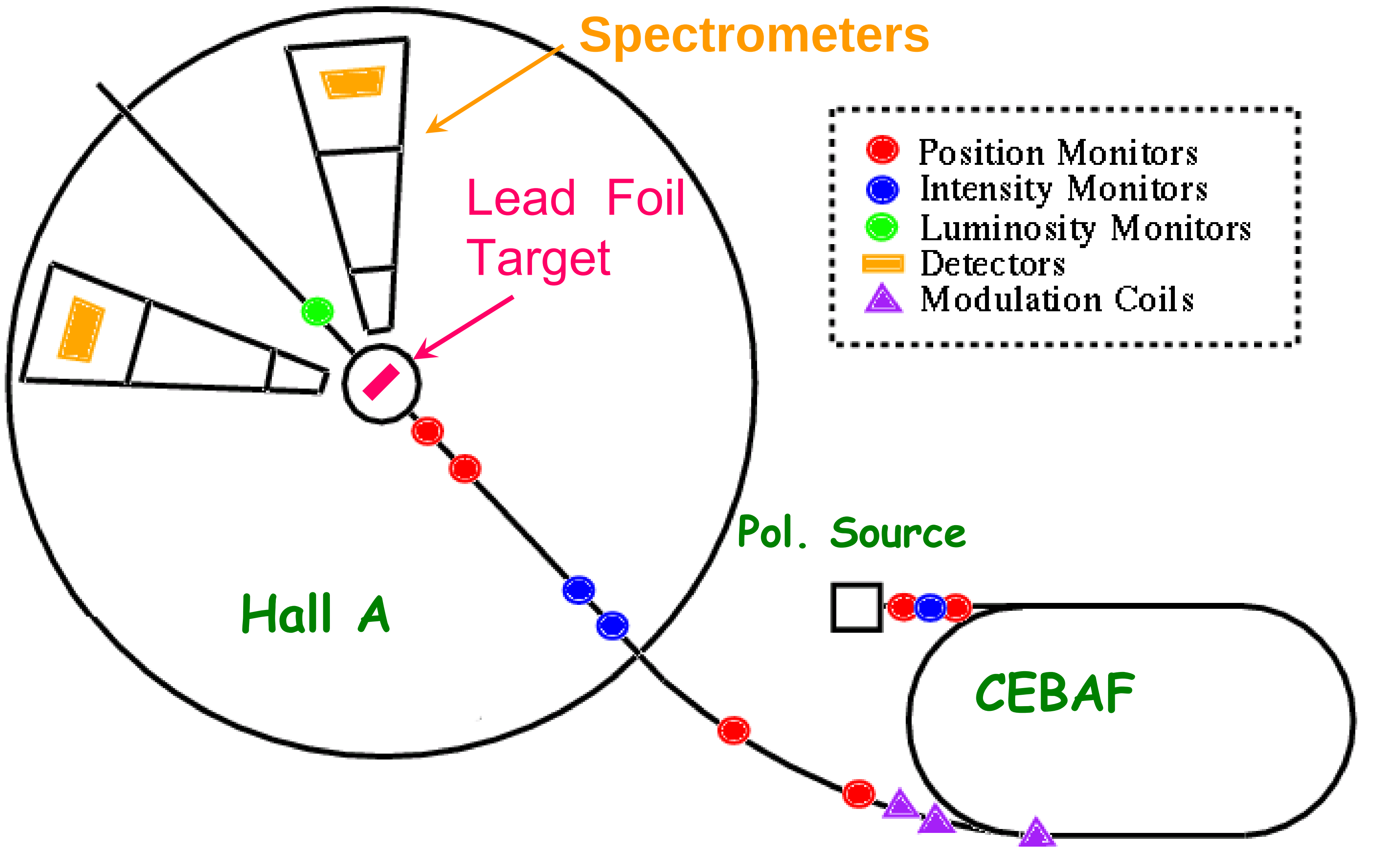
Corrections to the Asymmetry are Mostly Negligible

- Coulomb Distortions ~20% = the biggest correction.
- Transverse Asymmetry (to be measured)
- Strangeness
- Electric Form Factor of Neutron
- Parity Admixtures
- Dispersion Corrections
- Meson Exchange Currents
- Shape Dependence
- Isospin Corrections
- Radiative Corrections
- Excited States
- Target Impurities

} Horowitz, *et.al.* PRC 63 025501

PREX in Hall A at JLab



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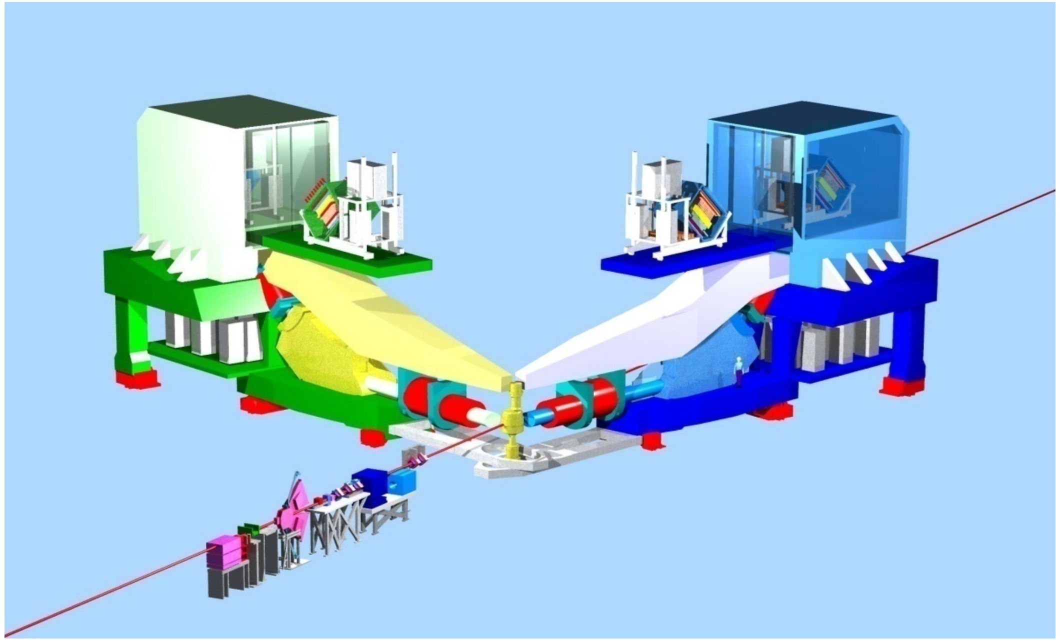
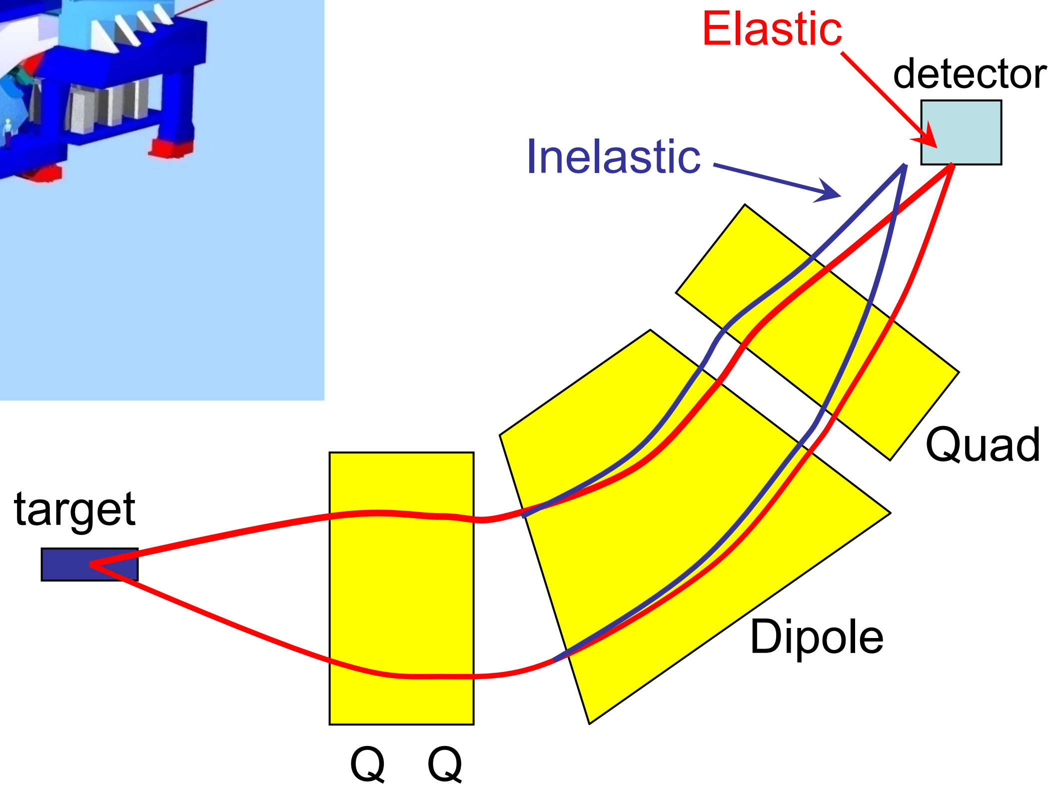
High Resolution Spectrometers



Left-Right symmetry to control transverse polarization systematic

Spectrometer Concept:

Resolve Elastic



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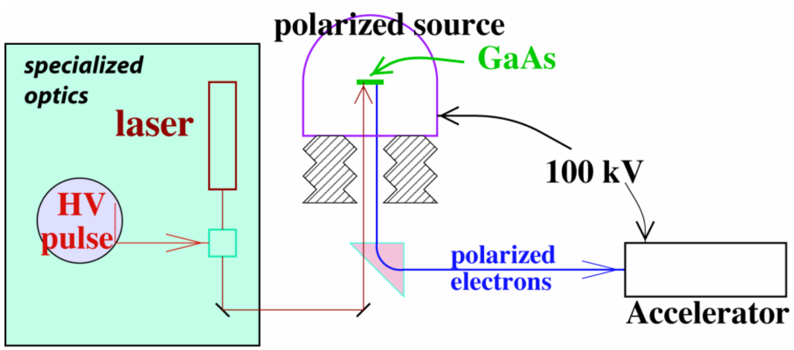
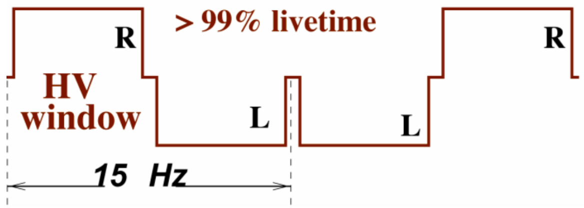
Experimental Method



rapid, random, helicity flipping

Rapid, Random Helicity Flips



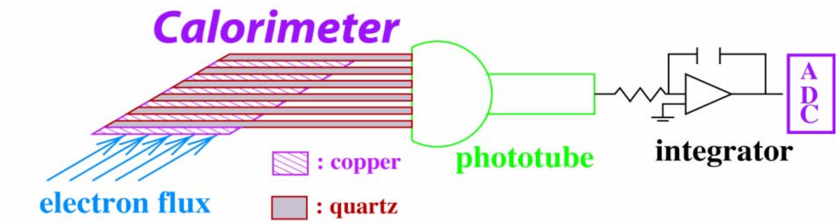
Measure flux F for each window

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

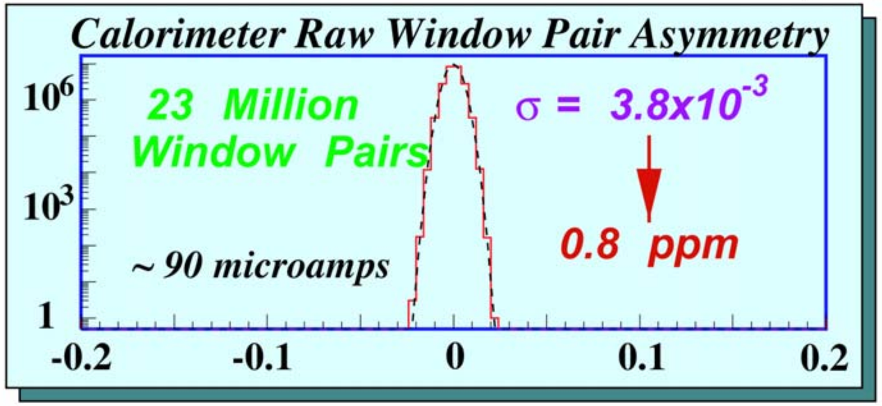
Flux Integration Technique:

HAPPEX: 2 MHz

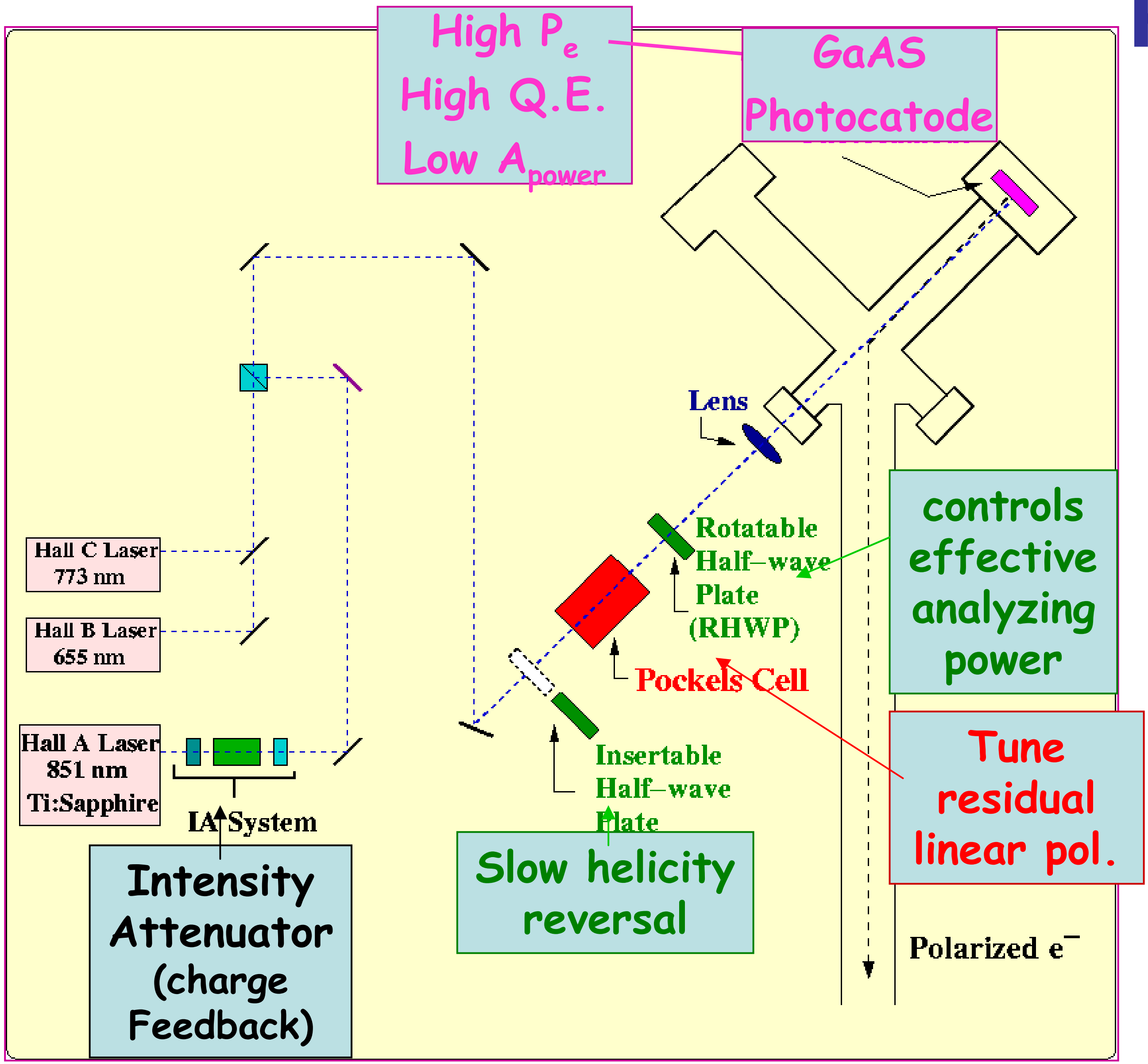
PREX: 850 MHz



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



No non-gaussian tails to +/- 5σ



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Polarized Source

- Optical pumping of solid-state photocathode
- High Polarization
- Pockels cell allows rapid helicity flip
- Careful configuration to reduce beam asymmetries.
- Slow helicity reversal to further cancel beam asymmetries

Important Systematic : **PITA Effect**

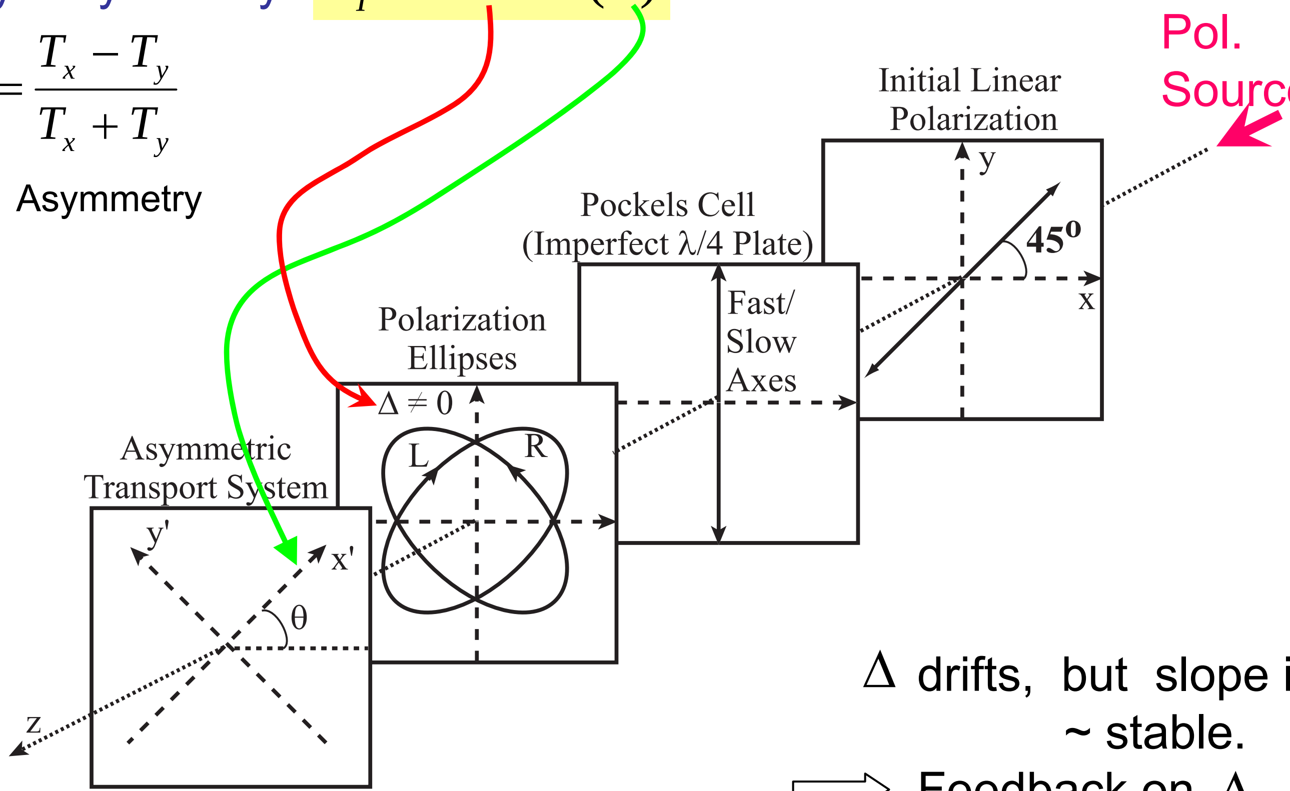
Polarization **I**nduced **T**ransport **A**symmetry

Intensity Asymmetry $A_I = \varepsilon\,\Delta\sin(\theta)$

where $\varepsilon = \dfrac{T_x - T_y}{T_x + T_y}$

Transport Asymmetry

Laser at Pol. Source

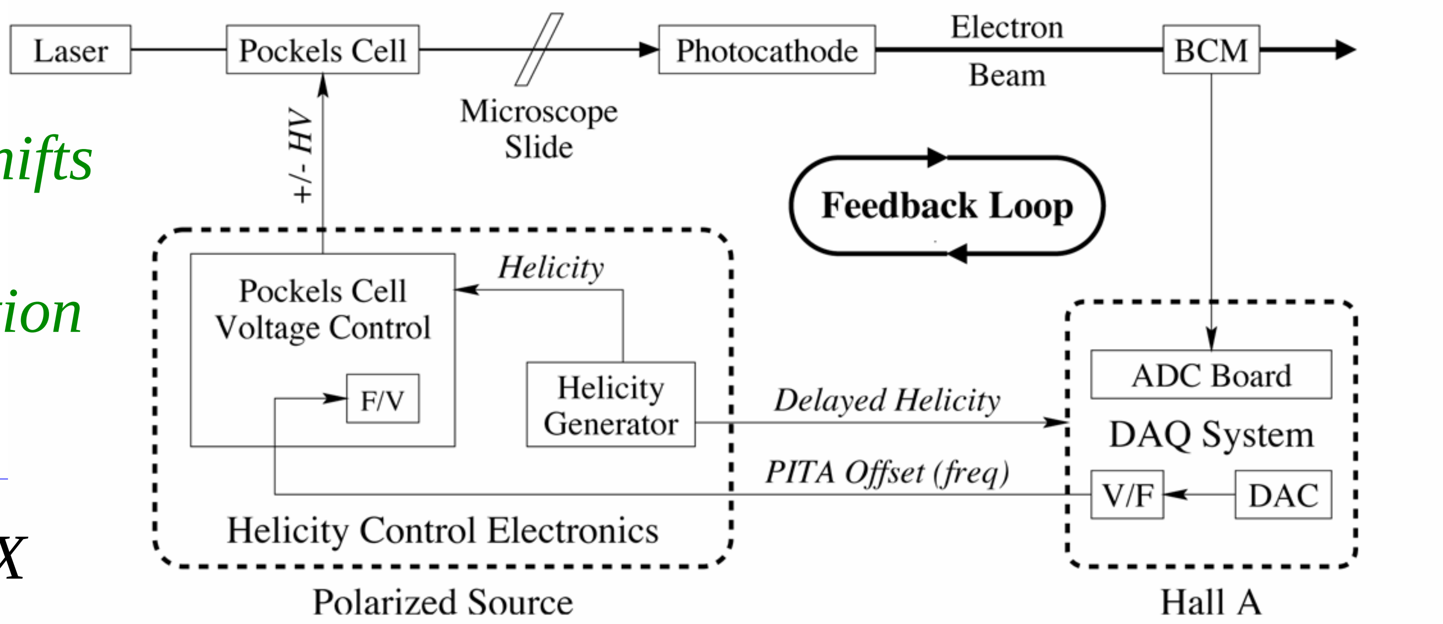


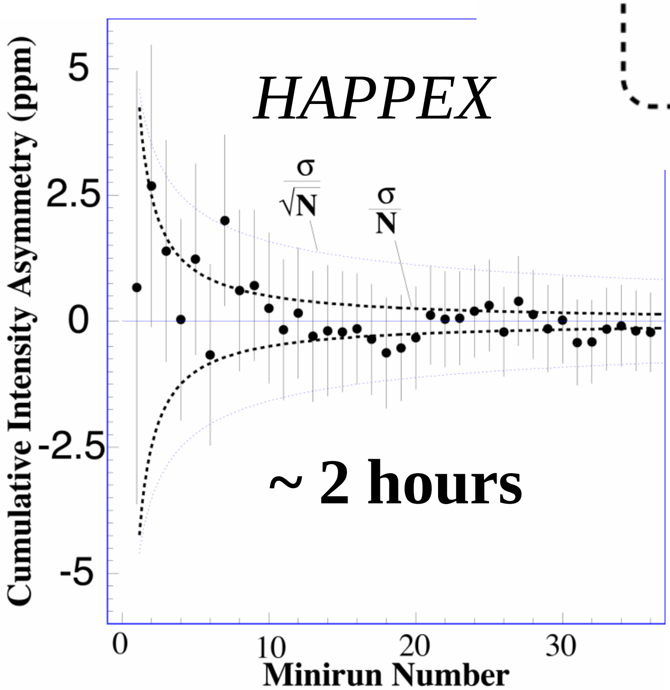
Δ drifts, but slope is ~ stable.

⇨ Feedback on Δ

Intensity Feedback

Adjustments for small phase shifts to make close to circular polarization





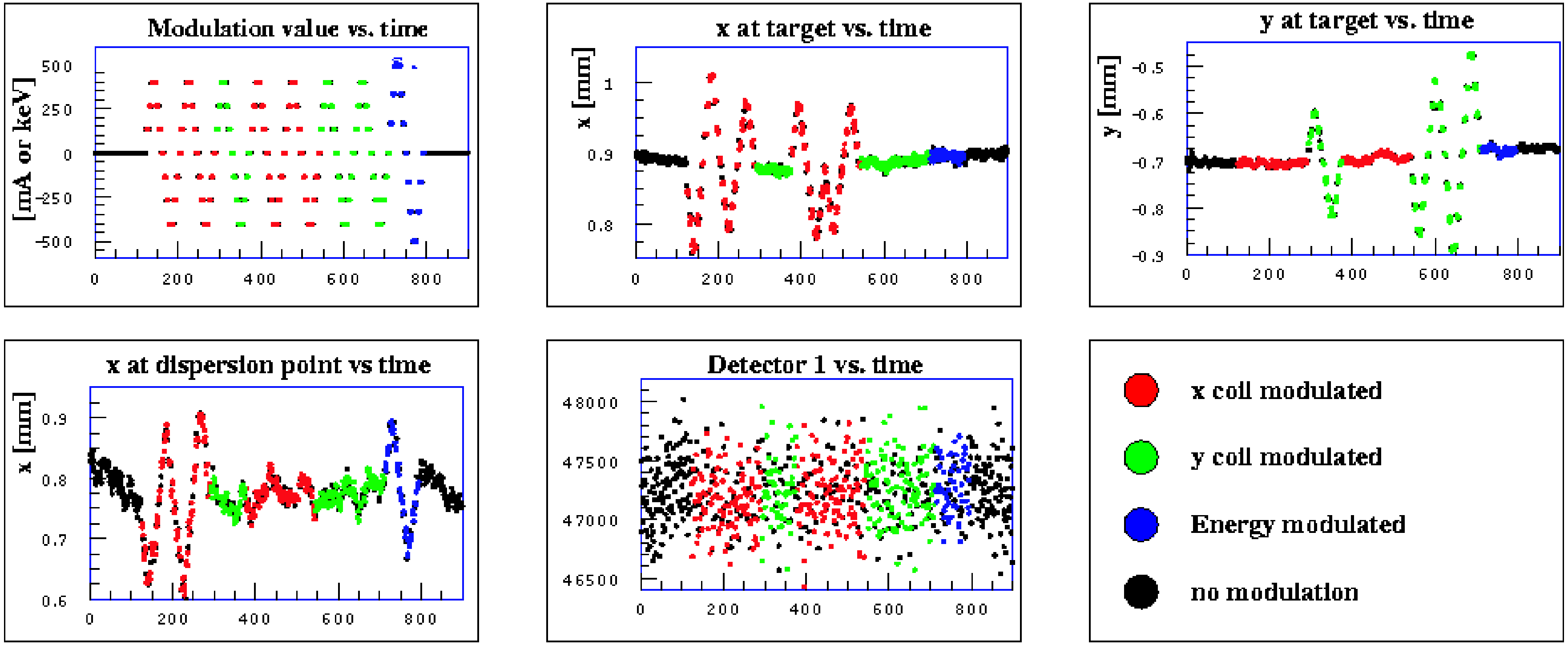
Low jitter and high accuracy allows sub-ppm Cumulative charge asymmetry in ~ 1 hour

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

Beam Asymmetries

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

Slopes from
- natural beam jitter (regression)
- beam modulation (dithering)



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Helicity Correlated Differences: Position, Angle, Energy

Scale +/- 10 nm

BPM X1

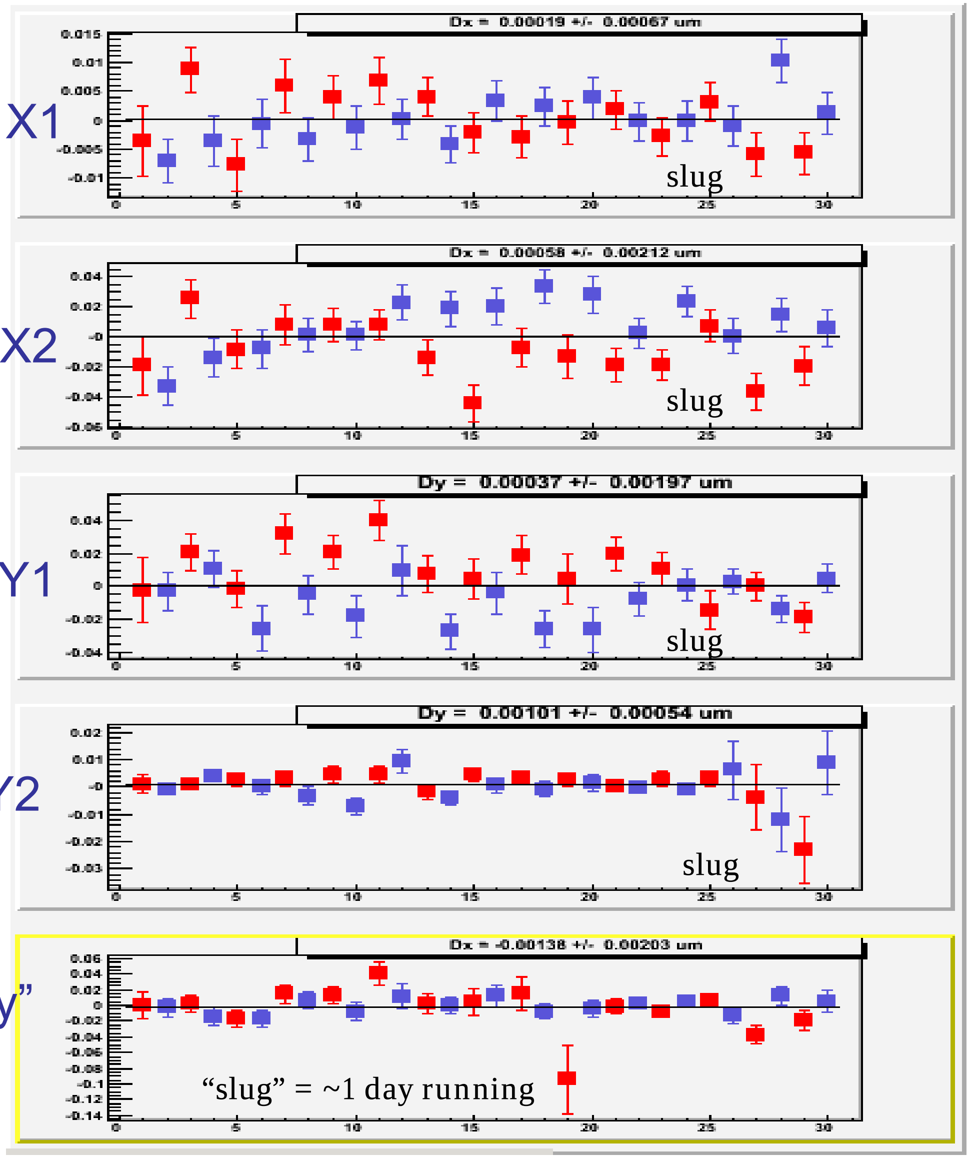
Spectacular results from HAPPEX-H show we can do PREX.

BPM X2

BPM Y1

BPM Y2

"Energy" BPM



Position Diffs average to ~ 1 nm

- Good model for controlling laser systematic at source
- Accelerator setup (betatron matching, phase advance)

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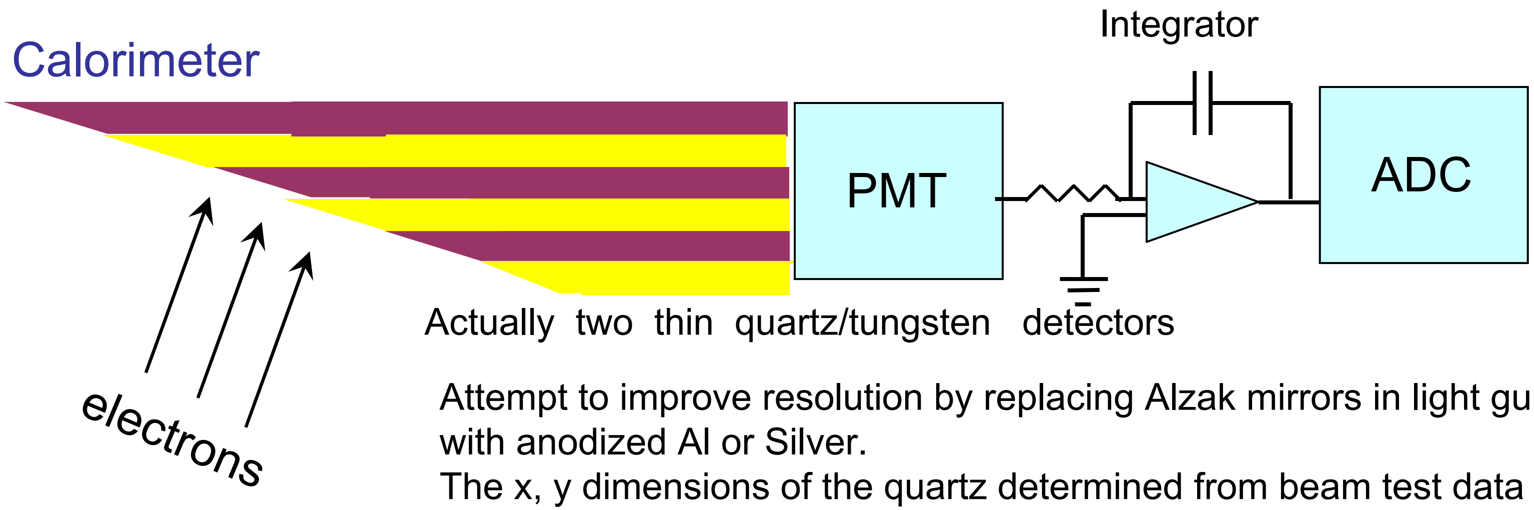
Integrating Detection

- Integrate in 30 msec helicity period.
- Deadtime free.
- 18 bit ADC with < 10^{-4} nonlinearity.
- Backgrounds & inelastics separated (HRS).



Attempt to improve resolution by replacing Alzak mirrors in light guide with anodized Al or Silver.
The x, y dimensions of the quartz determined from beam test data and MC (HAMC) simulations. (11 x 14 cm)
Quartz thickness to be optimized with MC.
New HRS optics tune focuses elastic events both in x & y at the PREx detector location.

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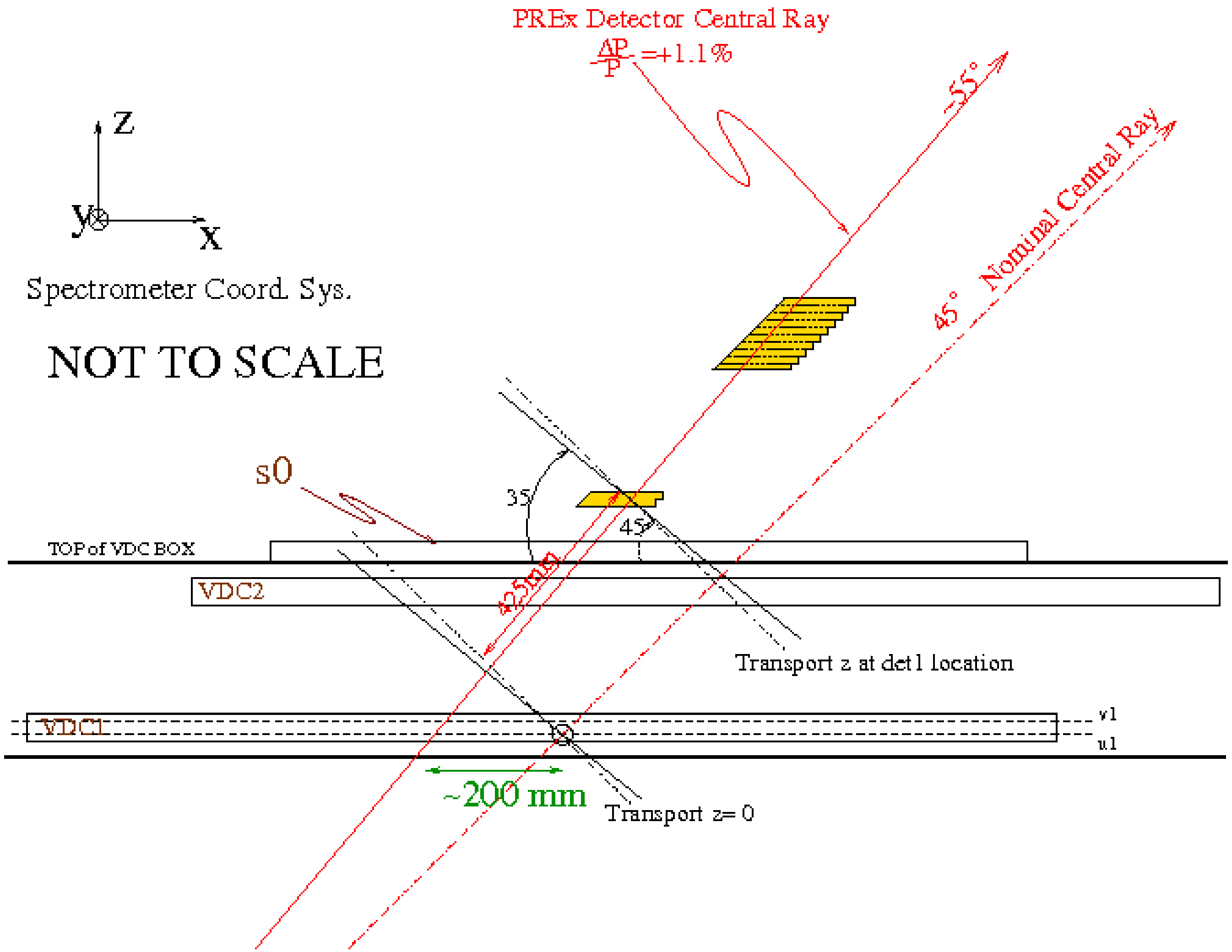
PREx Detector Central Ray
$\frac{\Delta P}{P}$ =+1.1%
~55°
45° Nominal Central Ray
Z
y
X
Spectrometer Coord. Sys.
NOT TO SCALE
s0
35
45
TOP of VDC BOX
VDC2
425mm
Transport z at det1 location
VDC1
v1
u1
~200 mm
Transport z= 0

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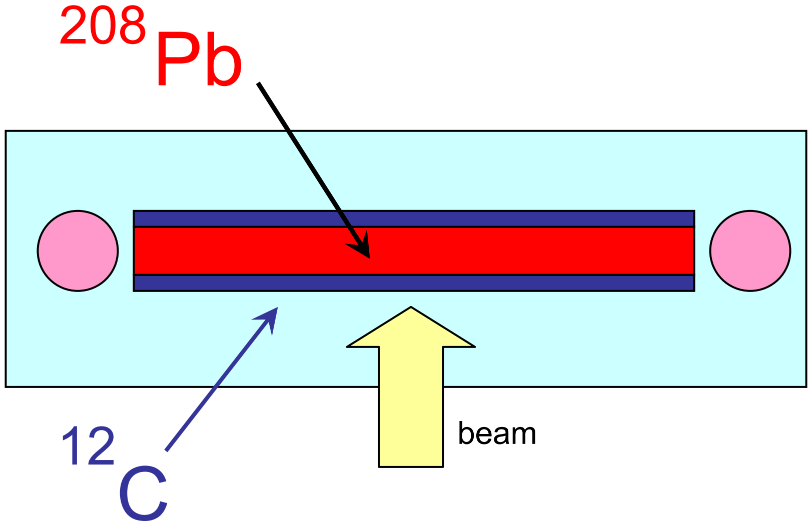
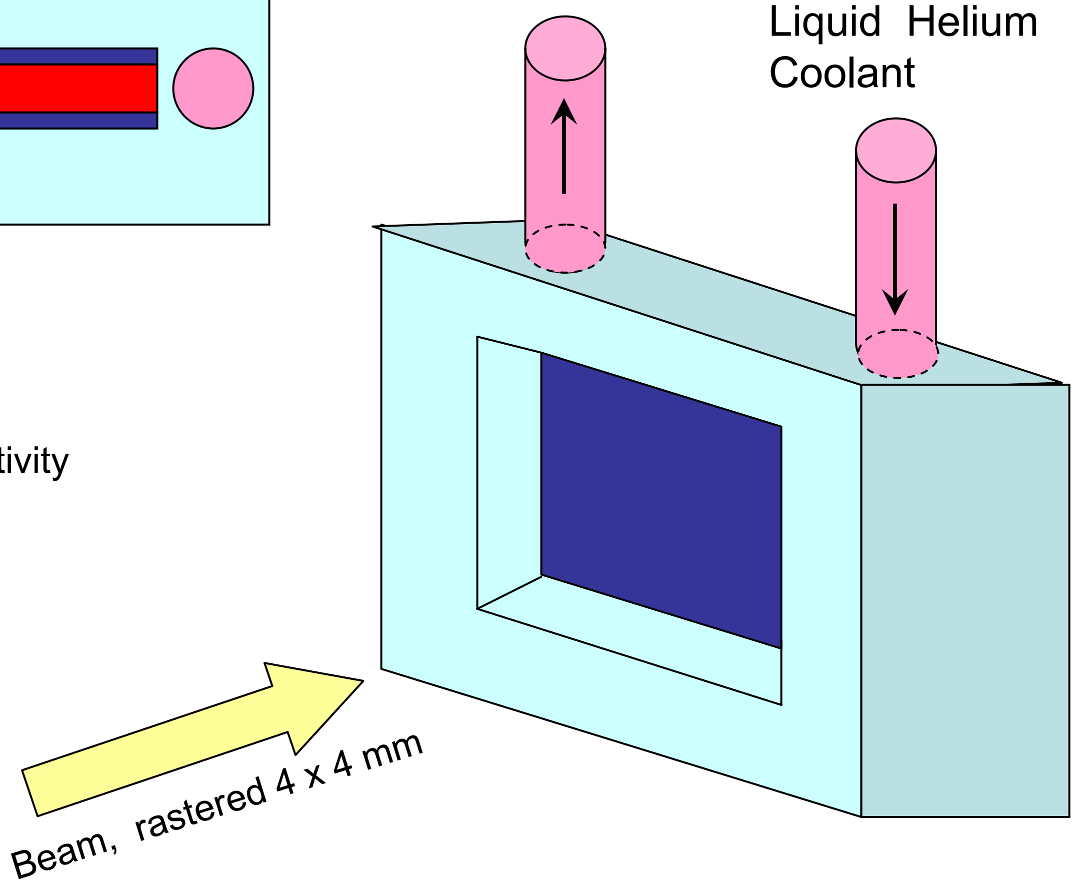
Lead Target



Diamond Backing:

- High Thermal Conductivity
- Negligible Systematics



Successfuly tested

5 days	at	60 uA
1 shift	at	80 uA
3 hrs	at	100 uA

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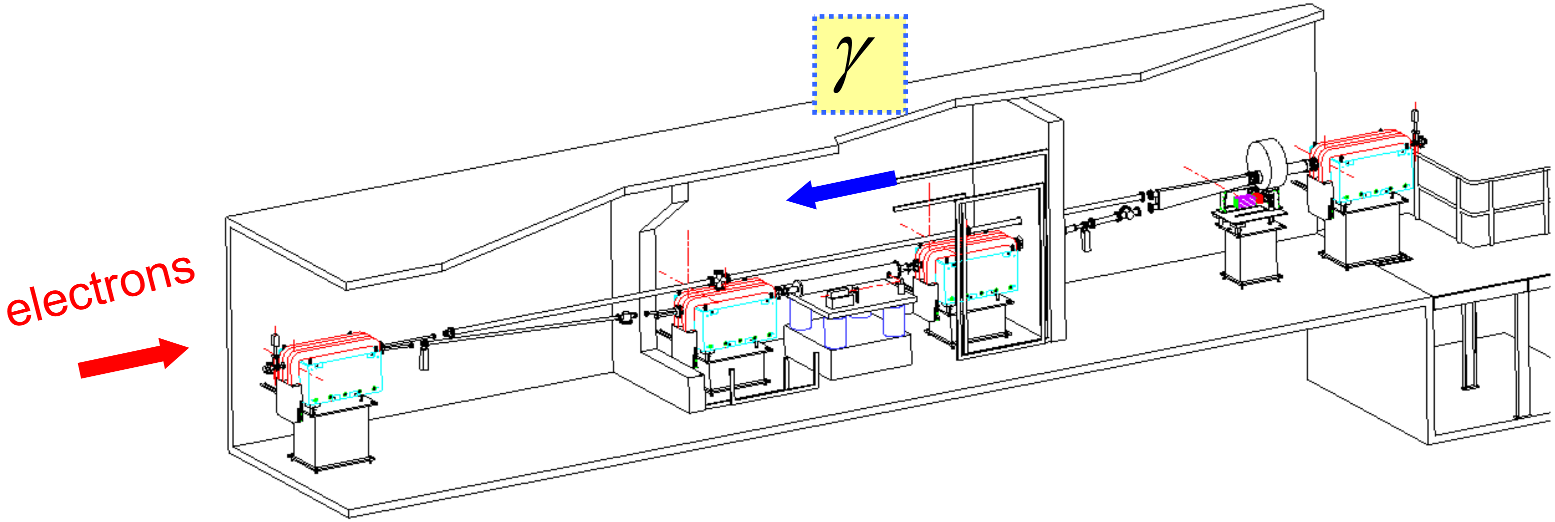
Polarimetry

Upgrade of Compton Polarimeter

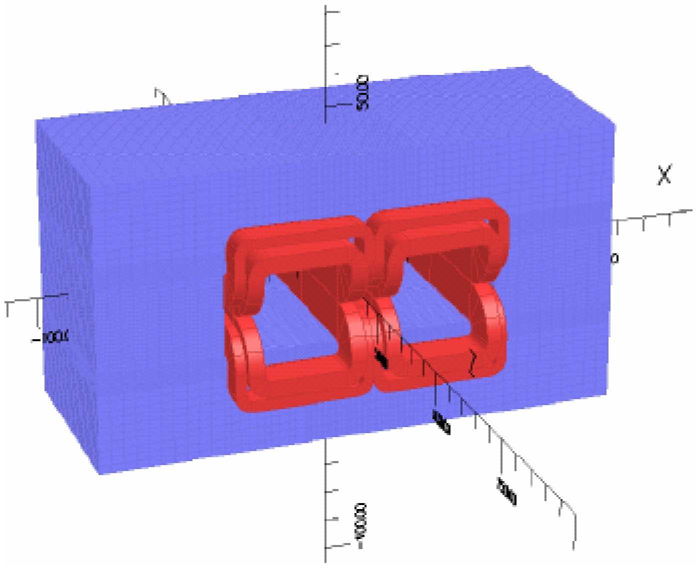


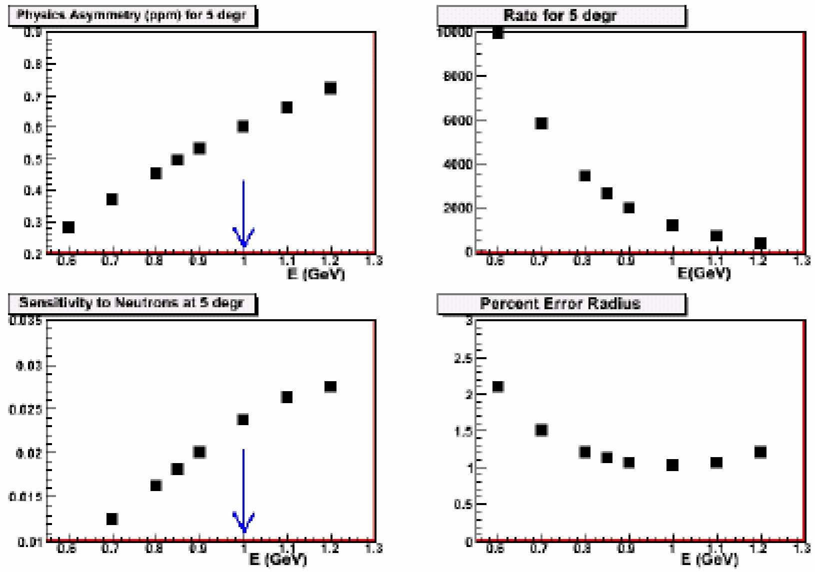
To reach 1% accuracy:

- **Green** **Laser** ➔ Green Fabry-Perot cavity **(increased sensitivity at low E)**
- **Integrating Method** **(removes some systematics of analyzing power)**
- **New Photon and Electron Detectors** **(new GSO photon calorimeter, FADC based photon integration DAQ)**

Upgrade Møller polarimeter: 4 Tesla field saturated iron foil, new FADC DAQ

New Septum Magnet





Designed by Paul Brindza and Al Gavalya.

At 5^0 the new Optimal FOM is at 1.05 GeV (±0.05).

Higher E_{beam} helps with Compton polarimetry.

The septum magnet is being manufactured and will arrive in the Fall.

Transverse Polarization

Part I: Left/Right Asymmetry

Transverse Asymmetry

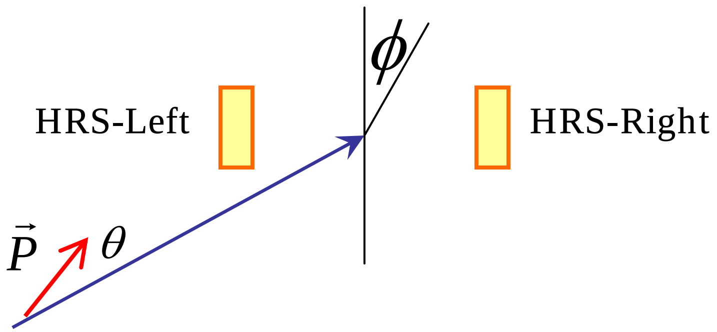
$$A_T \approx A_T^0 \; P_T \; \sin\phi$$

Theory est. (Afanasev)

$$A_T^0 = 5 \pm 1 \;\; ppm$$

Transverse polarization

$$P_T = P \sin\theta \qquad \theta \leq 3^o$$



Systematic Error for Parity

$$\rightarrow \quad \delta A = \delta\left(A_T^0 \; \xi \; P_T\right)$$

"Error in"

ξ = Left-right apparatus asymmetry

Control θ w/ slow feedback on polarized source solenoids.

$\delta A_T^0 = \pm 1 \;\; ppm$ measure in ~ 1 hr (+ 8 hr setup)

Need $\xi \, P_T \ll 10^{-3} \pm 10^{-3}$

correction   syst. err.

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Transverse Polarization

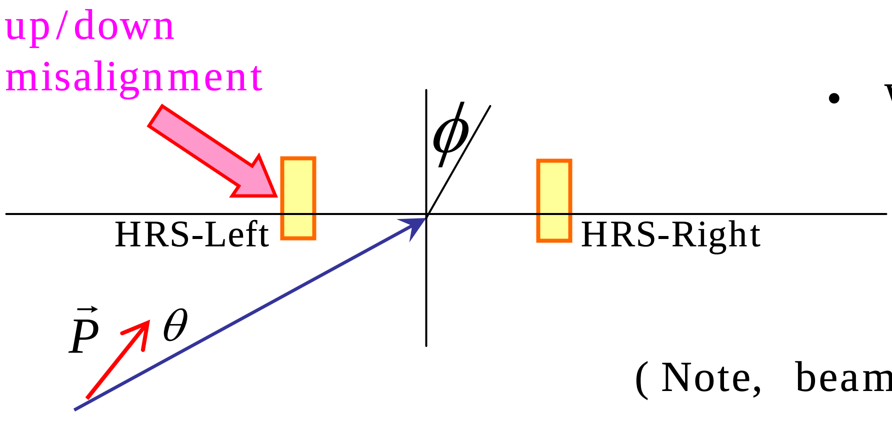
Part II: Up/Down Asymmetry

Vertical misalignment

Horizontal polarization
e.g. from (g-2)

$< \cos\ \phi > \neq 0 \quad \rightarrow$

$P_T = P \sin\theta$



Systematic Error for Parity

$$\delta A = \delta \left(A_T^0 \;\; P_T \; < \cos\ \phi > \right)$$

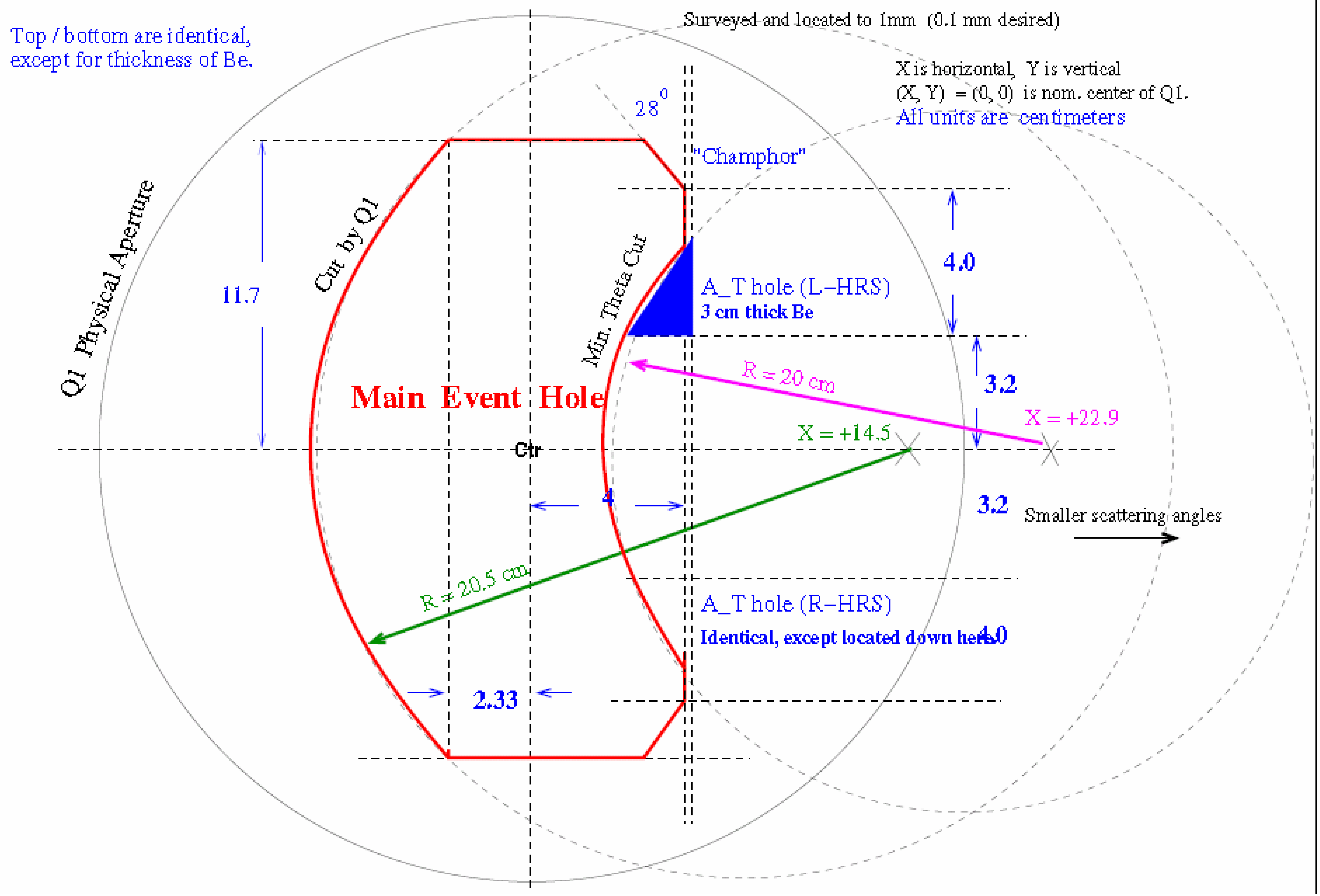
- Measured in situ using 2-piece detector.
- Study alignment with tracking & M.C.
- Wien angle feedback (θ)

Need

$$P_T < \cos\phi > \;\; \ll 10^{-3} \;\; \pm 10^{-3}$$

(Note, beam width is very tiny $\sim 100\ \mu m$)

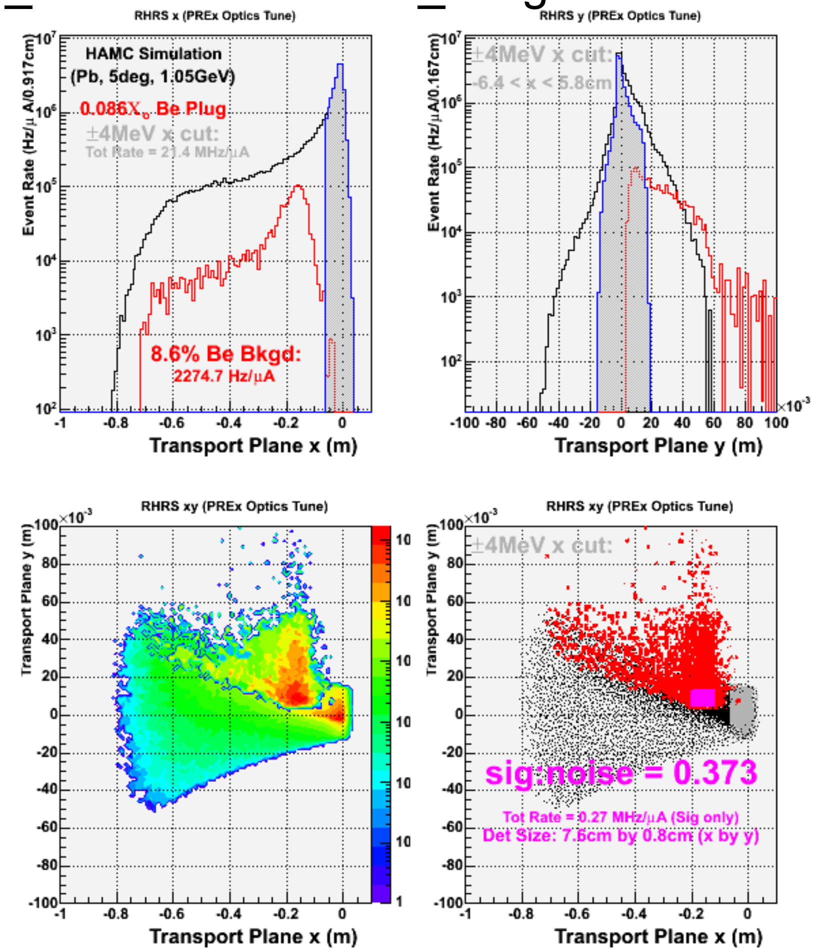
PREX Collimator



A_T detector design

Figure of Merit M = 1/E * 1/sqrt(R) * sqrt(1 + B/S)
where,
E = A_T enhancement for A_T hole events = 50.
R = Ratio of A_T hole detector to main Pb detector event rates
B/S = Ratio of bkgd under the A_T hole events to A_T signal

The optimum A_T detector dimension is ~7.6cm in x by 0.8cm in y. This gives Figure of Merit = 0.637 and error inflation ~1.186.



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Noise

- Need 100 ppm per window pair
- Position noise already good enough
- New 18-bit ADCs
  → Will improve BCM noise.
- Careful about cable runs, PMTs, grounds.
  → Will improve detector noise.
- Tests with Luminosity Monitor to demonstrate capability.

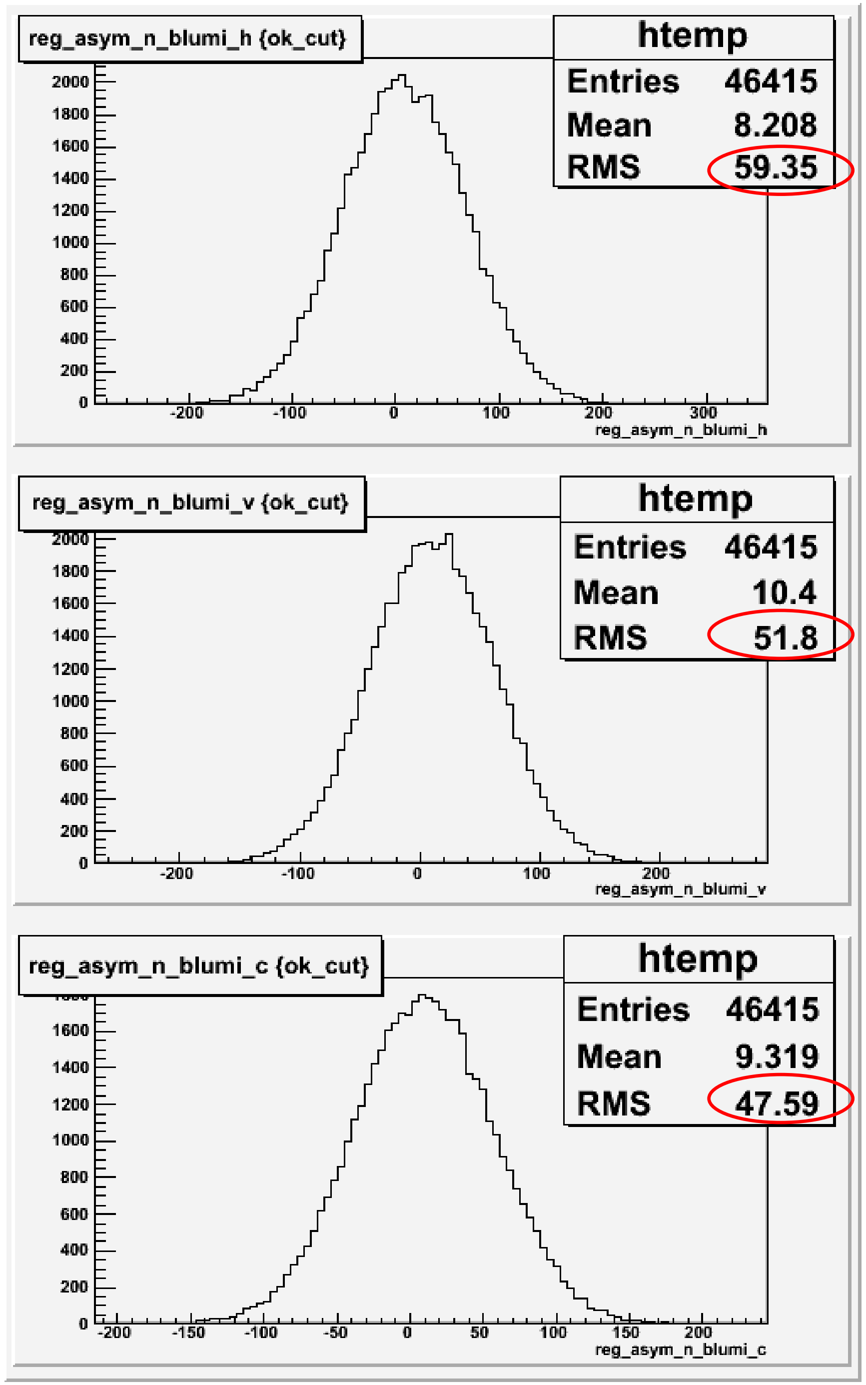
Asymmetries in Lumi Monitors

after beam noise subtraction

~ 50 ppm noise per pulse
→ milestone for electronics

(need < 100 ppm)

Jan 2008 Data

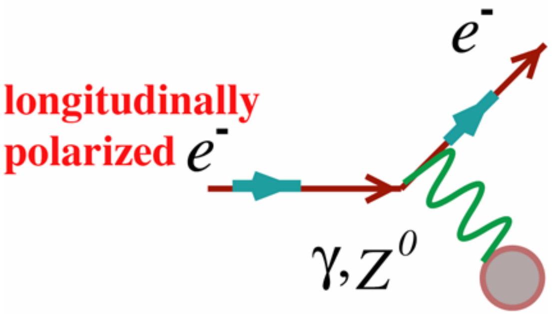


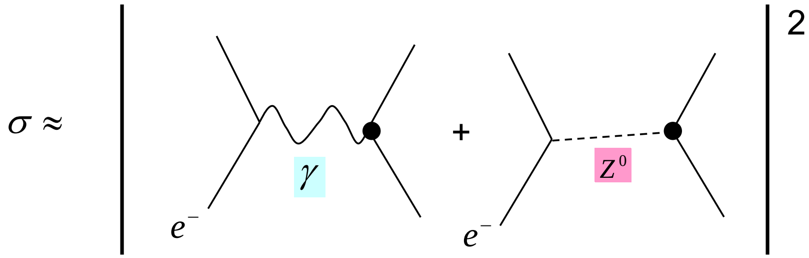
PREX: Summary

- PREX is an extremely challenging experiment:
  - $A_{PV} \approx 500 \pm 15$ ppb.
  - 1% polarimetry.
  - Helicity correlated beam asymmetry < 100 ± 10 ppb.
  - Beam position differences < 1 ± 0.1 nm.
  - Transverse beam polarization < 1%.
  - Noise < 100 ppm
  - (Not melting) Lead Target
  - Forward angle detection ➔ Septum magnet
  - Precision measurement of Q^2: ± 0.7% ➔ ± 0.02° accuracy in spectrometer angles
- However HAPPEX & test runs have demonstrated its feasibility.
- It will run in March-May 2010 and will measure the lead neutron radius with an unprecedented accuracy (1%). This result will have an impact on many other Physics fields (neutron stars, APV, heavy ions …).

Esperimenti di Violazione della Parità

- Misura accurata della asimmetria nei processi elastici (e DIS) di elettroni polarizzati longitudinalmente su nucleone/nucleo non polarizzato



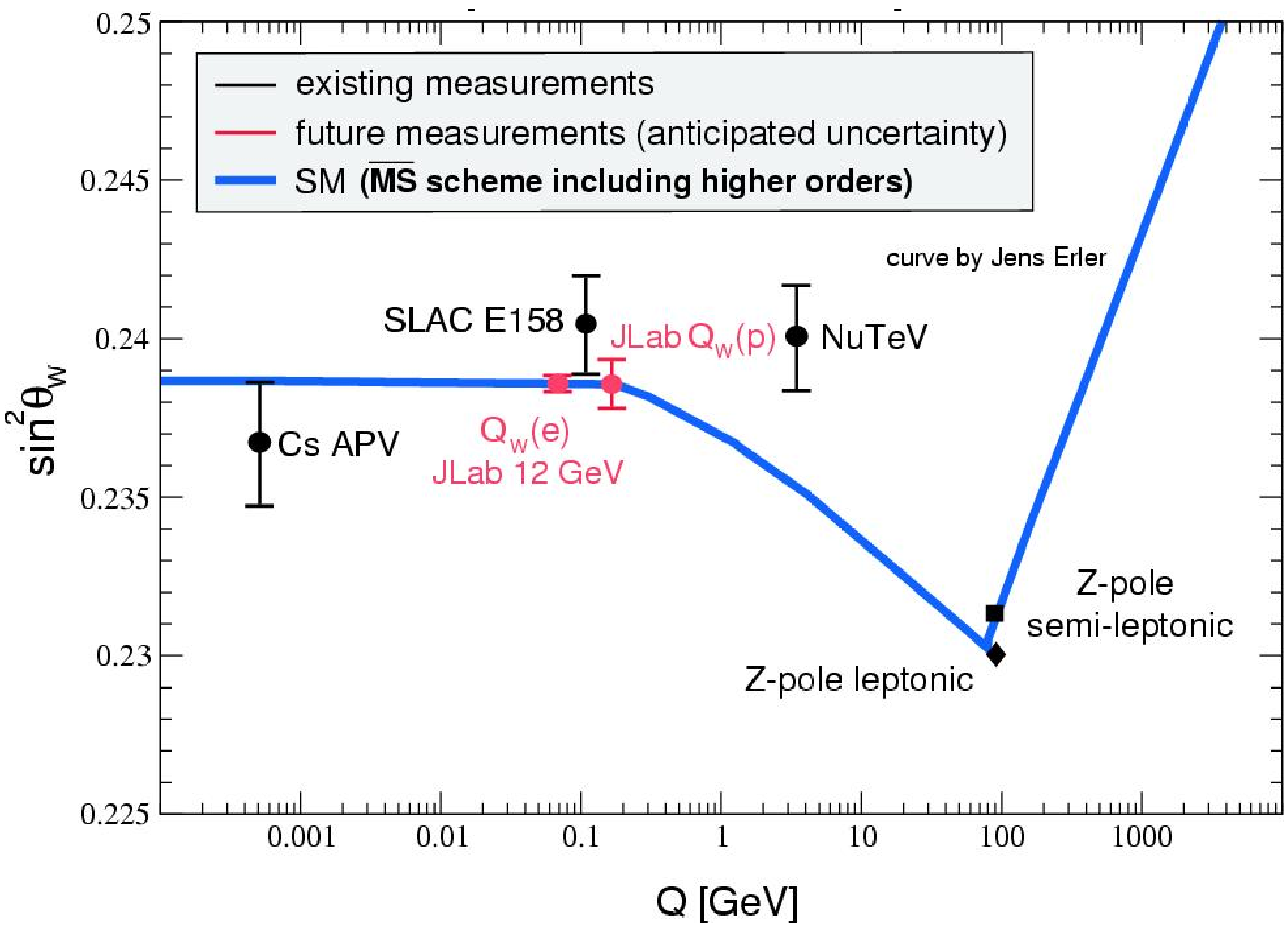


$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{Z^0}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left[1 - 4\sin^2\theta_W + \ldots\right]$$

$$Q^2 \sim 0.01 \div 1\ \mathrm{GeV}^2 \rightarrow A_{PV} \sim 10^{-7} \div 10^{-4}$$

- Accesso alle costanti di accoppiamento deboli elettroni-quark (u/d) delle correnti neutre, ovvero alla corrente debole del protone, ovvero all’angolo di mixing debole
- Pone limiti su esistenza di nuova fisica (PVDIS, QWeak, Möller)
- Ha permesso la misura del contributo dei quark s ai fattori di forma del nucleone (HAPPEX, G0)
- Permette la misura di importanti grandezze nucleari soppressi nei processi elettromagnetici $\Rightarrow$ PREX

Violazione di Parità e l'angolo di mixing a



Programma rilevante delle sale A e C