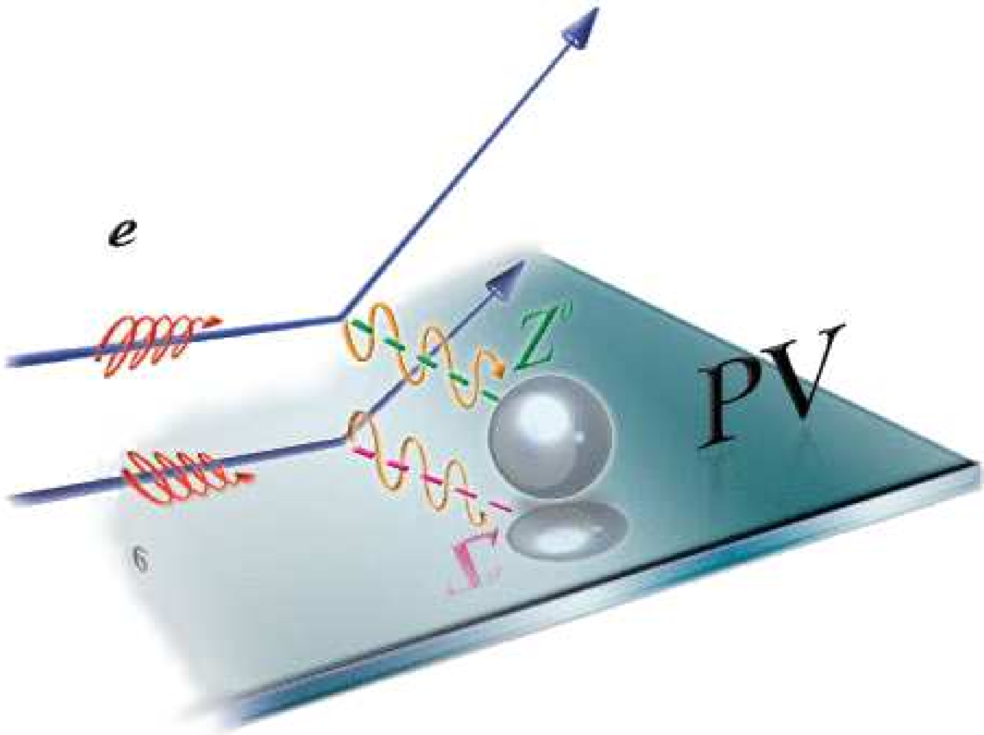
Parity-violating electron scattering on hydrogen and helium and strangeness in the nucleon

Hachemi Benaoum

Syracuse University

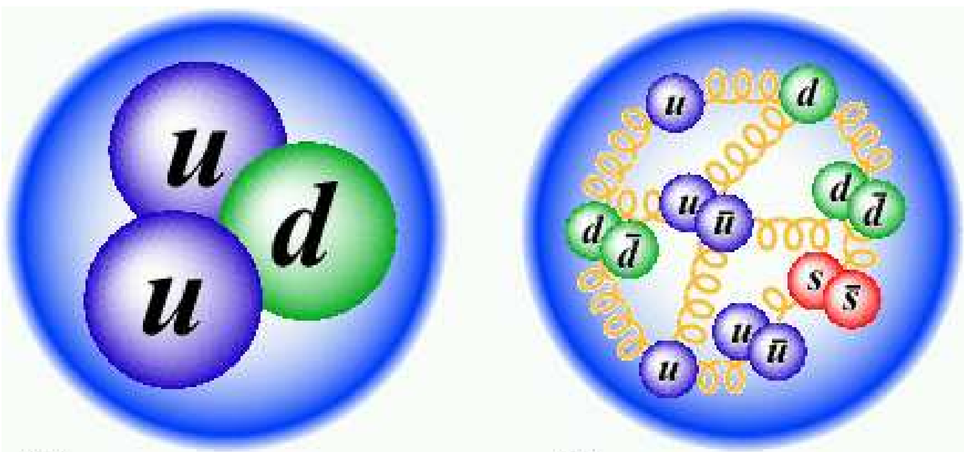
Outline

1. ***Strangeness in Nucleon***
2. ***Form Factors***
3. ***Parity violation***
4. ***The Happex experiment***
5. ***Conclusions***

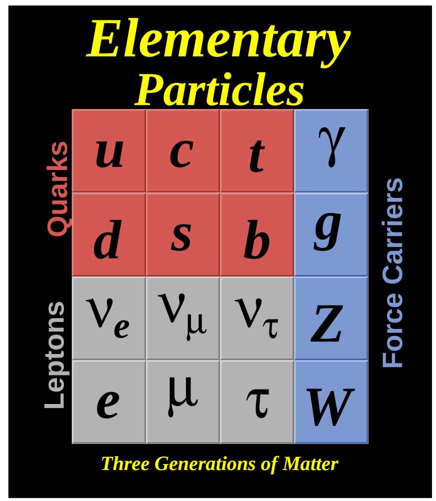


Strangeness in Nucleon

- Quark Model : Only u and d quarks in nucleon (valence quarks). No strangeness.
- QCD introduces color force between quarks carried by gluons g.
  - Nucleon from QCD : Valence quarks + Sea quarks + gluons.
  - Sea Quarks : $q\bar{q}$ pairs of **u, d, s** quarks arising from vacuum fluctuation.
  - Overall strangeness is zero, but s and $\bar{s}$ might not have identical distributions. So strangeness might manifest locally.



(a) (b)



Strangeness in Nucleon

Strange quark contribution to nucleon properties :

- Mass $\sigma_s =< N|\bar{s}s|N >$
  - From $\pi - N\ \sigma$ term : perhaps $> 5\%$ of nucleon mass due to strange quarks.
- Momentum
  - From $\nu - N$ Deep inelastic neutrino scattering :

    $\nu_\mu + d \longrightarrow \mu^- + c_{\hookrightarrow \mu^+ + \nu_\mu} \quad \propto |V_{cd}|^2 \sim \sin^2\theta_C$, highly suppressed

    $\nu_\mu + s \longrightarrow \mu^- + c_{\hookrightarrow \mu^+ + \nu_\mu} \quad \propto |V_{cs}|^2 \sim \cos^2\theta_C$, highly favoured
- Spin
  - The spin of the proton cannot be reproduced from the sum of the spin of quarks in nucleon (EMC experiment) $\Longrightarrow$ Spin crisis
  - $S = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G = \frac{1}{2}$, where $\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.20 \pm 0.10$

EM Form Factors

- Electromagnetic (EM) Form Factors
  - For pointlike particle with spin $1/2$, EM current is : $j_\mu^{EM} = Q_f \, \bar{\psi}_f \gamma_\mu \psi_f$
  - Hadronic matrix element of EM current between nucleon states, expressed in terms of two form factors F_1 and F_2 :

$$J_\mu^{EM} = \sum_q Q_q < \bar{N}|\bar{u}_q \gamma_\mu u_q|N >= \bar{N}\left(\gamma_\mu F_1^\gamma + \frac{i\sigma_{\mu\nu}q^\nu}{2M_N} F_2^\gamma\right) N$$

  - We usually use the Sachs definition of *electric* G_E^γ and *magnetic* G_M^γ form factor instead :

$$G_E^\gamma = F_1^\gamma - \tau F_2^\gamma, \quad G_M^\gamma = F_1^\gamma + F_2^\gamma, \quad \tau = \frac{Q^2}{4M_N^2}$$

  - Physically, G_E^γ and G_M^γ are just Fourier transform of eletric ρ_E and magnetic ρ_M charge density distributions :

$$\rho_{E,M}(\vec{r}) = \int \frac{d^3\vec{q}}{(2\pi)^3} G_{E,M}^\gamma(\vec{q})$$

EM Form Factors

- F_1 and F_2 are normalized for proton and neutron as :

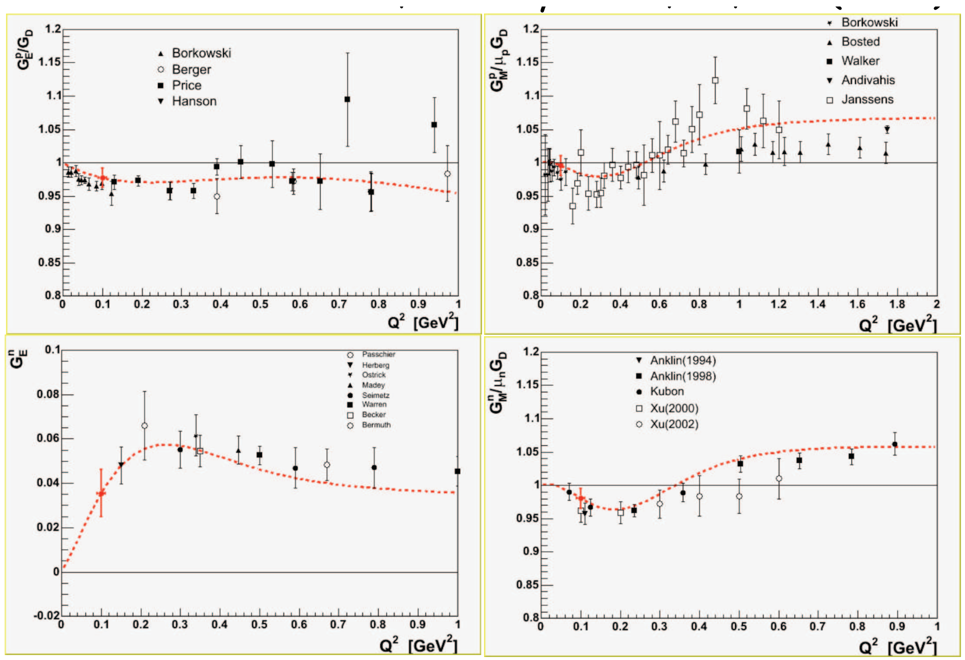
$$F_1^{p(\gamma)}(0) = 1, \quad F_2^{p(\gamma)}(0) = \kappa_p, \quad F_1^{n(\gamma)}(0) = 0, \quad F_2^{n(\gamma)}(0) = \kappa_n$$

such that

$$G_E^{p(\gamma)}(0) = 1, \quad G_M^{p(\gamma)}(0) = \mu_p = 2.79, \quad G_E^{n(\gamma)}(0) = 0, \quad G_M^{n(\gamma)}(0) = \mu_n = -1.91$$

- Experimental measurement of nucleon EM form factors vs. Q^2.

J. Friedrich and Th. Walcher
Eur. Phys. J. A17, 607 (2003)



NC Form Factors

- For pointlike particle with spin $1/2$: $J_\mu^{f(Z)} = \bar{u}_f (C_V^f - \gamma_5 C_A^f) u_f$ where $C_V^f = 2T_3^f - 4Q_f \sin^2\theta_W$, $C_A^f = -2T_3^f$.
- Weak neutral current for nucleon :

$$J_\mu^{NC} = \bar{N}\left(\gamma_\mu F_1^Z + \frac{i\sigma_{\mu\nu}q^\nu}{2M_N} F_2^Z + \gamma_\mu\gamma_5 G_A^Z + \frac{q_\mu}{M_N}\gamma_5 G_P^Z\right) N$$

  Contribution of pseudoscalar form factor G_P^Z proportional to lepton mass and can be neglected.
- Similarly, we use the Sachs *electric* and *magnetic* form factor parametrization :

$$G_E^Z = F_1^Z - \tau F_2^Z, \quad G_M^Z = F_1^Z + F_2^Z, \quad \tau = \frac{Q^2}{4M_N^2}$$

Flavor Decomposition of FF

They can be written in terms of quark form factors with relevant coupling constants :

$$G^{\gamma,p}_{E(M)} = \sum_{q=u,d,s} Q_q \, G^{q,p}_{E(M)} \;=\; \frac{2}{3} G^{u}_{E(M)} - \frac{1}{3} G^{d}_{E(M)} - \frac{1}{3} G^{s}_{E(M)}$$

$$G^{Z,p}_{E(M)} = \sum_{q=u,d,s} C^{q}_{V} \, G^{q,p}_{E(M)} \;=\; (1 - \frac{8}{3}\sin^2\theta_W) G^{u}_{E(M)} + (-1 + \frac{4}{3}\sin^2\theta_W)(G^{d}_{E(M)} + G^{s}_{E(M)})$$

Similar expression for axial form factor G_A .
Usual charge symmetry is assumed :

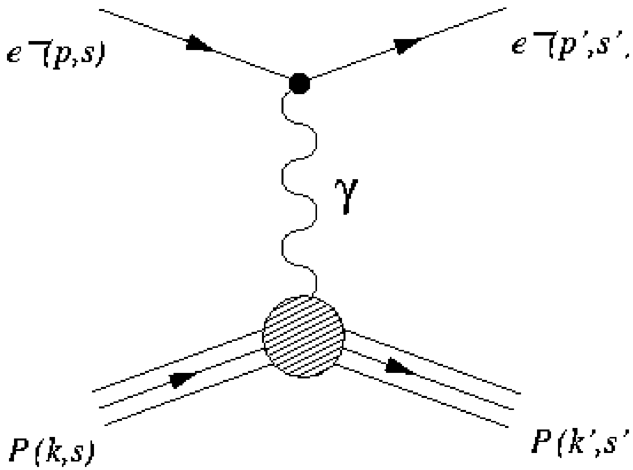
$$G^{u,p}_{E(M)} = G^{d,n}_{E(M)} \equiv G^{u}_{E(M)}$$
$$G^{d,p}_{E(M)} = G^{u,n}_{E(M)} \equiv G^{d}_{E(M)}$$

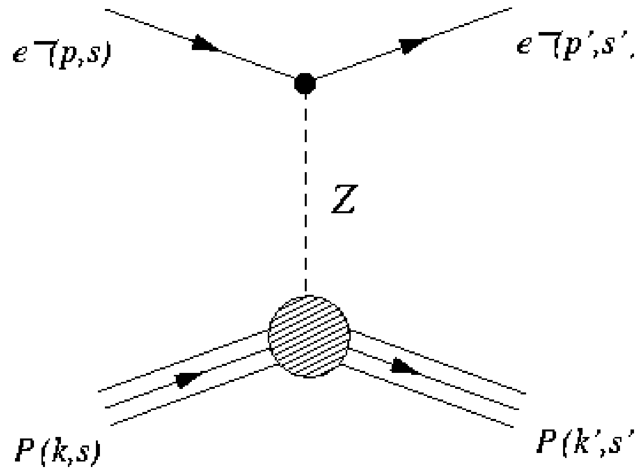
If G^s can be ignored, scattering from proton and neutron (*e.g.* deuteron) enough to determine FF for up and down quarks.

Z^0 exchange provides a third equation for determining G^s .

PV Electron Scattering

Scatter polarized electrons on target nucleons.





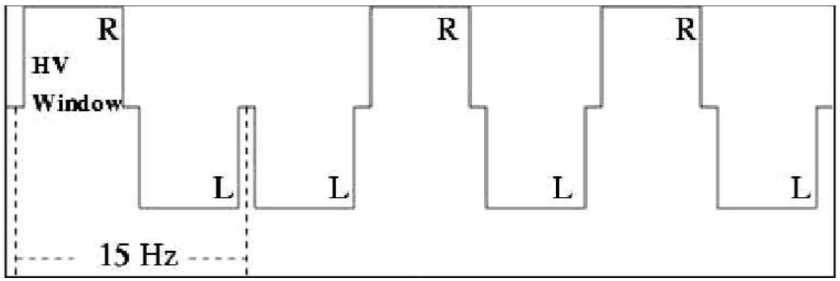
$$\sigma = |\mathcal{M}^\gamma + \mathcal{M}^Z|^2$$

$$\begin{aligned} A_{PV} &= \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{\mathcal{M}^{\gamma\star}\mathcal{M}^Z + \mathcal{M}^\gamma \mathcal{M}^{Z\star}}{|\mathcal{M}^\gamma|^2 + |\mathcal{M}^Z|^2} \approx 2\frac{\mathcal{M}^Z}{\mathcal{M}^\gamma} \\ &\approx \frac{Q^2}{{M_Z}^2} \end{aligned}$$

Measurement of PV Asymmetries

$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} \sim 10^{-6} \equiv 1ppm$$

- 5% statistical precision on $1ppm \Longrightarrow$ requires 4×10^{14} counts
- Measurement of PV asymmetry by rapid helicity flip at $30Hz$ (i.e. $33ms$).
- High luminosity : thick targets, high beam current.
- Control noise (target, electronics).
- High beam polarization and rapid flip.
- Beam must look the same for the two helicity states.



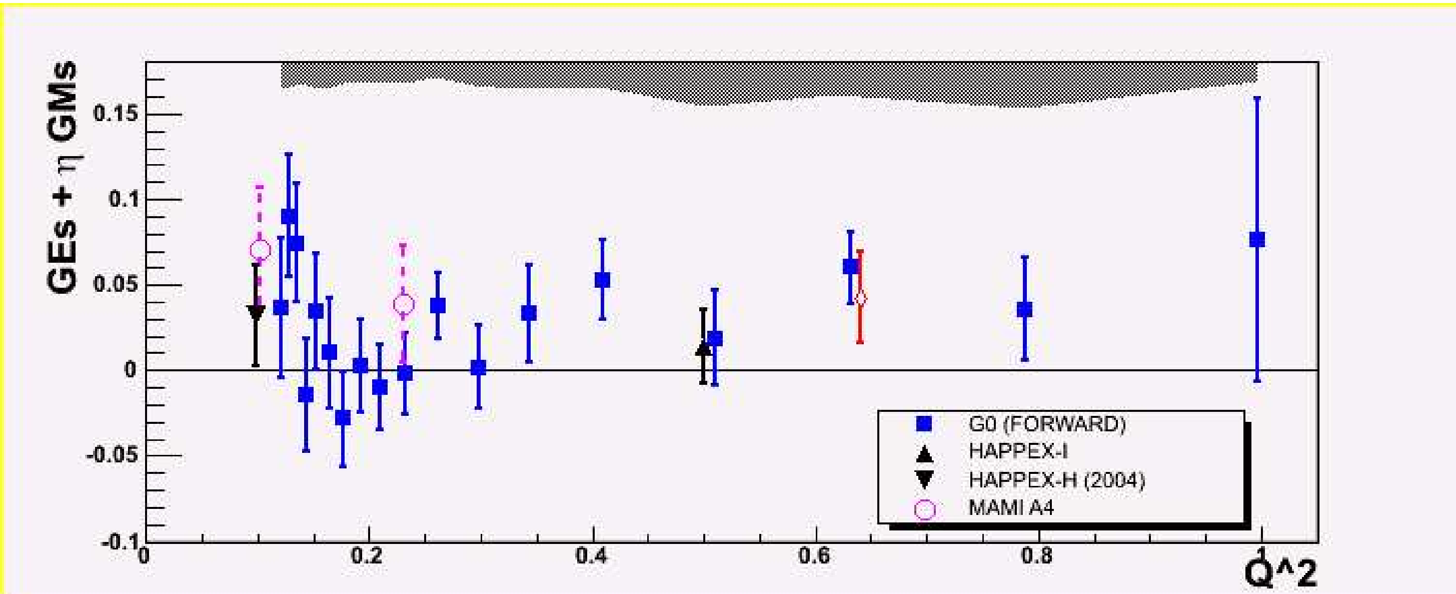
Previous Results

Experiment	Target	$Q^2\ GeV^2$	Asym ppm	Result
SAMPLE	H_2	0.1	$-5.61 \pm 0.67 \pm 0.88$	$G_M^s = 0.37 \pm 0.20 \pm 0.26 \pm 0.07$
SAMPLE	D_2	0.1	$-7.77 \pm 0.73 \pm 0.62$	$G_M^s = 0.23 \pm 0.36 \pm 0.40$
SAMPLE	D_2	0.038	$-3.51 \pm 0.57 \pm 0.58$	
HAPPEX I	H_2	0.477	$-14.92 \pm 0.98 \pm 0.56$	$G_E^s + 0.392 G_M^s = 0.014 \pm 0.020 \pm 0.010$
HAPPEX II	H_2	0.099	$-1.14 \pm 0.24 \pm 0.06$	$G_E^s + 0.08 G_M^s = 0.030 \pm 0.025 \pm 0.006 \pm 0.012$
HAPPEX II	^4He	0.091	$6.72 \pm 0.84 \pm 0.21$	$G_E^s = -0.038 \pm 0.042 \pm 0.010$
A4	H_2	0.230	$-5.44 \pm 0.54 \pm 0.26$	$G_E^s + 0.225 G_M^s = 0.039 \pm 0.034$
A4	H_2	0.108	$-1.36 \pm 0.29 \pm 0.13$	$G_E^s + 0.106 G_M^s = 0.071 \pm 0.036$
G0	H_2	0.1 to 1.0	$-1.$ to $-40.$	see next slide

G0 forward angle results

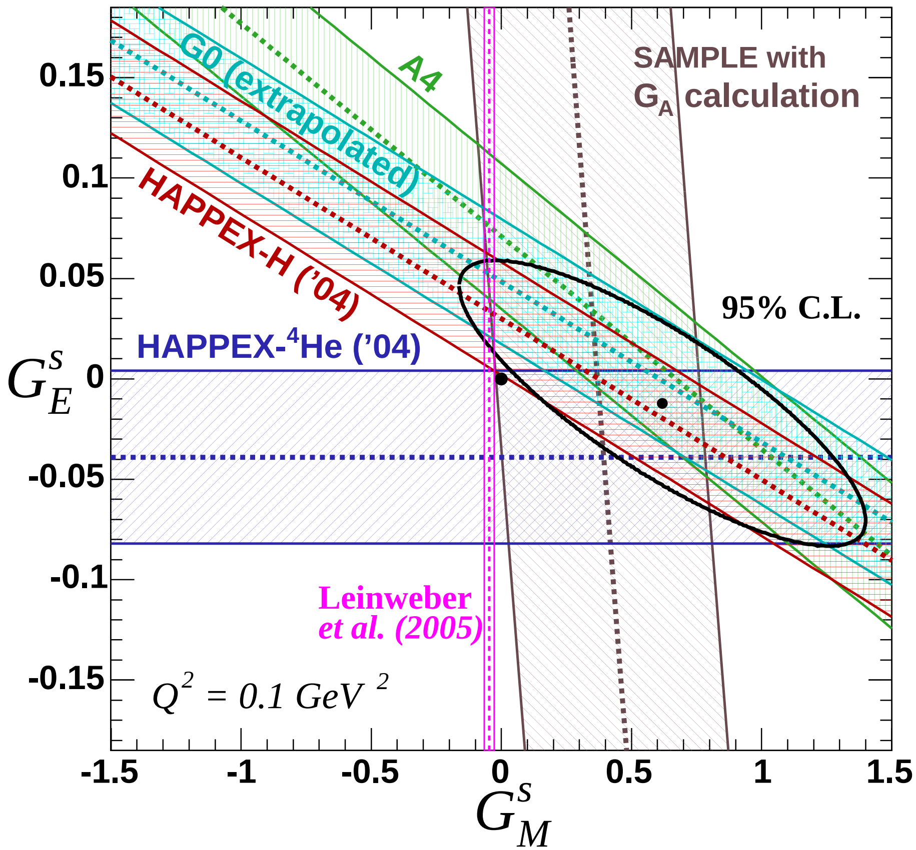
Measurement by G0 suggested :

- large values at $Q^2 \sim 0.1 GeV^2$
- possible large concellation at $Q^2 \sim 0.2 GeV^2$
- possible large values at $Q^2 > 0.4 GeV^2$



World Data at $Q^2 \sim 0.1 GeV^2$

Note : excellent agreement of world data set.



$$G_E^s = -0.12 \pm 0.29$$
$$G_M^s = 0.62 \pm 0.32$$

This implies that $\sim 9.6\% \pm 5\%$ of nucleon magnetic moment is strange.

PV Electron Scattering

For Proton :

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{\epsilon G_E^p G_E^Z + \tau G_M^p G_M^Z - \delta G_M^p G_A^p}{\epsilon {G_E^p}^2 + \tau {G_M^p}^2}$$

where ϵ,τ and δ kinematics parameters.

- ϵ and τ terms contribute for forward angle.
- τ and δ terms contribute for backward angle.

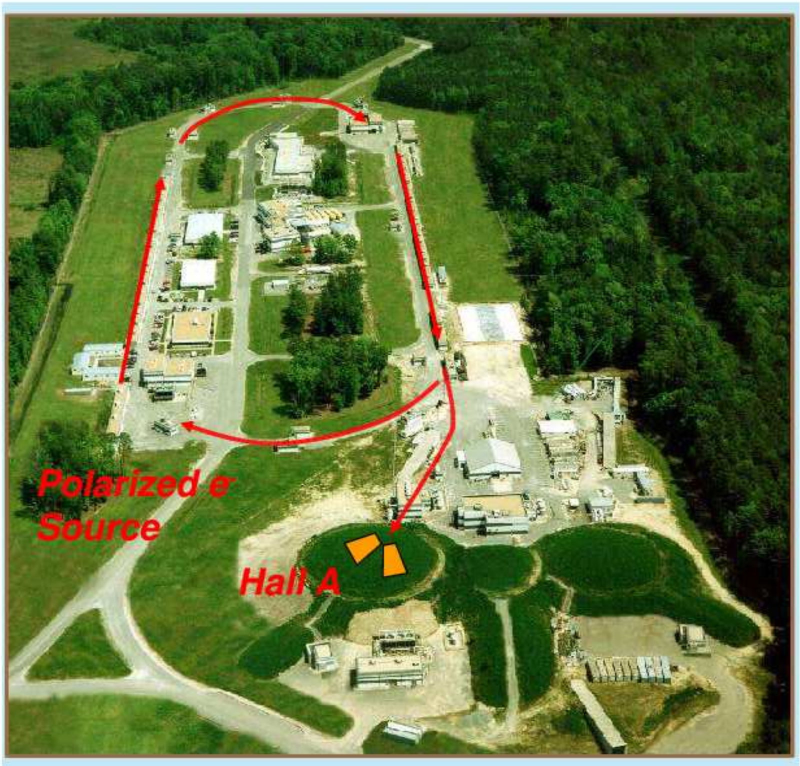
$$G_{E,M}^Z = (1 - 4\sin^2\theta_W) G_{E,M}^p - G_{E,M}^n - G_{E,M}^s$$

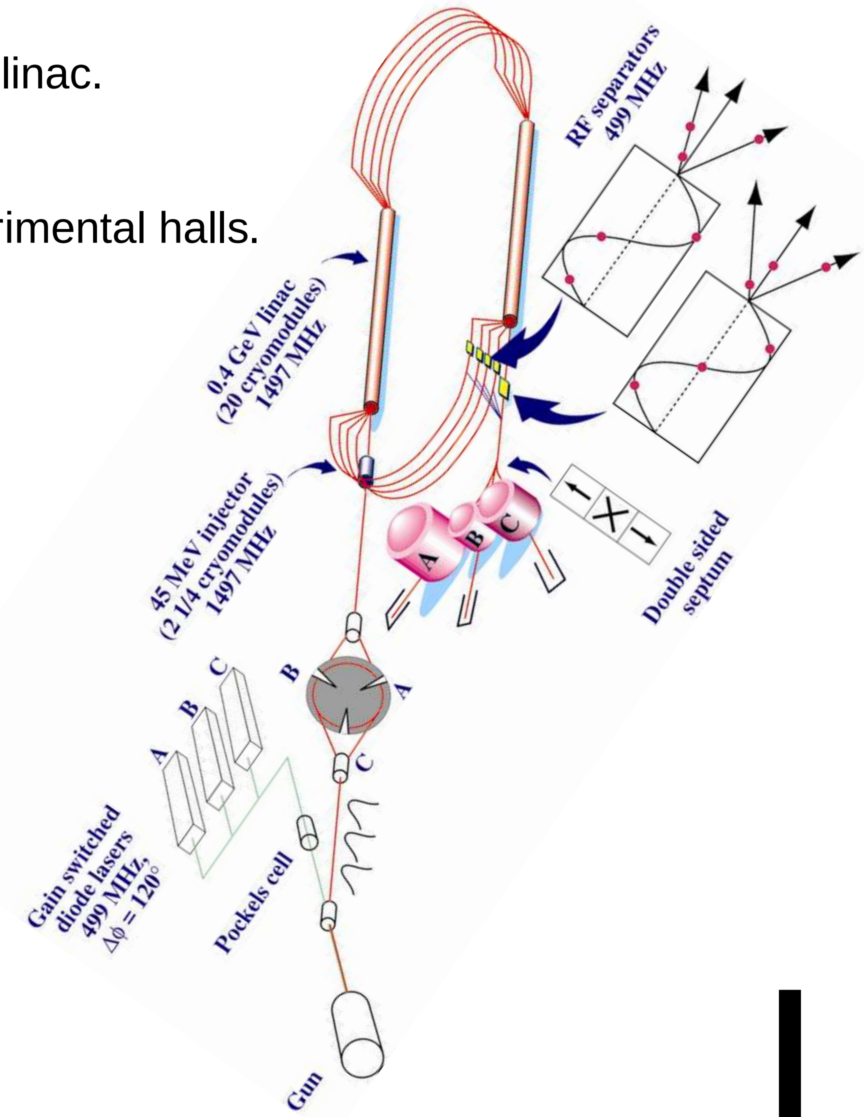
For ^{4}He :

$$A_{PV} = \frac{G_F Q^2}{\pi\alpha\sqrt{2}} \left(\sin^2\theta_W + \frac{G_E^s}{2(G_E^p + G_E^n)} \right)$$

CEBAF at JLab

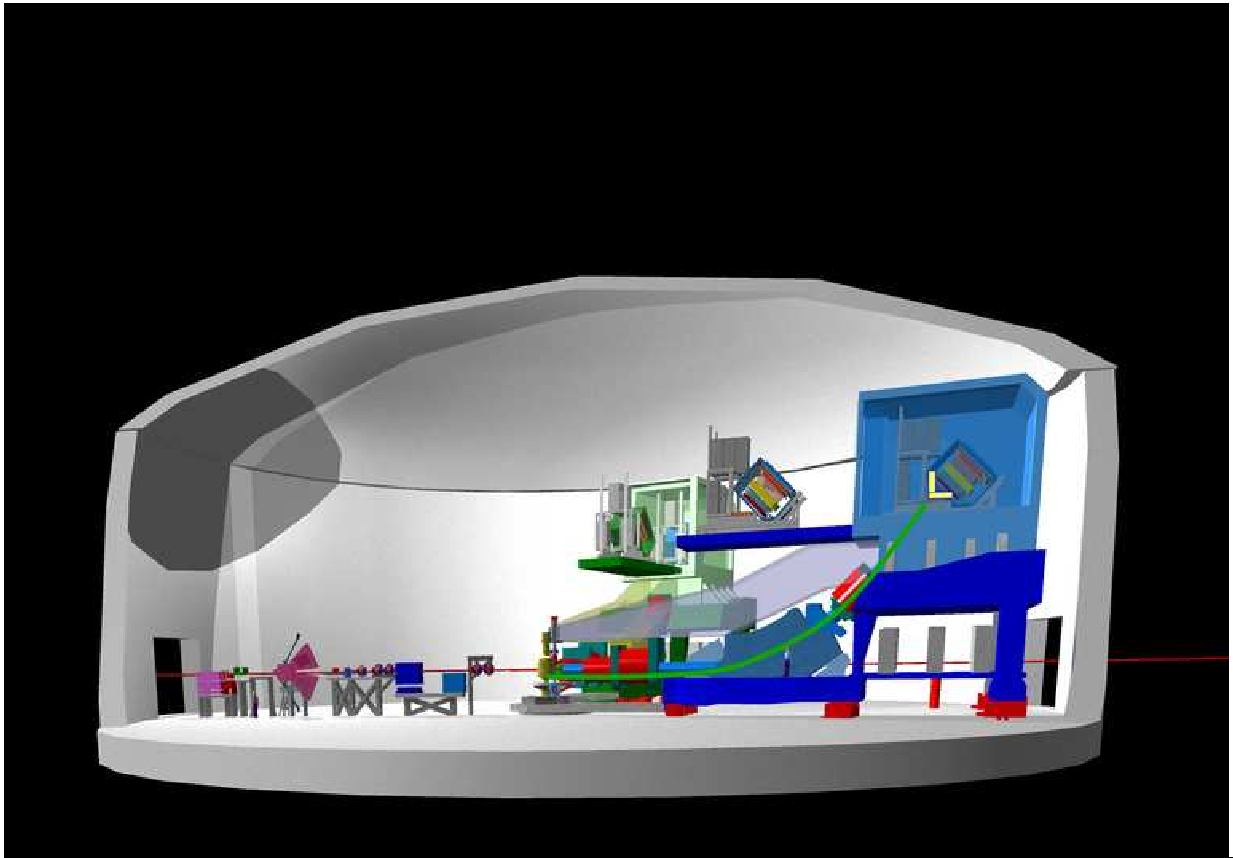
- Superconducting, continuous wave, recirculating linac.
- Up to 5 passes, up to 1.2 GeV per pass.
- Independent extraction and separation to 3 experimental halls.





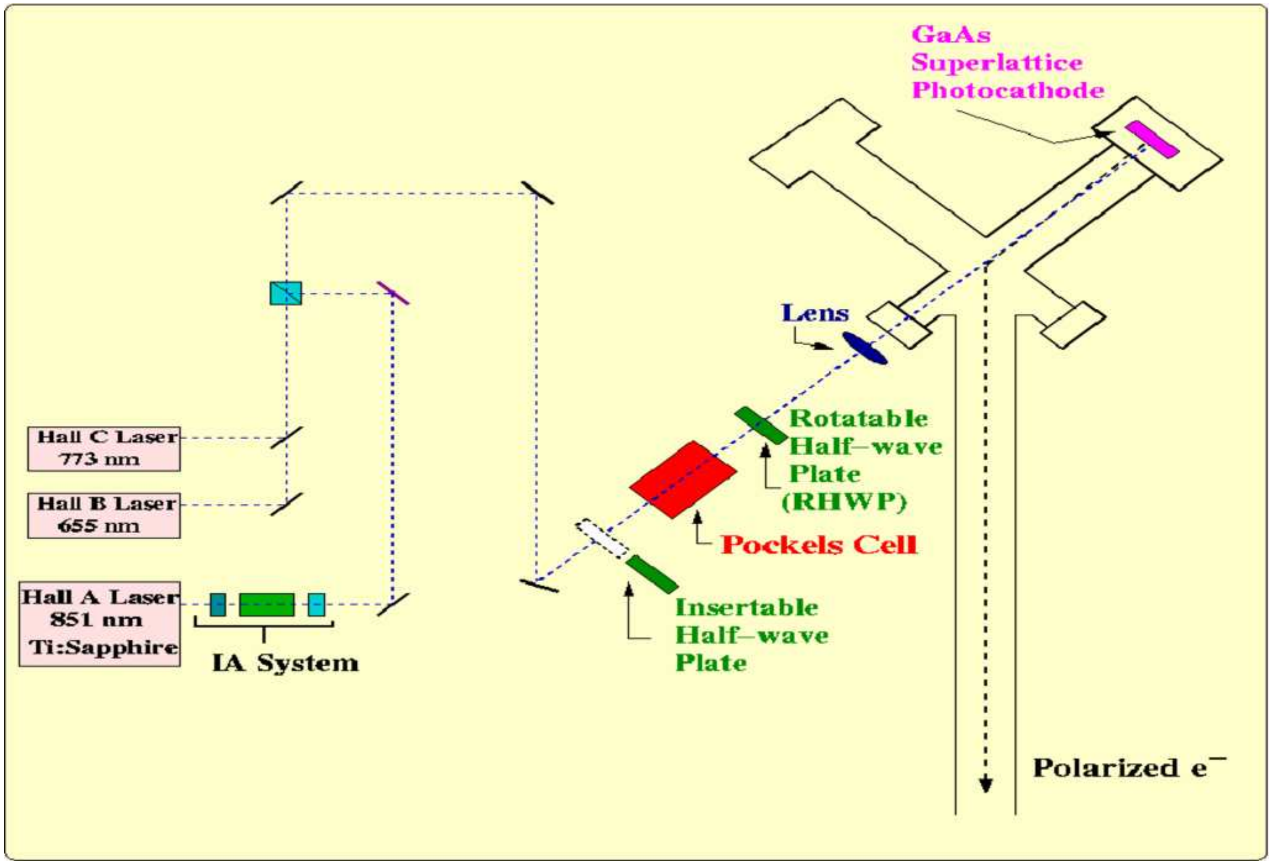
HAPPEX (2nd generation)

- Kinematics : $E = 3GeV, \theta = 6^{\circ}, Q^2 = 0.1GeV^2$
- Hydrogen : $G_E^s + \alpha G_M^s$
- ^{4}He : Pure G_E^s

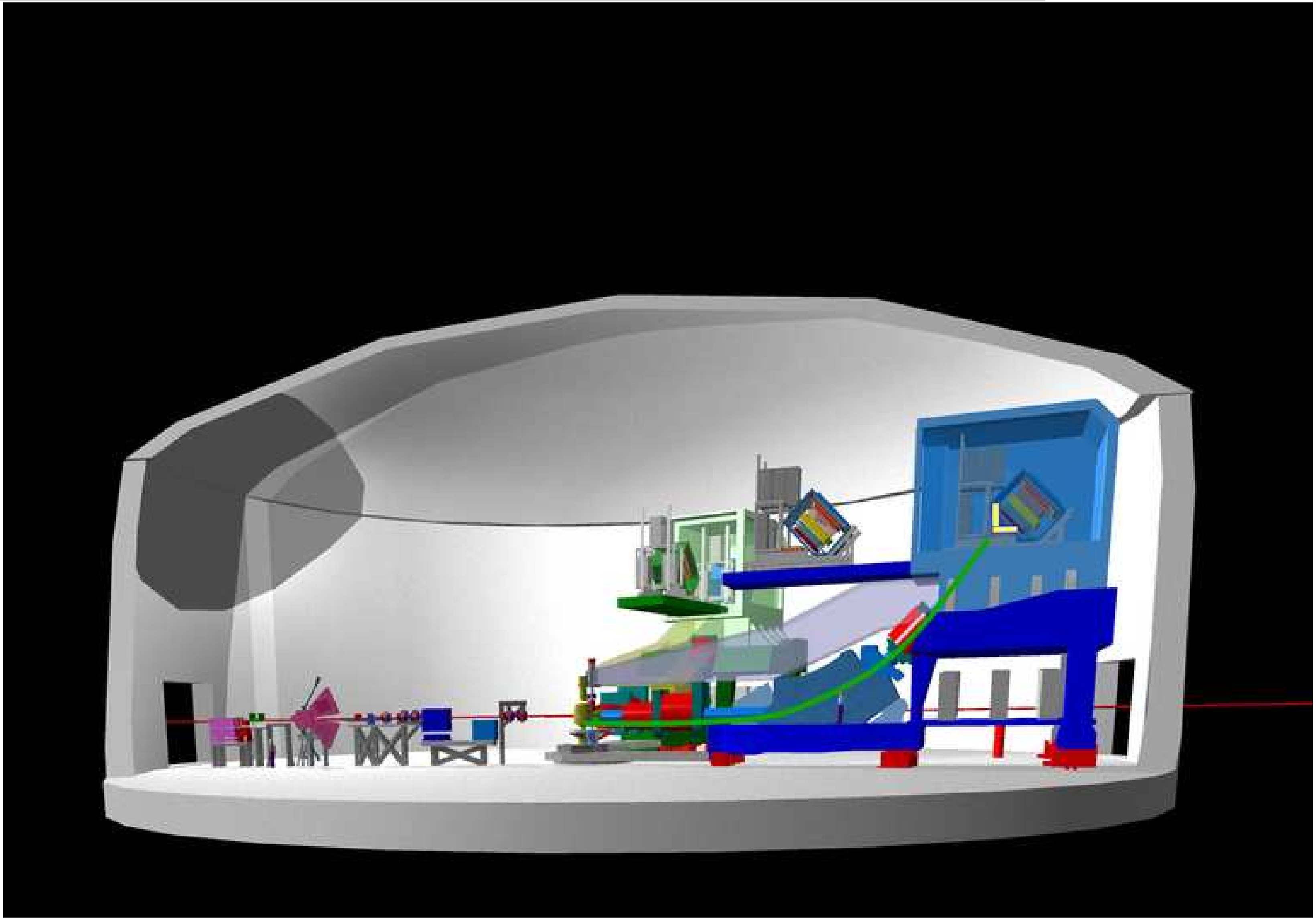


Polarized Source

- 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.

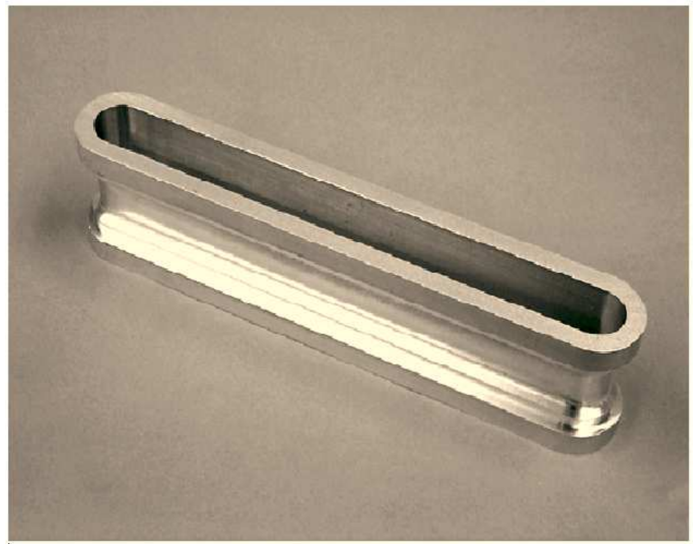


Hall A

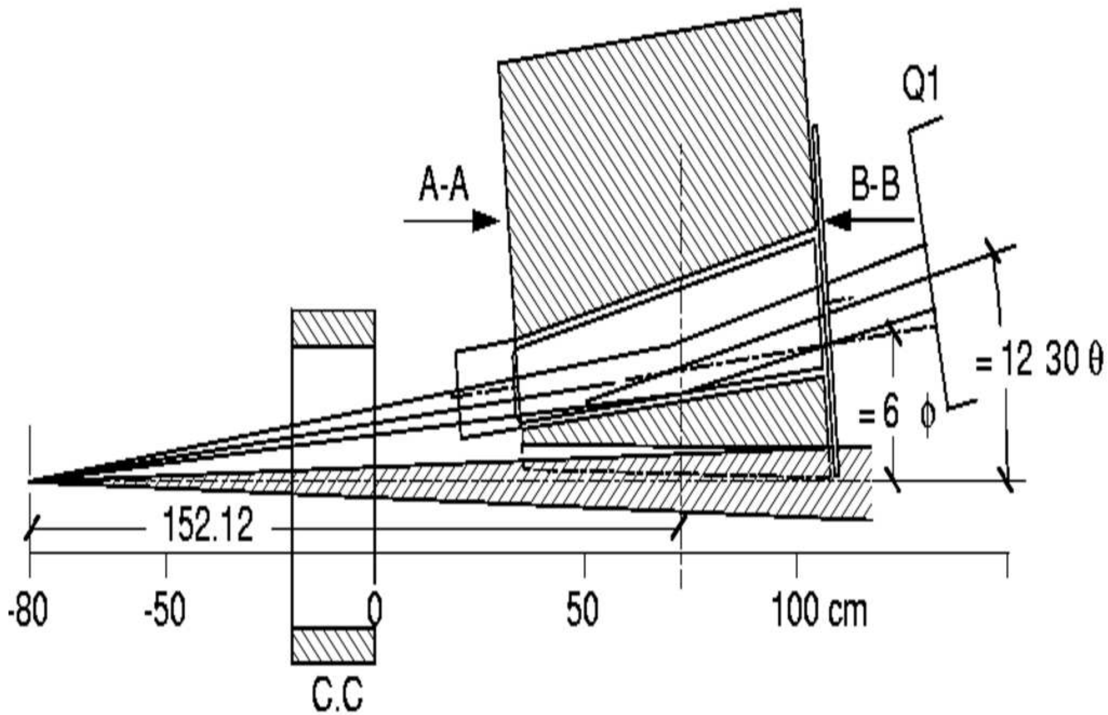


Target

- 20 cm Racetrack with transverse croygen flow.
- 20 cm LH_2.
- 20 cm ^{4}He gas cell.



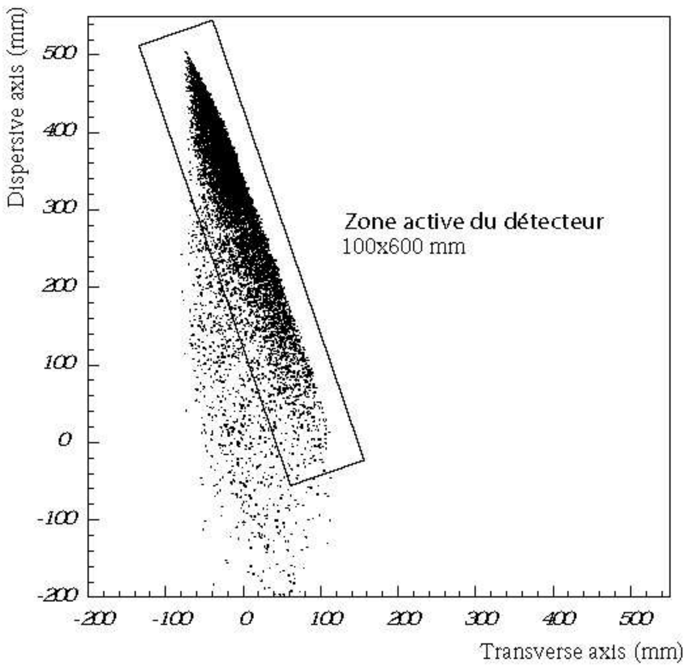
Septum Magnets

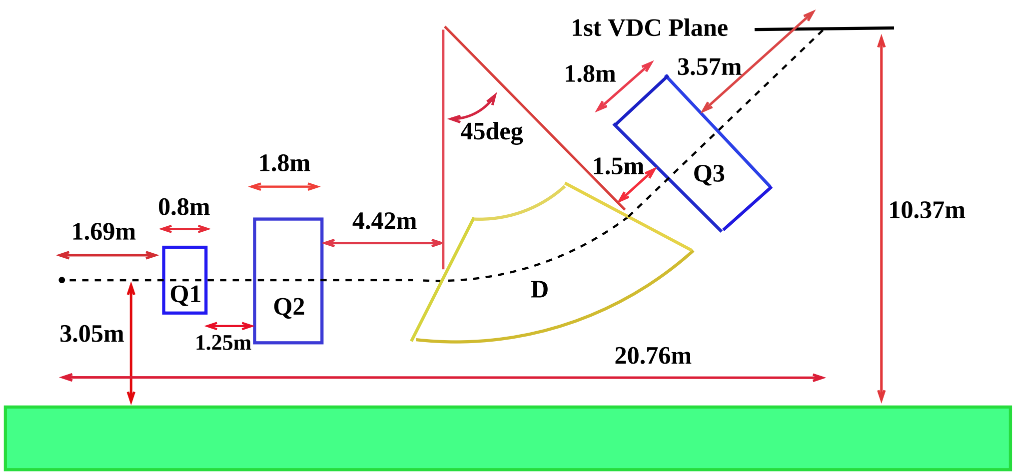


- Electrons scattered at 6° sent to the high resolution spectrometer at 12.5°.
- Superconducting magnets with low power, sensitive to scattered flux from target.
- Sweeper Magnet, to sit inside the scattering chamber, used in 2005 to reduce the flux of low energy Moller electrons.

High Resolution Spectrometers

- QQDQ superconducting magnets.
- Clean separation of elastic events by HRS optics.

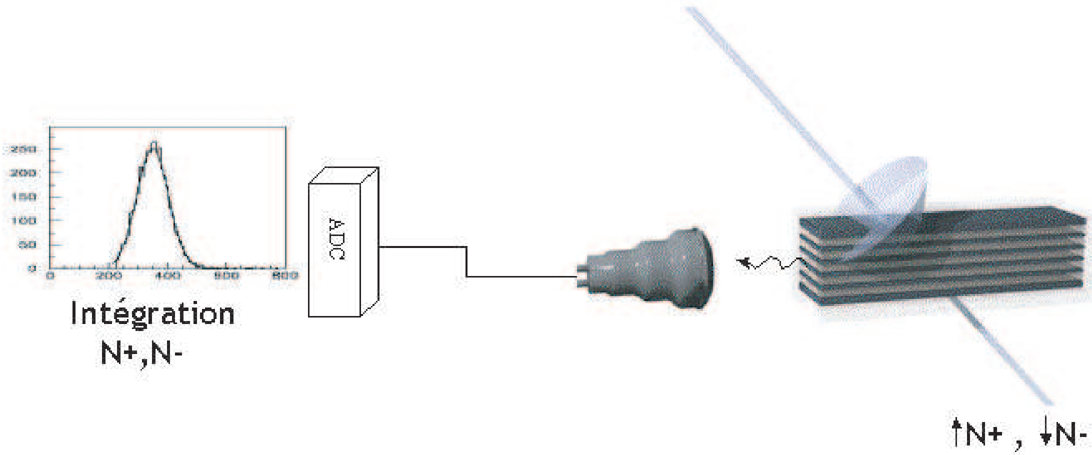


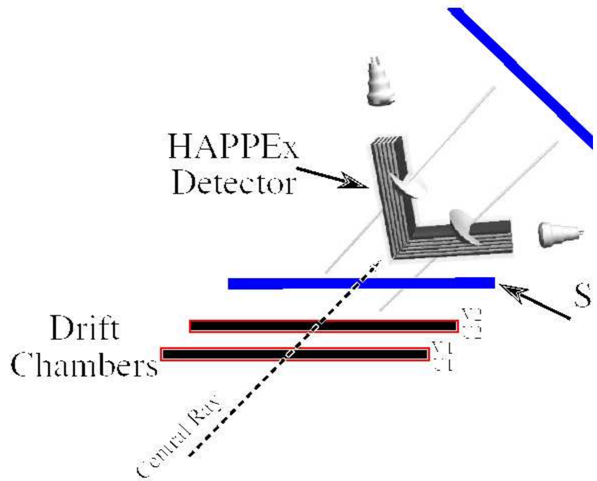


HRS Design Layout

Detectors

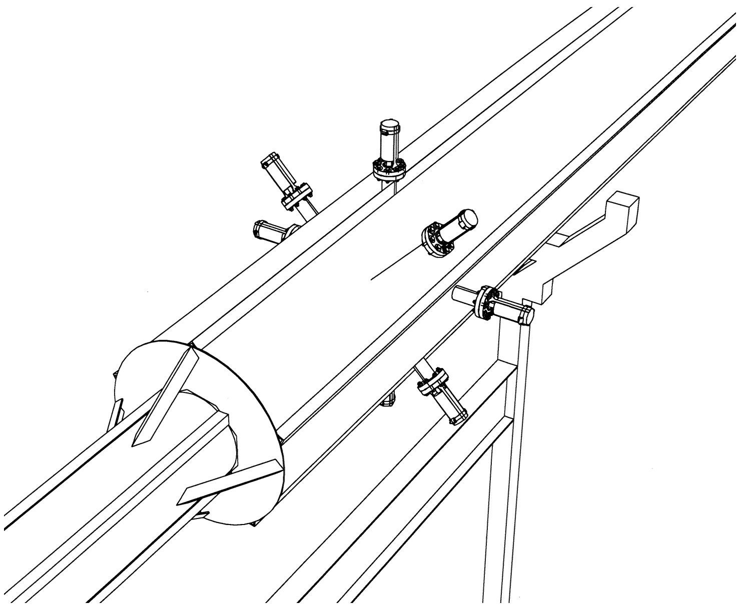
- Cerenkov shower calorimeter made of brass and quartz layers.
- Cerenkov light is collected by PMT.
- Signal is integrated over each helicity window.

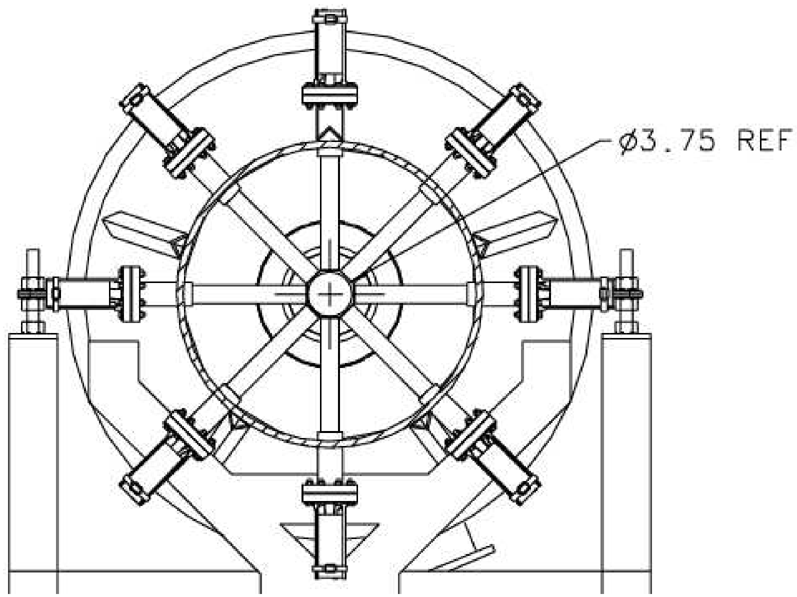




Luminosity Monitor

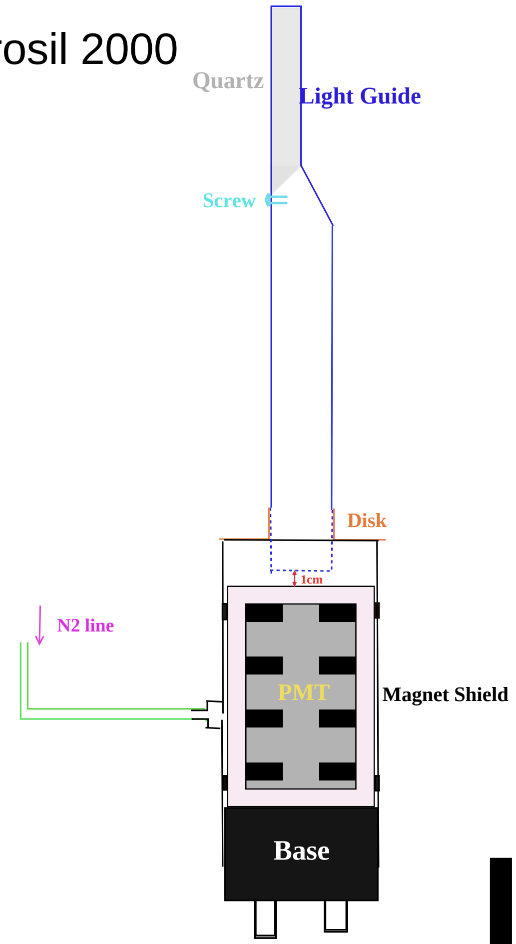
- Located at 7 m from the target.
- Consists of eight symmetrically placed detectors.
- Scattering angle seen by these Lumis is $0.5° - 0.8°$.
- Signal in Lumis is dominated by Moller and elastic electrons.





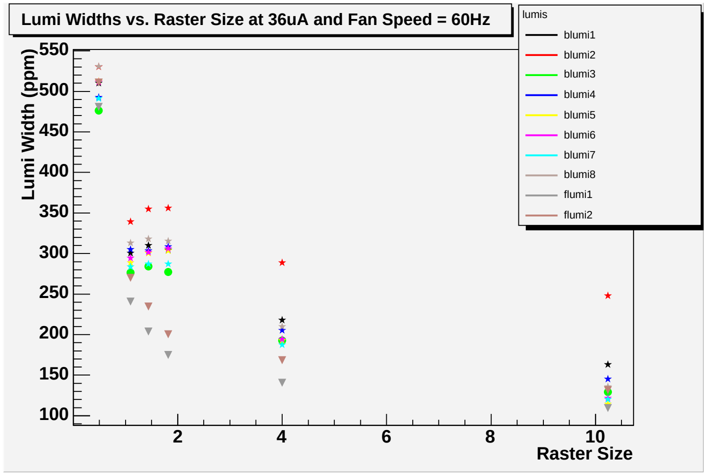
Luminosity Monitor

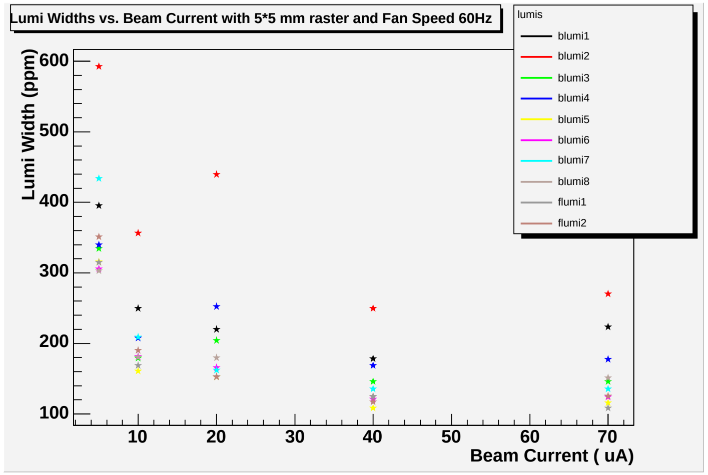
- It has 3 major parts :
  - Quartz : 1 cm $\times$ $\times$ 2 cm $\times$ 6 cm , rectangular bar of Spectrosil 2000 standard optical polish on all 6 faces.
  - Air Light–Guide : 40.5 cm long made of aluminium.
  - Photomultiplier.
- Cerenkov detectors.

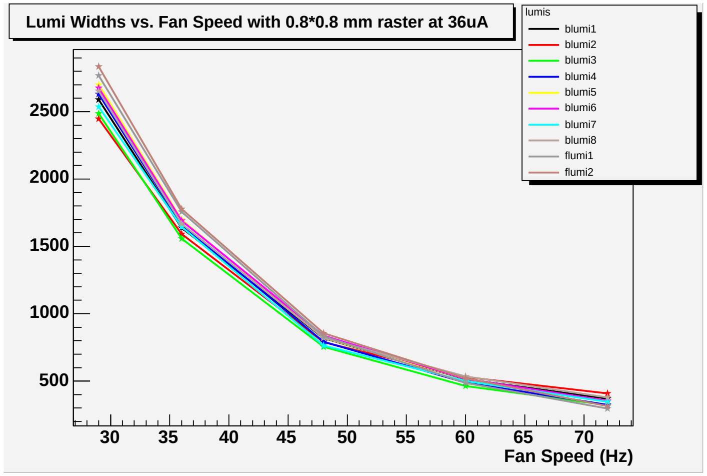


Luminosity Monitor

Used to study target boiling.







Analysis Overview

- Blinded Analysis
  - Online monitoring of the result.
  - Offline by calcuting the raw asymmetry, corrections to it and corrected asymmetry.
- Determining beam polarization, background corrections and average Q^2.
- Unblinding.
- Extracting the physical asymmetry.
- Calculating theoretical non-strange asymmetry.
- Extracting the strange form factors.

Physical Asymmetry

Integrated signal from detector : $S = S_E + \sum_i S_B^i$

$S_E(S_B^i)$ contribution from elastic scattering (background).
The experimental asymmetry $A_{exp} \equiv A_{corr}$:

$$A_{exp} = \frac{S^R - S^L}{S^R + S^L} = A_E \left(1 - \sum_i f_i\right) + \sum_i f_i A_{B\ i}$$

Therefore, the asymmetry from elastic scattering is :

$$A_E = \frac{A_{exp} - \sum_i f_i A_{B\ i}}{1 - \sum_i f_i}$$

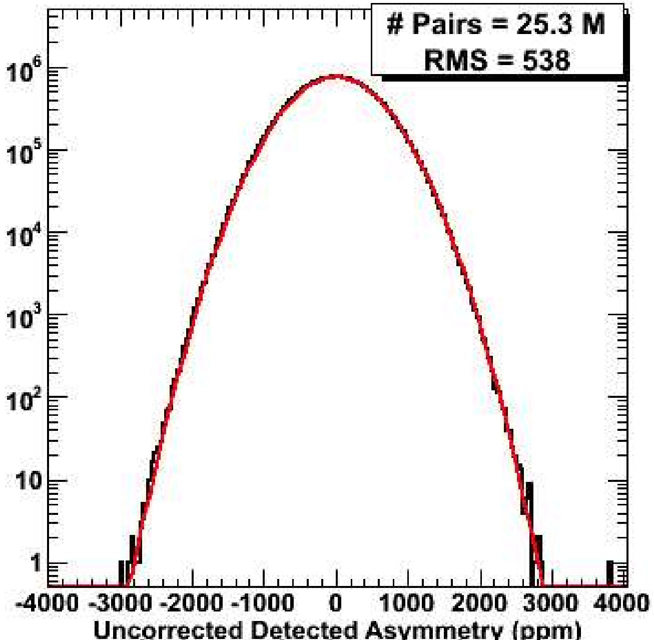
The physics asymmetry A_{phy} formed by correcting for beam polarization and finite acceptance :

$$A_{phy} = \frac{K}{P_b} A_E = \frac{K}{P_b} \frac{A_{exp} - \sum_i f_i A_{B\ i}}{1 - \sum_i f_i}$$

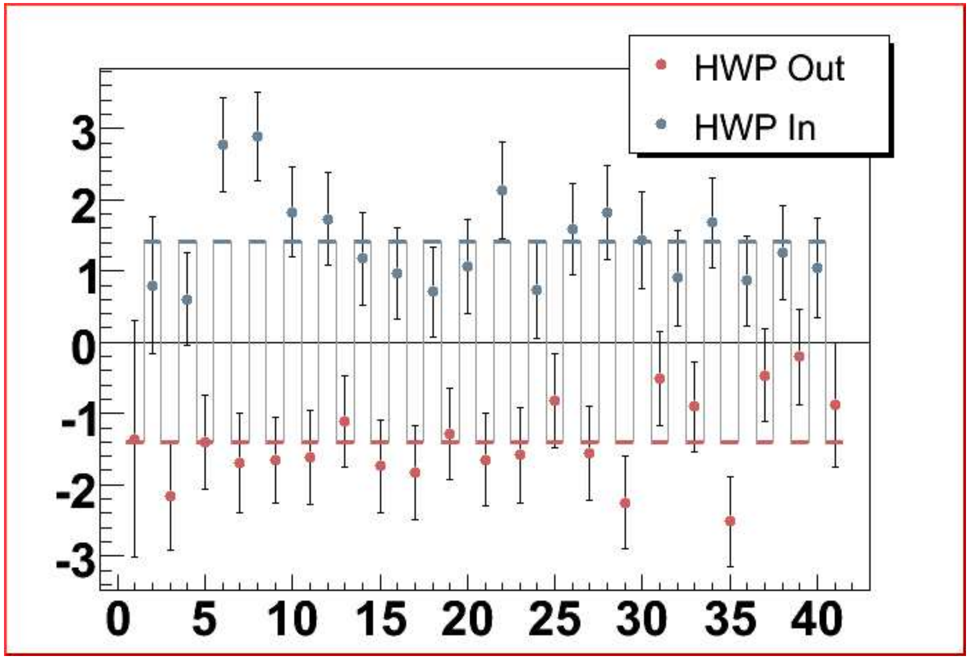
Hydrogen Results

Raw parity violating asymmetry has :

- 25 Millions pairs
- width 540 ppm
- Correction to Raw asymmetry 11 ppb
- $A_{raw} = -1.418 \pm 0.105_{stat}\ ppm$
- $Q^2 = 0.1089 \pm 0.0011\ GeV^2$



Helicity Window Pair Asym.

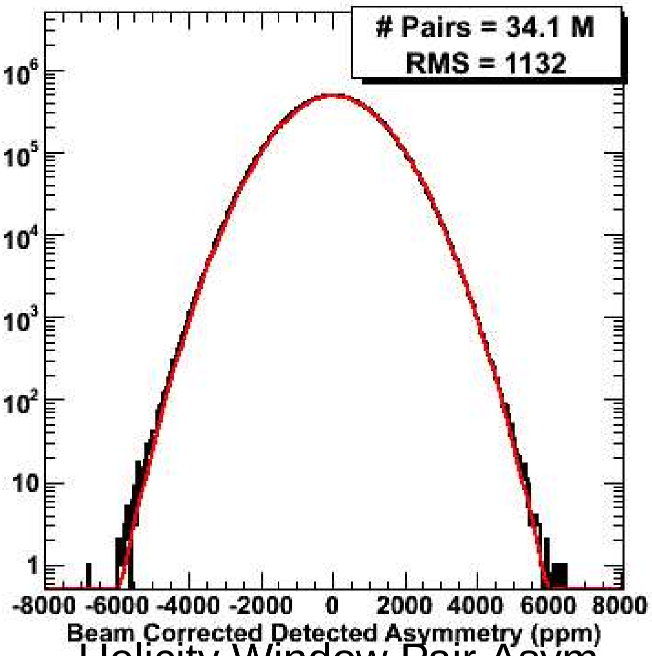


Asymmetry in ppm vs. Slug

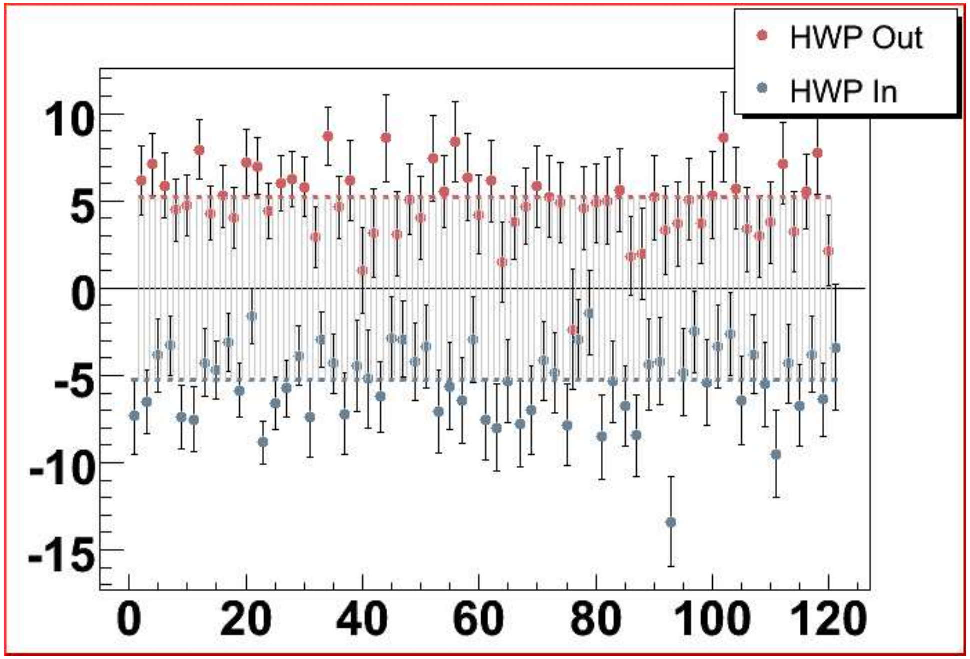
Helium Results

Raw parity violating asymmetry has :

- 35 Millions pairs
- width 1130 ppm
- Correction to Raw asymmetry 0.12 ppm
- $A_{raw} = 5.253 \pm 0.191_{stat}\ ppm$
- $Q^2 = 0.07725 \pm 0.0007\ GeV^2$

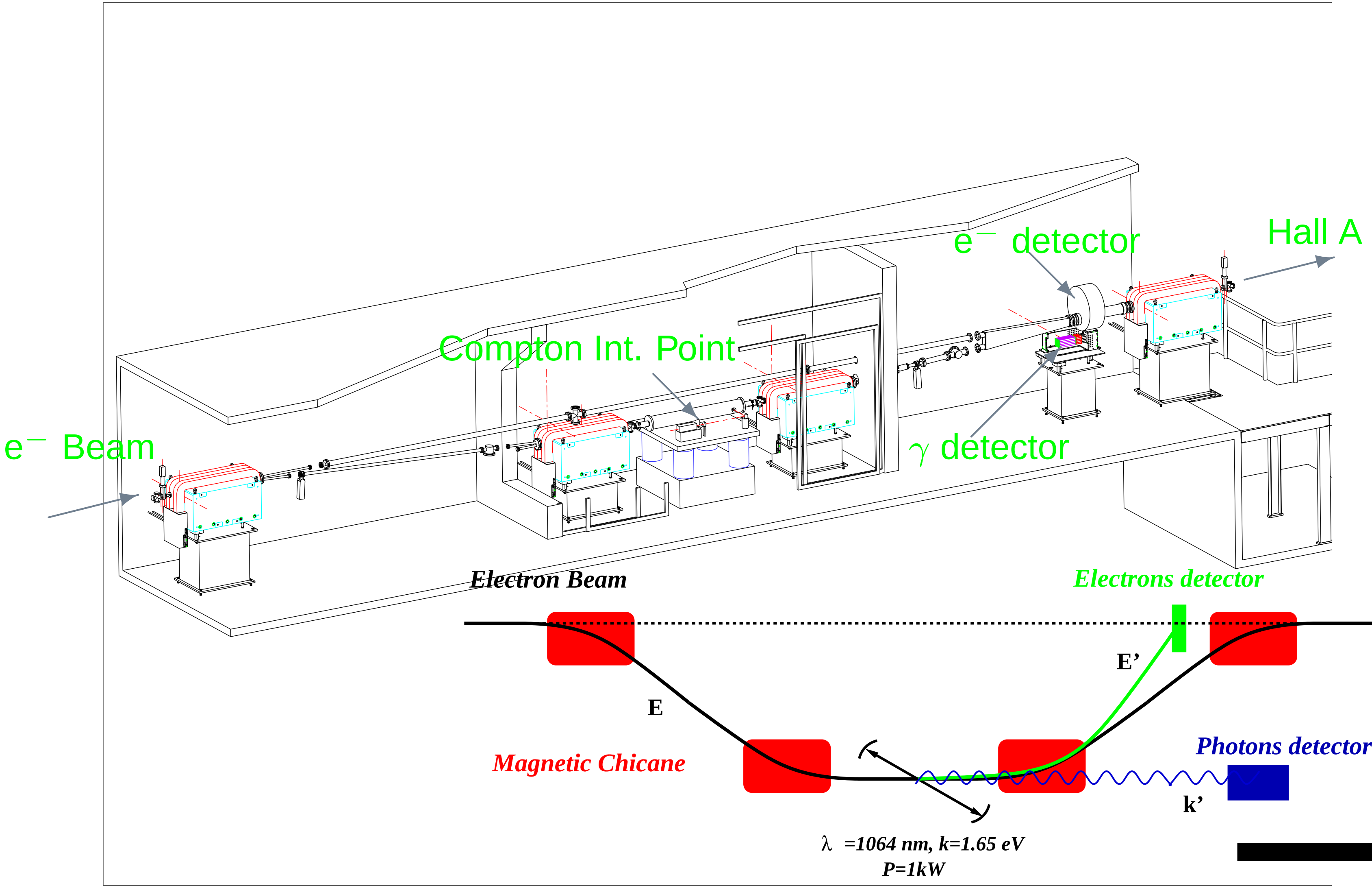


Helicity Window Pair Asym.



Asymmetry in ppm vs. Slug

Compton Polarimetry



Compton Polarimetry

- Continuous and non-invasive measurement of the beam polarization.
- Beam polarization from electron and photon analyses.
- Cross-checked with Hall A Moller, $5\ MeV$ Mott.

$\vec{e} + \vec{\gamma} \rightarrow e + \gamma$ cross section : $\frac{d\sigma^{\pm}}{d\rho} = \frac{d\sigma_0}{d\rho}\ (1 \pm A_l(\rho)\ P_e\ P_\gamma)$

The experimental asymmetry $A_{exp}^{Compton}$ is :

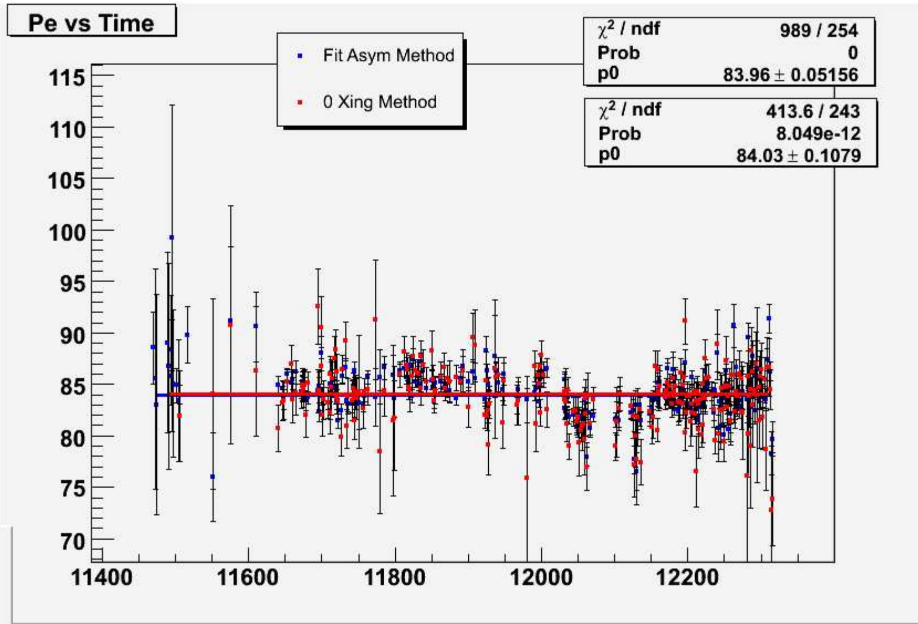
$$A_{exp}^{Compton} = \frac{\mathcal{N}^+ - \mathcal{N}^-}{\mathcal{N}^+ + \mathcal{N}^-} = P_e\ P_\gamma\ A_l\ (\rho)\,, \qquad \rho = k'/k'_{max}$$

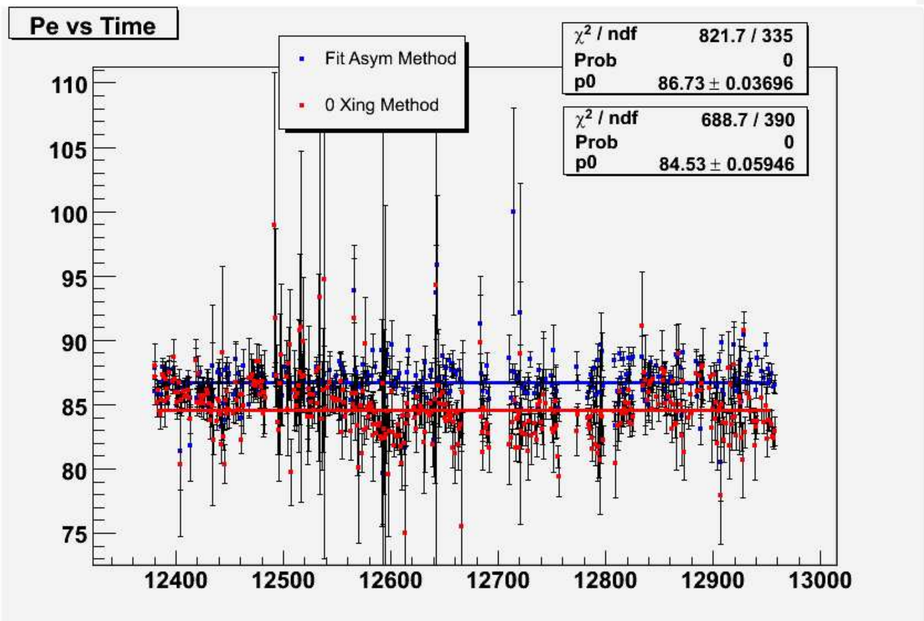
Longitudinal electron polarization is :

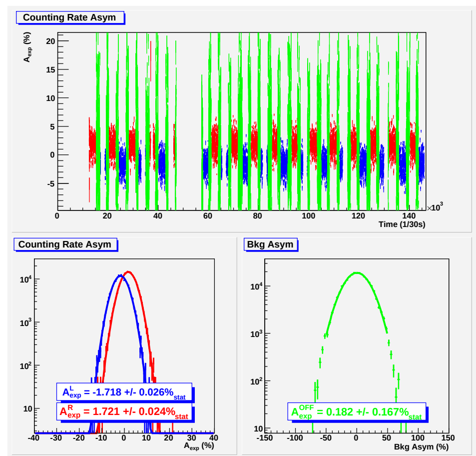
$$P_e = \frac{A_{exp}^{Compton}}{P_\gamma\ A_l\ (\rho)}$$

Compton Polarimetry

- Helium : $P_e = 84.4 \pm 0.89\%$
- Hydrogen : $P_e = 87.1 \pm 0.81\%$

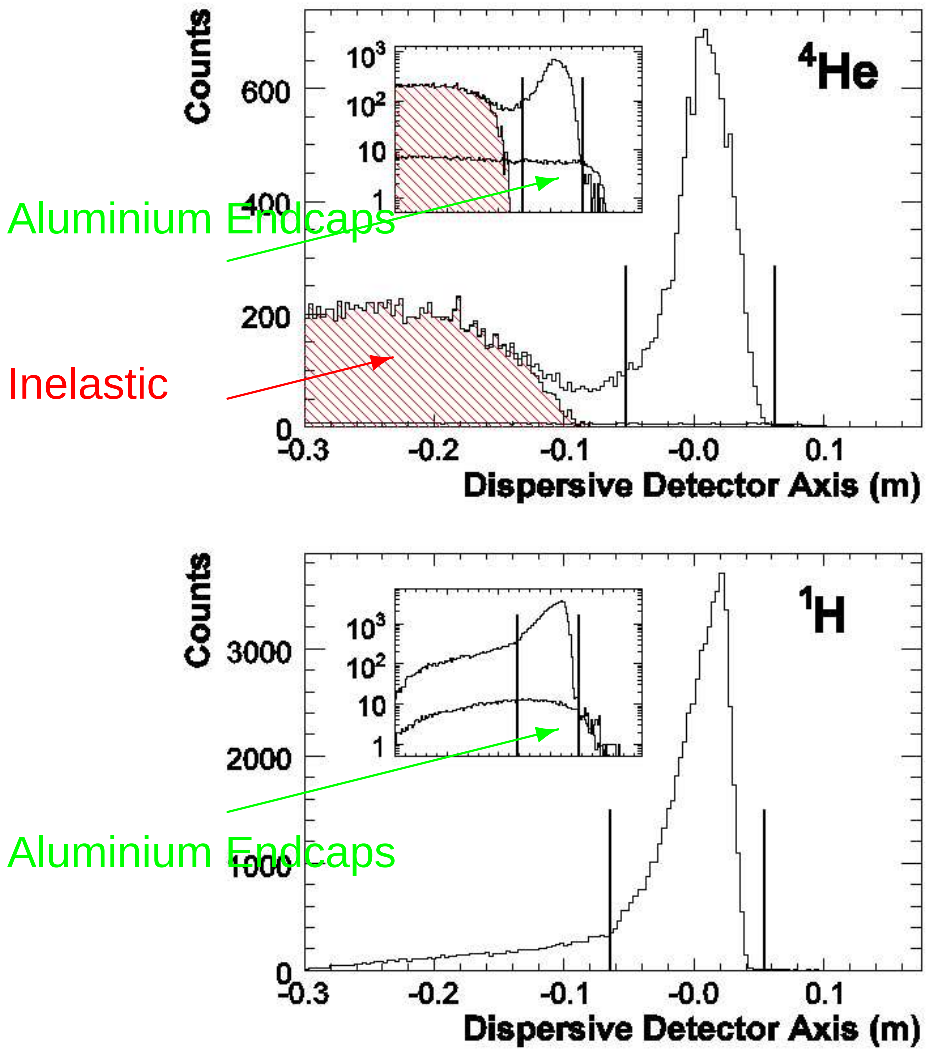






Backgrounds

- Aluminium target window.
- Inelastic and rescattering.



Error Budget Helium

False Asymmetries		59 ppb
position	57 ppb	
energy	12 ppb	
transverse asymmetry	8 ppb	
Polarization		67 ppb
Linearity		58 ppb
BCM linearity	9 ppb	
Detector linearity	57 ppb	
Radiative Corrections		6 ppb
Q^2 uncertainty		58 ppb
Backgrounds		41 ppb
Al-QE	32 ppb	
He-QE	20 ppb	
Rescatter QE	14 ppb	
Rescatter D	0 ppb	
Poletip	5 ppb	
Total Systematic Error		124 ppb

Error Budget Hydrogen

False Asymmetries		15 ppb
position	14 ppb	
energy	0 ppb	
transverse asymmetry	4 ppb	
Polarization		15 ppb
Linearity		15 ppb
BCM linearity	9 ppb	
Detector linearity	11 ppb	
Radiative Corrections		3 ppb
Q^2 **uncertainty**		27 ppb
Backgrounds		20 ppb
Al-QE	19 ppb	
Rescatter	4 ppb	
Poletip	3 ppb	
Total Systematic Error		43 ppb

HAPPEX II 2005 Results

- HAPPEX-^{4}He :
  - $Q^2 = 0.0772 \pm 0.0007 GeV^2$
  - $A_{PV} = +6.40 \pm 0.23_{stat} \pm 0.12_{syst} ppm$
  - $A\left(G^s = 0\right) = +6.37 ppm$
- HAPPEX-H :
  - $Q^2 = 0.1089 \pm 0.0011 GeV^2$
  - $A_{PV} = -1.58 \pm 0.12_{stat} \pm 0.04_{syst} ppm$
  - $A\left(G^s = 0\right) = -1.66 \pm 0.05 ppm$

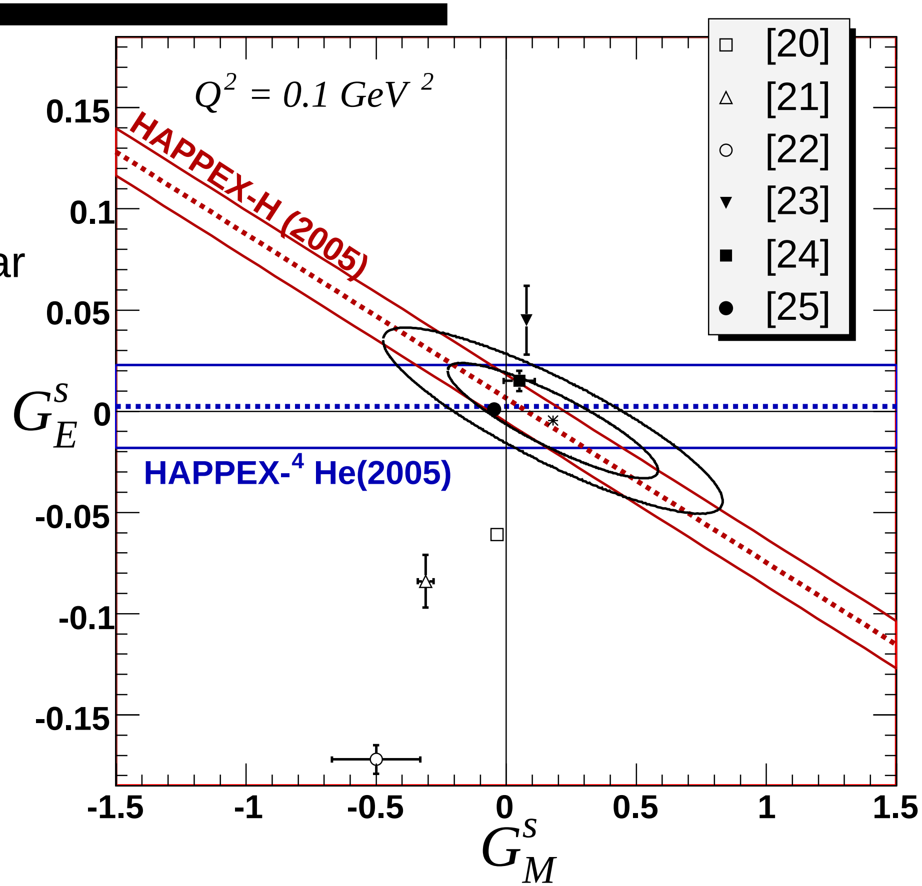
Extracted strange form factors :

- $G_E^s = 0.002 \pm 0.014_{stat} \pm 0.007_{syst}$
- $G_E^s + 0.088 G_M^s = 0.007 \pm 0.011_{stat} \pm 0.004_{syst} \pm 0.004_{FF}$

HAPPEX II 2005 Results

Three bands :

- Inner : projected to axis for 1-D error bar
- Middle : 68% probability contour
- Outer : 95% probability contour
- Best fit gives :
  - $G_E^s = -0.005 \pm 0.019$.
  - $G_M^s = 0.18 \pm 0.27$.



- $\sim 0.17\% \pm 0.63\%$ of nucleon electric moment is strange.
- $\sim 2.8\% \pm 4.3\%$ of nucleon magnetic moment is strange.

Conclusions

- Happex 2nd generation has measured the nucleon electric and magnetic moment of the nucleon at $Q^2 \sim 0.1\ GeV^2$.
- Tight upper-bound shows that strange quarks $< 1\%$ of charge density, $< 5\%$ of magnetic density of the proton.
- It has been ruled out suggested large contributions at $0.1\ GeV^2$ by G0.
- Happex 3rd generation at high $Q^2 = 0.6\ GeV^2$.
- PREX experiment to measure parity-violating electron scattering on ^{208}Pb.
- QWeak at Jlab to measure the weak charge of the proton $Q_W = 1 - 4\sin^2\theta_W$ at $Q^2 = 0.03\ GeV^2$.