# Parity violation - Experiment

EINN 2007, Milos, Greece – September 14, 2007

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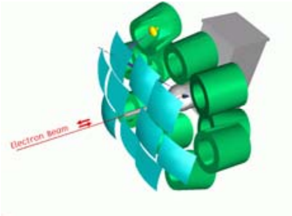
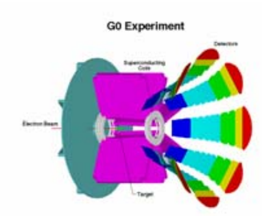
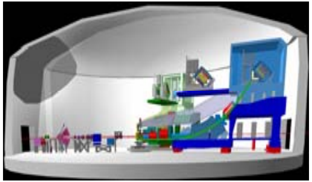


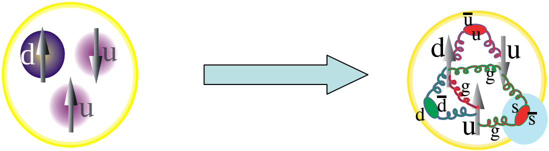



- Strange Form Factors
- Experimental concepts
- 10 years of measurements
- Results, outlook

Jacques Arvieux

# Strangeness in the nucleon




Constituent Quarks QCD: sea quarks, gluons…

$$< N \,|\, \bar{s}s \,|\, N >$$

πN scattering
Contribution of s-quarks to the mass

$$< N \,|\, \bar{s}\gamma^{\mu}\gamma^{5}s \,|\, N >$$

DIS
Contribution of s-quarks to the spin

$$< N \,|\, \bar{s}\gamma^{\mu}s \,|\, N >$$

Parity violating electron scattering
Contribution of s-quarks to the vector current

# Strangeness in the Nucleon

Flavour Decomposition of form factors:

$$G^{p}_{E,M} = \frac{2}{3} G^{p,u}_{E,M} - \frac{1}{3} G^{p,d}_{E,M} - \frac{1}{3} G^{p,s}_{E,M}$$

$$G^{n}_{E,M} = \frac{2}{3} G^{n,u}_{E,M} - \frac{1}{3} G^{n,d}_{E,M} - \frac{1}{3} G^{n,s}_{E,M}$$

4 equations, 12 unknown quantities…

# Charge Symmetry

Proton and neutron form an isospin dublett with
$T=1/2$ and $T_3=+1/2$ (p) and $T_3=-1/2$ (n)

$$G_{E,M}^{p,u} = G_{E,M}^{n,d}$$

$$G_{E,M}^{p,d} = G_{E,M}^{n,u}$$

$$G_{E,M}^{p,s} = G_{E,M}^{n,s}$$

# Strangeness in the Nucleon

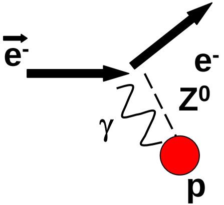
Charge symmetry:

$$G^p_{E,M} = \frac{2}{3} G^u_{E,M} - \frac{1}{3} G^d_{E,M} - \frac{1}{3} G^s_{E,M}$$

$$G^n_{E,M} = \frac{2}{3} G^d_{E,M} - \frac{1}{3} G^u_{E,M} - \frac{1}{3} G^s_{E,M}$$

4 equations, 6 unknown quantities…

# Weak interaction



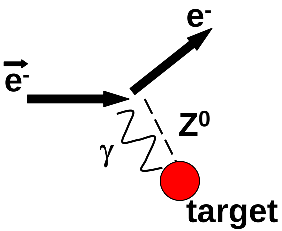

Exchange of photon and $Z^0$

Universality of quark distribution

$$G^{p,Z}_{E,M} = \left(\frac{1}{4} - \frac{2}{3}\sin^2\Theta_W\right)G^u_{E,M} - \left(\frac{1}{4} - \frac{1}{3}\sin^2\Theta_W\right)G^d_{E,M} - \left(\frac{1}{4} - \frac{1}{3}\sin^2\Theta_W\right)G^s_{E,M}$$

Two more equations => Problem in principle solved

# Parity violating electron scattering




- Polarised electron beam
- Unpolarised target

$$\sigma \propto \left| M^{EM} + M^{NC} \right|^2 \approx 1 + 10^{-6} + 10^{-12}$$

Direct measurement not possible

=> Asymmetry measurement

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{\left|M^{NC}\right|}{\left|M^{EM}\right|} \sim \frac{Q^2}{(M_Z)^2} \approx 10^{-6}$$

# Extraction of form factors

Parity violating asymmetry (proton target):

$$A^{PV} = A_V + A_A + A_S$$

$$A_V = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left((1-4\sin^2\Theta_w) - \frac{\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n)}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2}\right)$$

**Standard model calculation**

$$A_A = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left(-\frac{(1-4\sin^2\Theta_w)\sqrt{1-\varepsilon^2}\sqrt{\tau(1+\tau)}G_M^p G_A^p)}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2}\right)$$

**Axial form factor**

$$A_S = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left(-\frac{\varepsilon G_E^p G_E^s + \tau G_M^p G_M^s)}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2}\right)$$

**Strange form factors**

# Measurement of form factors

Three quantities to measure: $G_E^s$, $G_M^s$, $G_A$

Strangeness contribution ($G_E^s$, $G_M^s$)

Large electroweak corrections? Nuclear anapole moment ($G_A$)

For a specific momentum transfer $Q^2$: At least three measurements

| Scattering experiment | sensitive to |
|---|---|
| • e + p (elastic), forward angles: | $G_E^s$ and $G_M^s$ |
| • e + p (elastic), backward angles: | $G_M^s$ and $G_A$ |
| • e + $^4$He (elastic), forward angles: | $G_E^s$ |
| • e + d (quasi-elastic), backward angles: | $G_M^s$ and $G_A$ |

# Parity violation experiments

| | e+p forward | e+p backward | e+$^4$He forward | e+d backward |
|---|---|---|---|---|
| Sample | | **0.1 (GeV/c)$^2$** | | **0.04 (GeV/c)$^2$**<br>**0.1 (GeV/c)$^2$** |
| Happex | **0.1 (GeV/c)$^2$**<br>**0.48 (GeV/c)$^2$**<br>0.6 (GeV/c)$^2$ | | **0.1 (GeV/c)$^2$** | |
| A4 | **0.1 (GeV/c)$^2$**<br>**0.23 (GeV/c)$^2$**<br>0.6 (GeV/c)$^2$ | **0.23 (GeV/c)$^2$**<br>0.48 (GeV/c)$^2$ | | **0.23 (GeV/c)$^2$** |
| $G^0$ | **(0.12… 1.0) (GeV/c)$^2$** | **0.23 (GeV/c)$^2$**<br>**0.62 (GeV/c)$^2$** | | **0.23 (GeV/c)$^2$**<br>**0.62 (GeV/c)$^2$** |

# Experimental requirements

•Statistics: $A^{PV} \approx 10^{-6}$ $\Delta A^{PV} = \frac{1}{P \cdot \sqrt{N}}$

$N \approx 10^{12} - 10^{14}$

Large cross section and/or large acceptance, high luminosity, high polarisation

•Systematics:

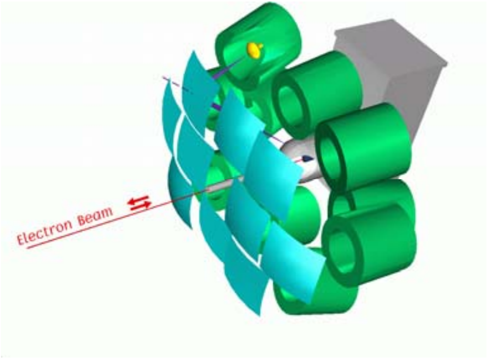
- Separation of elastic and inelastic events
- Control of helicity correlated beam properties

# Parity experiments

First cycle (1998 - 2005):

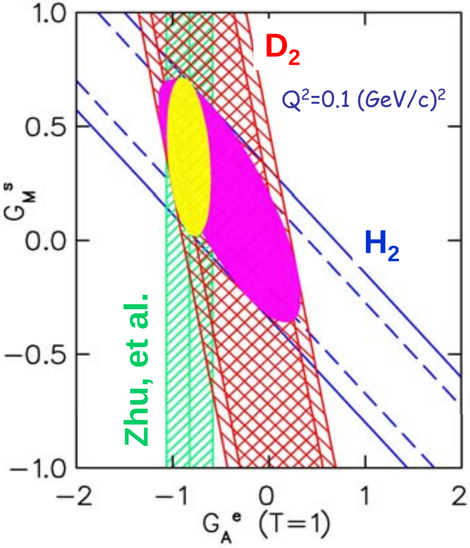
- SAMPLE
- HAPPEX I
- A4 forward angle
- $G^0$ forward angle

# SAMPLE, MIT-Bates




- Backward angle, $Q^2$=0.1 $(GeV/c)^2$
- Large acceptance (1.5 sr) air cherenkov detector
- Beam energy (200 MeV) near pion threshold
- Background measurements with shutters closed
- Hydrogen and Deuterium target

# SAMPLE, MIT-Bates



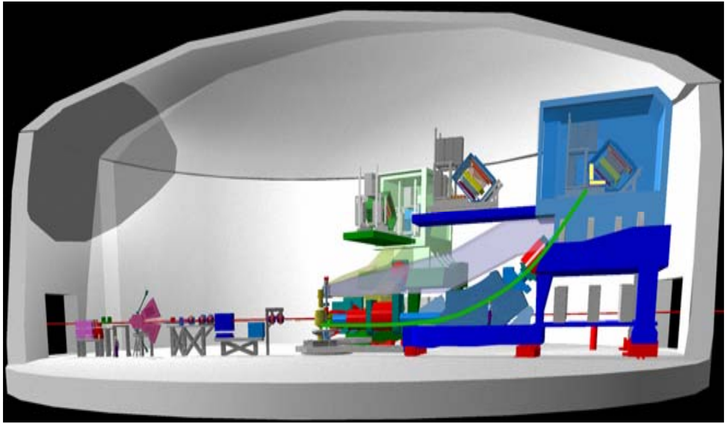

$A^{PV}$ = (-5.61 ± 0.67 ± 0.88) ppm

$G_A$(T=1) = -0.53 ± 0.57 ± 0.50

Using Zhu et al. for $G_A^e$(T=1):

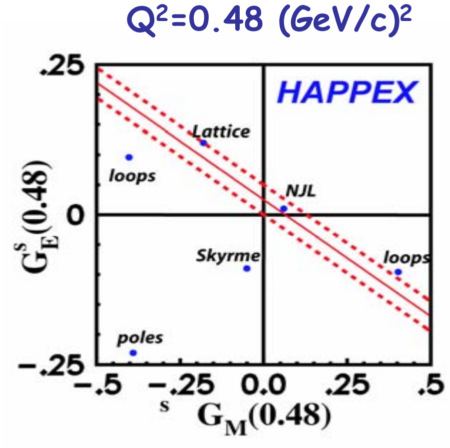
$G_M^s$ = 0.37 ± 0.20 ± 0.26 ± 0.07

# HAPPEX, Jefferson Lab



- Small forward angles, $Q^2$=0.48 $(GeV/c)^2$ and 0.1 $(GeV/c)^2$
- Small acceptance (5 msr) high resolution spectrometer
- Hydrogen and Helium target

# HAPPEX I - Results



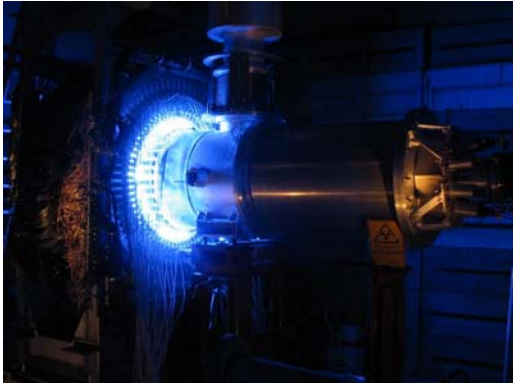

- E=3.3 GeV, θ=12.3 °
- Experimental result:

$A^{PV}$= (-15.05 ± 0.98 ± 0.56) ppm

- Linear combination of $G_E^s$ and $G_M^s$:

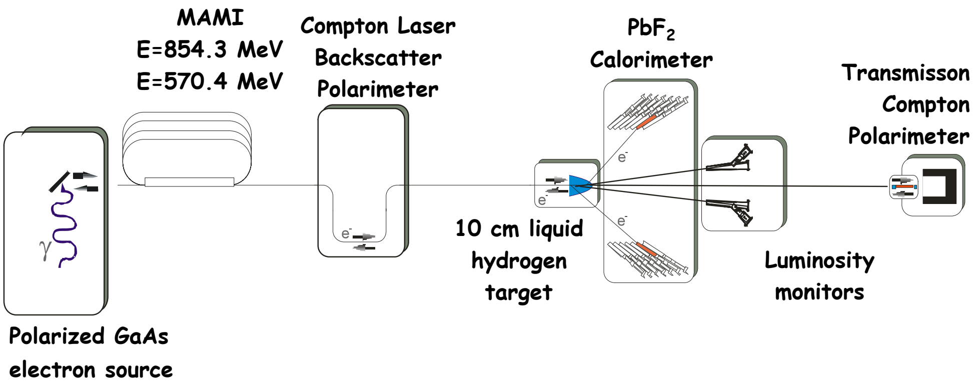
$G_E^s + 0.39\, G_M^s = 0.025 \pm 0.020 \pm 0.014$

# A4 Experiment, MAMI



- Forward and backward angles, $Q^2$=0.1 $(GeV/c)^2$ , 0.23 (GeV/c)2
- Large acceptance (0.6 sr) $PbF_2$ cherenkov calorimeter
- Measurement of full energy spectrum (elastic + inelastic)
- Separation of elastic via cut
- Hydrogen and Deuterium target

# A4 Experiment at MAMI



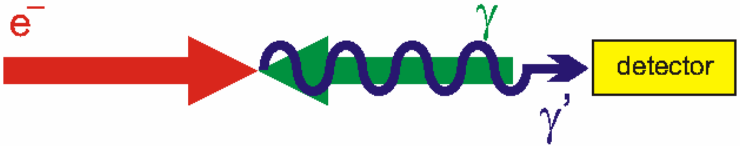

I=20 μA, P=80%

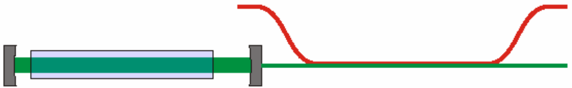
Forward angle configuration

# Compton Backscatter Polarimeter

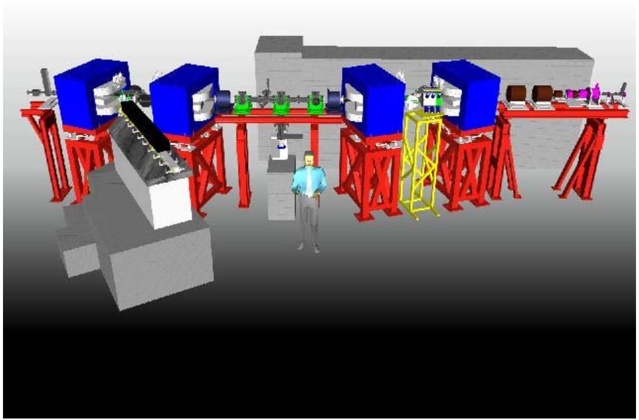
Measured asymmetry: $$A_{exp} = P \cdot A_{PV}$$

=> P has to be measured!
Principle of compton backscatter polarimeter

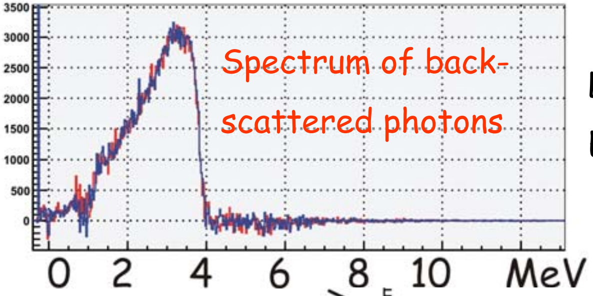


# Compton Backscatter Polarimeter



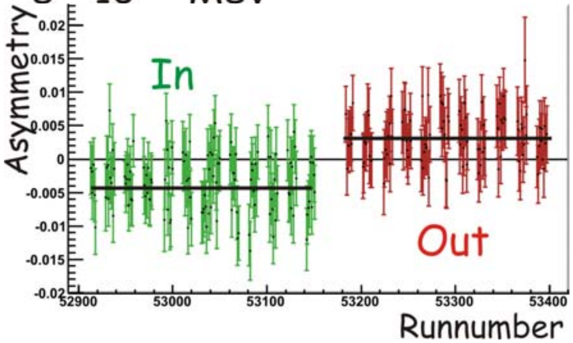
# Compton Backscatter Polarimeter




Low beam energy:

$E_{beam}$=315 MeV !

$A_{compton} \sim P_{beam}$



# $PbF_2$ Calorimeter

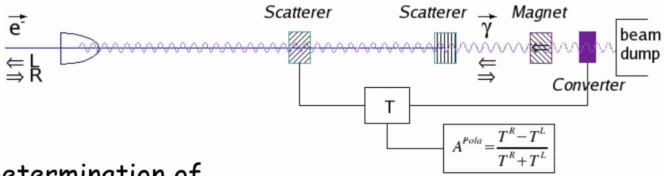
- 1022 $PbF_2$ crystals in 7 rings and 146 frames
- Pure Cherenkov radiator, intrinsically fast
- Solid angle:

$\Omega$=0.6 sr, $0 \leq \Phi \leq 2\pi$

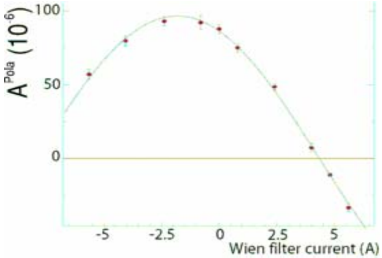
$30° \leq \Theta \leq 40°$ or $140° \leq \Theta \leq 150°$

- Total rate $\approx 100$ MHz
- Sum of 3x3 crystals

# Transmission Compton Polarimeter (TCP)

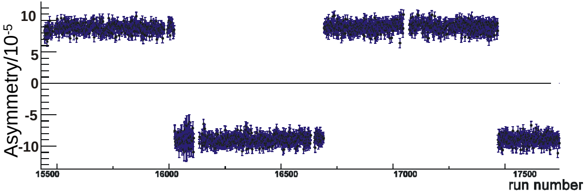



•Determination of electron spin angle

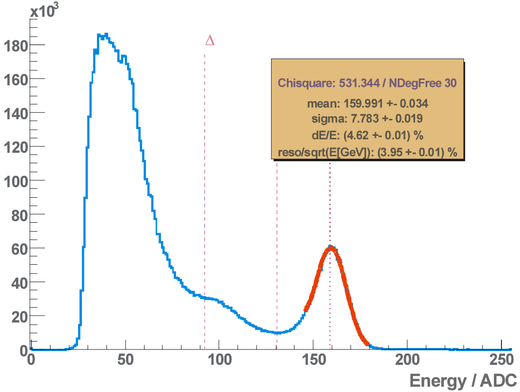



•Relative measurement of polarization

•Control of halfwave plate status



# A4, forward angles




## $PbF_2$ Energy spectrum

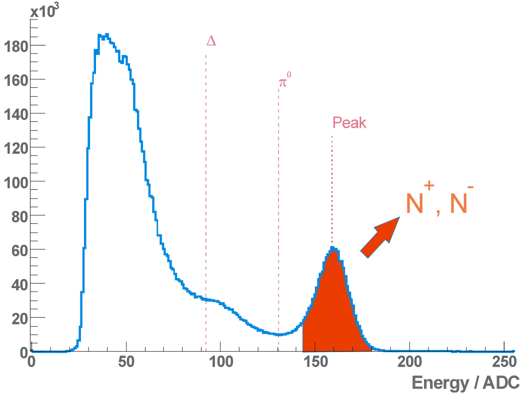
Single channel, $\Theta$=34.1°

**E=854.3 MeV**

$Q^2$=0.23 $(GeV/c)^2$

I = 20μA, t = 2.5min

# Forward angle measurements




- Calculate low ADC cut:

$$E_{Cut} = E_{\pi^0} + k \cdot \sigma_R$$

Can be choosen, We use k=1.6

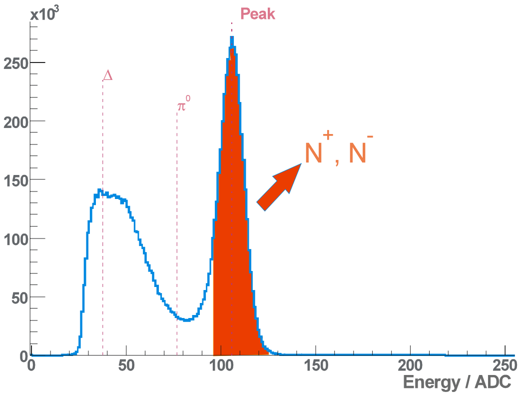
From fit

- High ADC cut:

No difficulty

→ Elastic events $N^+, N^-$

# A4, forward angles




## $PbF_2$ Energy spectrum

Single channel, Θ=34.1°

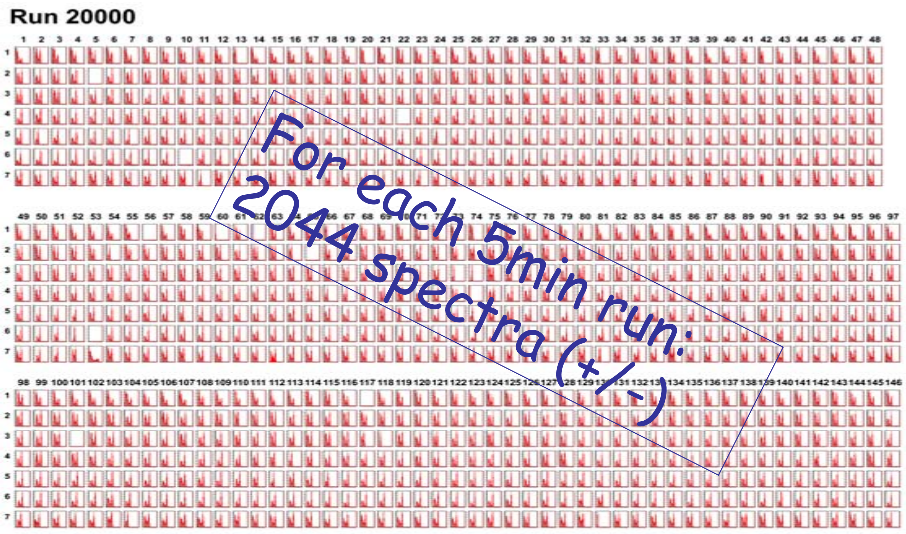
**E = 570.4 MeV**

$Q^2$ = 0.11 $(GeV/c)^2$

I = 20μA, t = 2.5min

Also clean extraction of elastic events

# Analysis



# Analysis

- Elastic events for one run: $N^+ = \sum_{c=1}^{1022} N_c^+ , N^- = \sum_{c=1}^{1022} N_c^-$

- Experimental Asymmetry: $$A_{ex} = \frac{\frac{N^+}{\rho^+} - \frac{N^-}{\rho^-}}{\frac{N^+}{\rho^+} + \frac{N^-}{\rho^-}}$$ with ρ target density

$$A_{ex} = P \cdot A_{phys} + \sum_{i=1}^{6} a_i X_i$$

P: Beam polarisation
$X_1$: Current asymmetry
$X_2$: Horiz. position diff.
$X_3$: Verti. Position diff.
$X_4$: Horiz. angle diff.
$X_5$: Verti. angle diff.
$X_6$: Energy diff.

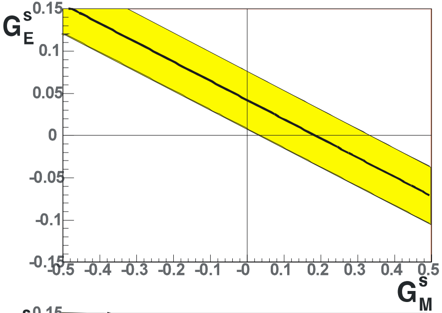
- Determination of $a_i$ via multiple linear regression

# A4@MAMI, forward angle

$Q^2$= 0.23 $(GeV/c)^2$

$A_{PV}$=(-5.44±0.54$_{stat}$±0.26$_{syst}$) ppm

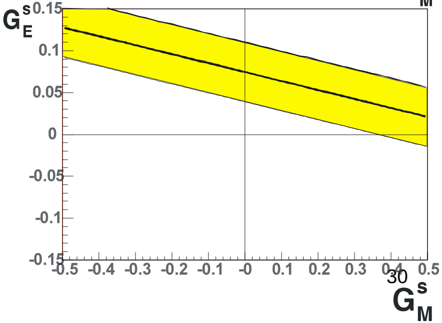
$G_E^s + 0.23\, G_M^s = 0.039 \pm 0.036$



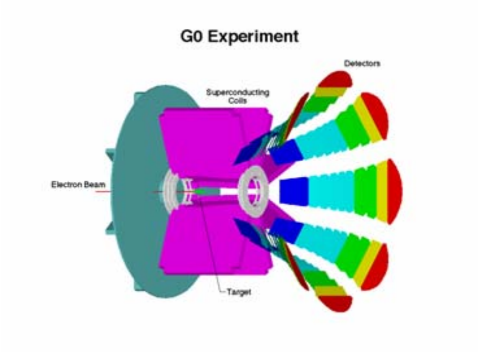

$Q^2$= 0.11 $(GeV/c)^2$

$A_{PV}$=(-1.36± 0.29$_{stat}$±0.13$_{syst}$) ppm

$G_E^s + 0.11\, G_M^s = 0.071 \pm 0.036$

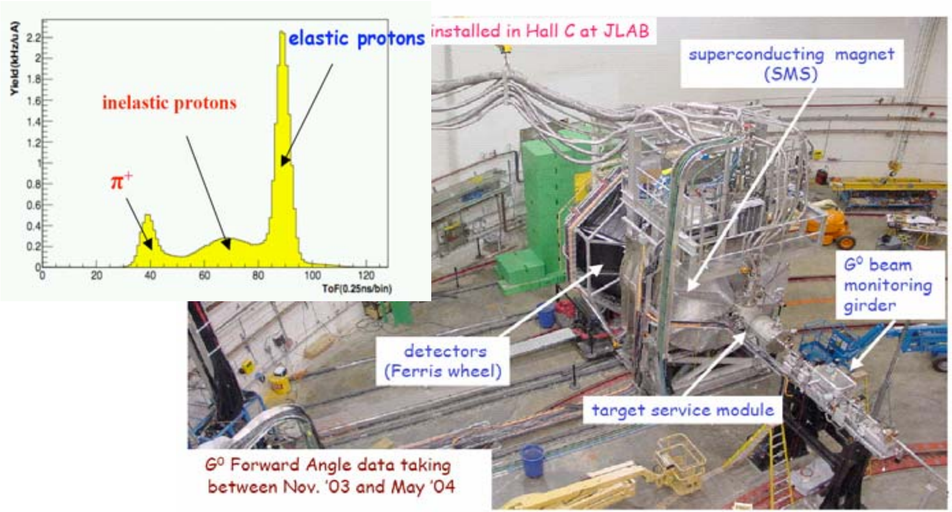


# $G^0$, Jefferson Lab



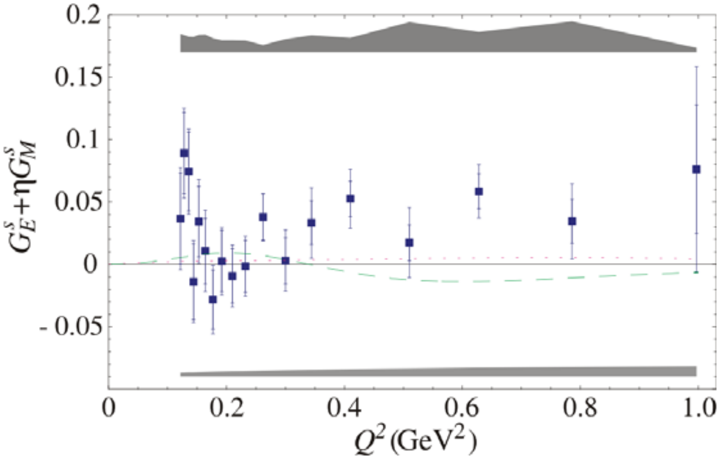

- Forward and backward angles
- Forward angles: Simultaneous measurement of several $Q^2$ between 0.12 $(GeV/c)^2$ and 1.00 (GeV/c)2
- Backward angles: $Q^2$= 0.23 and 0.62 (GeV/c)2
- Large acceptance (0.9 sr) recoil protons spectrometer
- Time of flight measurement
- Hydrogen and Deuterium target

# $G^0$, Jefferson Lab




G⁰ Forward Angle data taking between Nov. '03 and May '04

# $G^0$, Jefferson Lab




Forward angle: Linear combinations of $G_E^s + \eta\, G_M^s$

# Parity experiments

Second cycle (2005 - 2008):

- HAPPEx II, HAPPEx III
- A4 backward angle
- $G^0$ backward angle

# HAPPEx II (second generation)

- **Installation of septum magnets**
  **E=3 GeV   $\theta$=6°   $Q^2$ ~ 0.1 $(GeV/c)^2$**
- **Hydrogen and Helium target**

**Hydrogen** : $G^s_E + \alpha\, G^s_M$

**$^4$He**: Pure $G^s_E$ : $A^{PV} = -\frac{A_0}{2}\left(2\sin^2\theta_W + \frac{G_E^s}{G_E^{p\gamma} + G_E^{n\gamma}}\right)$

# HAPPEx II (second generation)

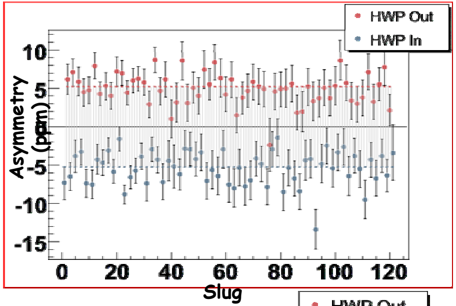
- $^4$He Preliminary Results

  Raw Parity Violating Asymmetry

  $A_{raw}$ correction ~ 0.12 ppm

  $Q^2$ = 0.07725 ± 0.0007 $GeV^2$

  $A_{raw}$ = 5.253 ppm ± 0.191 ppm (stat)



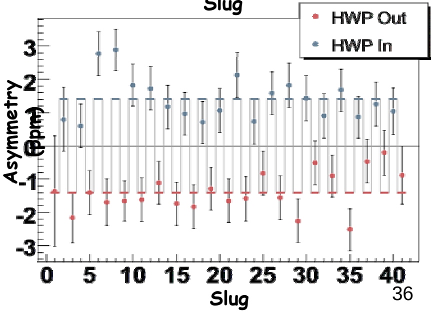

- $^1$H Preliminary Results

  Raw Parity Violating Asymmetry

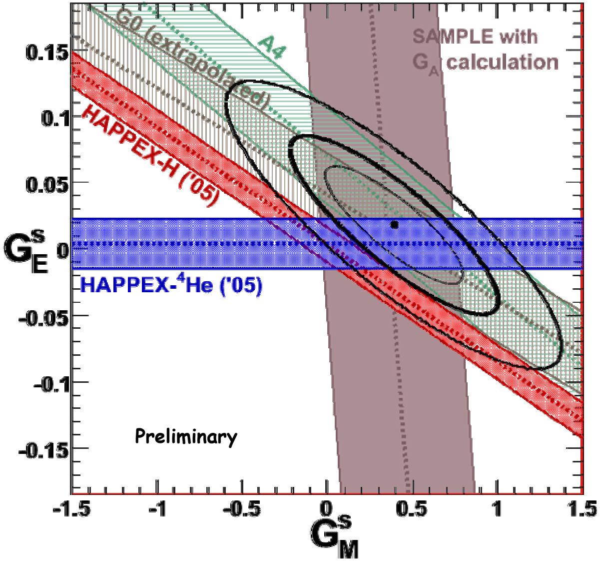
  $A_{raw}$ correction ~ 0.11 ppb

  $Q^2$ = 0.1089 ± 0.0011$GeV^2$

  $A_{raw}$ = -1.418 ppm ± 0.105 ppm (stat)



# HAPPEX-II 2005 Preliminary Results




Three bands:

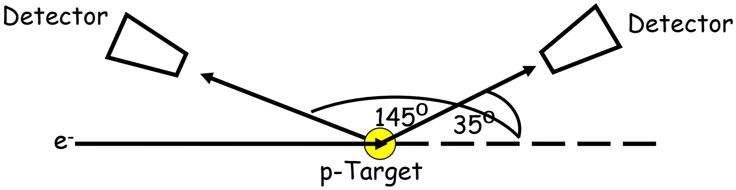
1. Inner: Project to axis for 1-D error bar
2. Middle: 68% probability contour
3. Outer: 95% probability contour

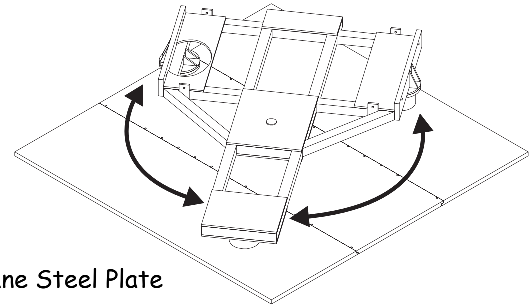
$G_M^s = 0.28 \pm 0.20$

$G_E^s = -0.006 \pm 0.016$

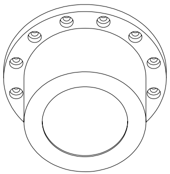
*Caution: the combined fit is approximate. Correlated errors and assumptions not taken into account*

# A4 backward measurements



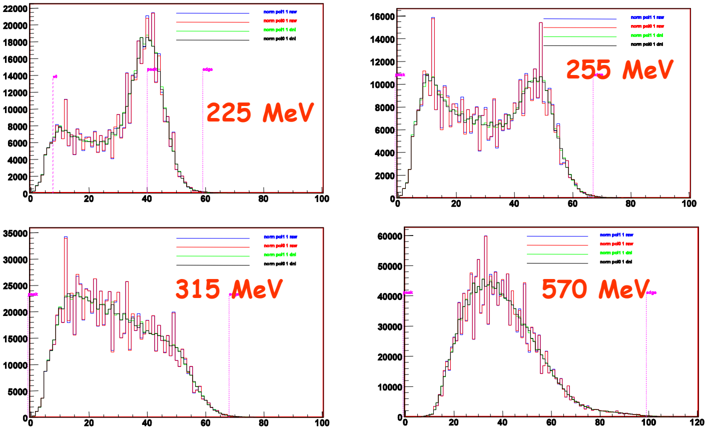
Plane Steel Plate



Hydraulic Oil Plunger

# A4 Detector rearrangement

# A4 backward measurements

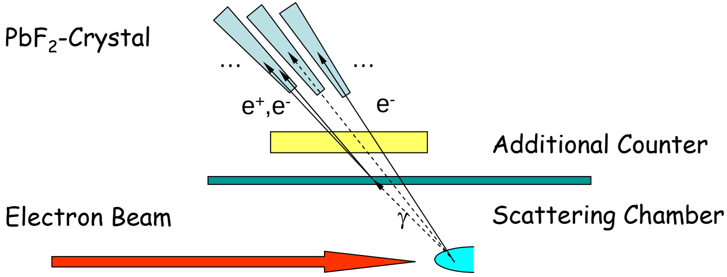



Additional background in the energy region of the elastic peak:

Photons from $\pi^0$ decay. Pions coming from

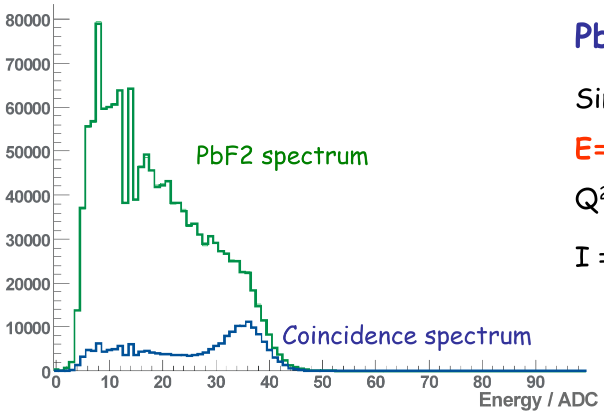
- Pion electroproduction
- Pion photoproduction

# Additional scintillator system




Separation of charged and neutral particles

# Backward angle




## $PbF_2$ Energy spectrum

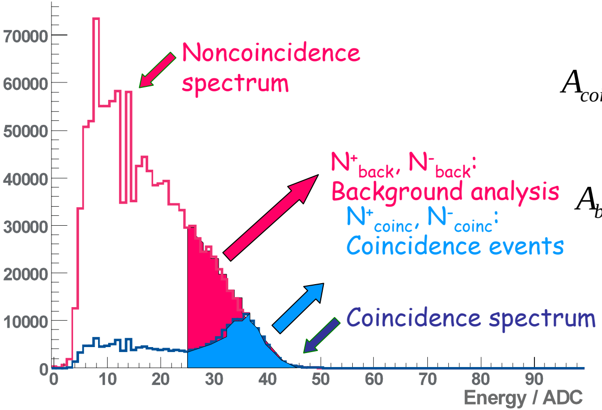
Single channel, $\Theta$=145.9°

**E=315.1 MeV**

$Q^2$=0.23 $(GeV/c)^2$

I = 20μA, t = 2.5min

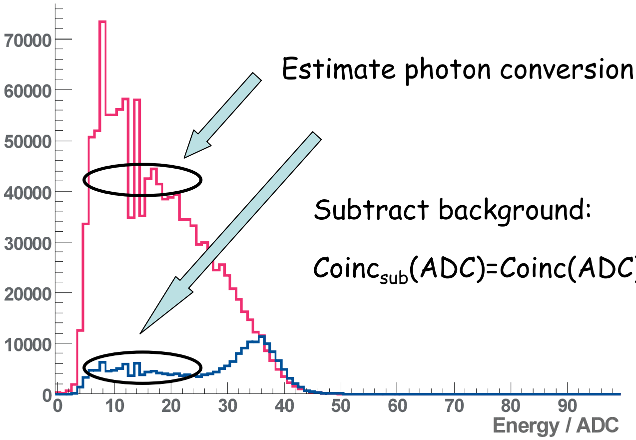
# Backward angle




$$A_{coinc} = \frac{N^{+}_{coinc} - N^{-}_{coinc}}{N^{+}_{coinc} + N^{-}_{coinc}}$$

$$A_{back} = \frac{N^{+}_{back} - N^{-}_{back}}{N^{+}_{back} + N^{-}_{back}}$$

# Background subtraction



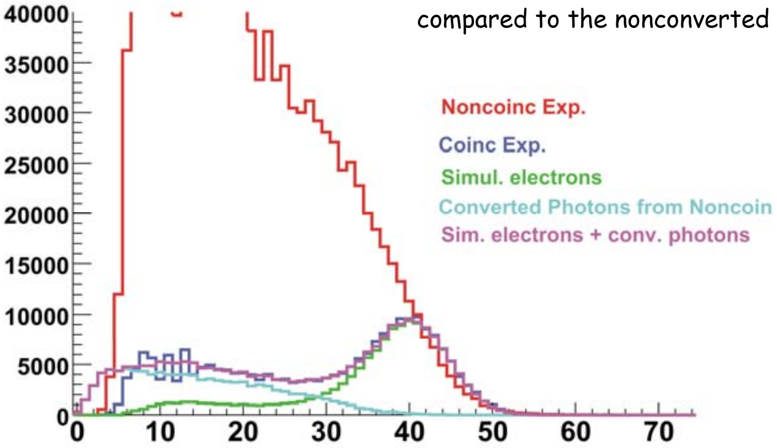

Estimate photon conversion factor f

Subtract background:

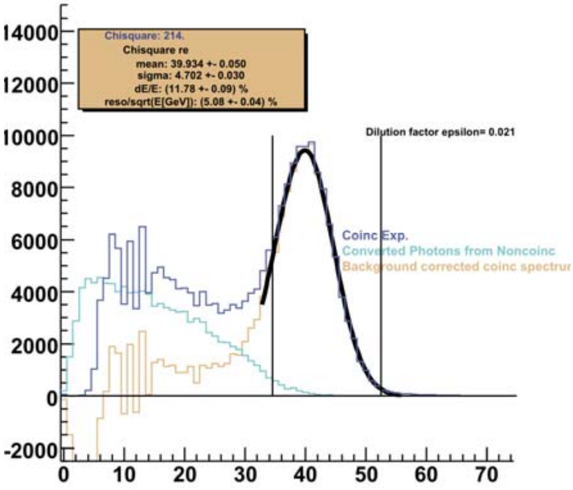
$Coinc_{sub}(ADC)=Coinc(ADC)-f\times Back(ADC)$

# Result of Monte Carlo Studies

- Conversion of photons (about 10%)
- Energy loss of converted photons compared to the nonconverted photons



# Result of Monte Carlo Studies

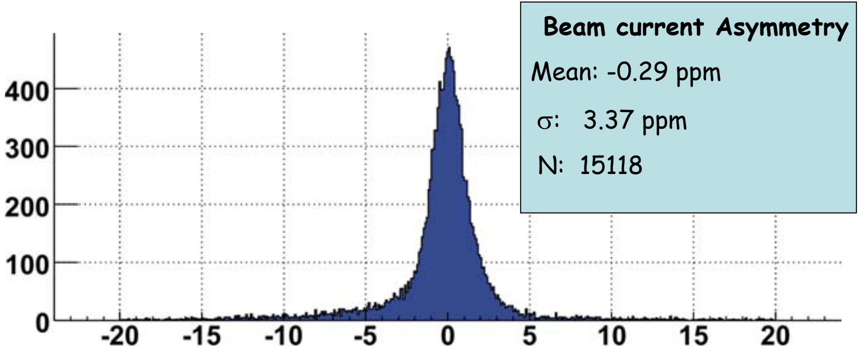



- Cut choosen:

  2% contribution of background in elastic cut

# Backward angle, beam parameter

Asymmetries and differences in current, position, angle, energy:
The smaller, the better

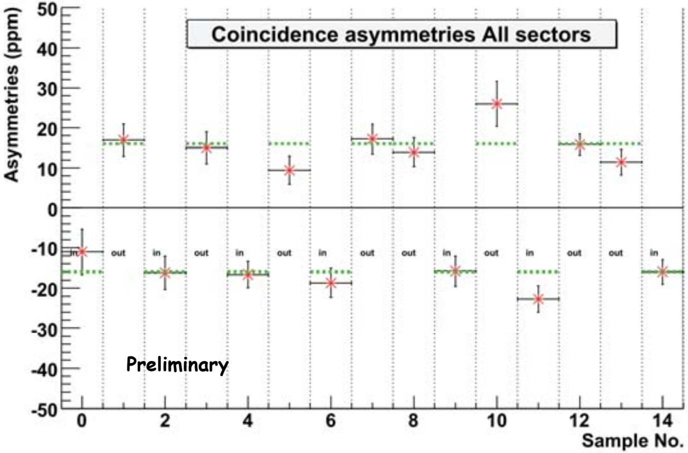


# Backward angle, beam parameter

| Beam parameter (helicity correlated) | False Asymmetry $\|A_{False}\|$ (Estimation) |
|---|---|
| Current Asymmetry $A_I$ -0.29 ppm | 0.29 ppm |
| Horiz. position diff. $\Delta X$ -0.09 μm | < 0.1 ppm |
| Verti. position diff. $\Delta Y$ -0.02 μm | < 0.1 ppm |
| Horiz. angle diff. $\Delta X'$ -9.1 nrad | < 0.1 ppm |
| Verti. angle diff. $\Delta Y'$ -2.5 nrad | < 0.1 ppm |
| Energy diff. $\Delta E$ -0.48 eV | < 0.1 ppm |

# A4, $Q^2$=0.23 (GeV/c)$^2$ backward

Coincidence data




About 1000 h of data

$N_{coinc}=2.1\times10^{12}$

$A_{coinc}$= (-15.96 ± 0.93$_{stat}$ ± 0.63$_{syst}$ ) ppm

$\chi2$/NDF=14.57/14=1.04

# $Q^2$=0.23 $(GeV/c)^2$ backward

Determination of $A^{PV}$: $$A_{coinc} = (1-\varepsilon)\cdot A_{PV} + \varepsilon \cdot A_{Back}$$

$A_{coinc}$= (-15.96 ± 1.13) ppm

$A_{back}$= (-3.25 ± 0.75) ppm

Dilution factor ε=0.02

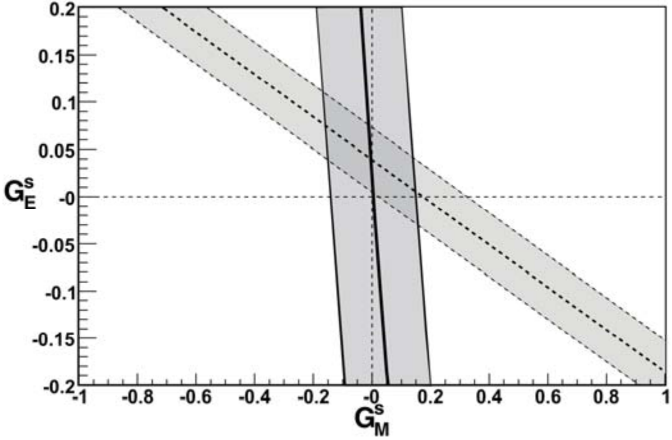
$A_{PV}$= (-16.22 ± 1.15) ppm

No strangeness: $A_0$=(-16.27 ± 1.22) ppm

$G_M^s + 0.25\, G_E^s = 0.004 \pm 0.146$

**Preliminary**

# A4, $Q^2$=0.23 (GeV/c)$^2$ combined results




$G_M^s$ = -0.01 ± 0.15

$G_E^s$ = 0.034 ± 0.050

Preliminary

# $G^0$ Backward program

=> Wait for the next talk!

# Summary and Outlook

- Parity violation experiments are a well established technique
- First round of PV Experiments (SAMPLE, HAPPEX I, A4, $G^0$) ruled out large strange contributions, at least at $Q^2$<0.5 (GeV/c)$^2$
- Second round puts clear constraints on strangeness contribution

- A4 deuterium program finished at end of 2007
- Strangeness at higher $Q^2$? => HAPPEX III
- New generation of PV experiments to start: $Q_{weak}$, PRex