A Measurement of Strangeness in the Nucleon Electromagnetic Form Factors — the G0 Forward Angle Experiment

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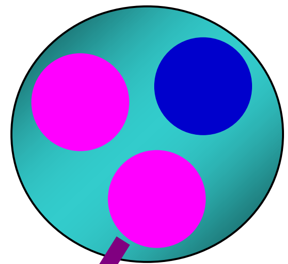
Thesis Research Work Performed at Jlab Hall C

Jlab Users Group Meeting, 06-19-2007

Strangeness in the Nucleon?

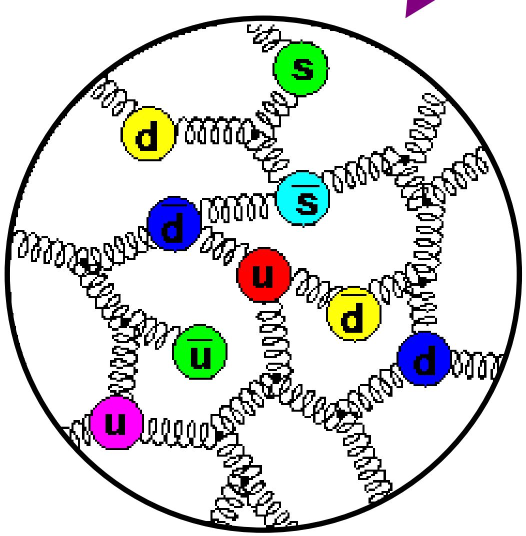
quark	*charge*
u, c, t	*2/3*
d, s, b	*-1/3*



Quark models:
Only u and d quarks in nucleons. No strangeness!

QCD introduces color force between quarks carried by gluons.

"Full QCD description"



- Quark-antiquark pairs and gluons make up the QCD vacuum ("sea").
- s$\bar{s}$ pair arise from the vacuum fluctuation.
- Overall strangeness is zero, but s and $\bar{s}$ might not have identical distributions. So strangeness might manifest locally. **Analogous to the charge distribution in neutron!**

Different Aspects of Nucleon Strangeness

- Contribution of s quark to the longitudinal momentum

$$\int_0^1 x(s(x)+\bar{s}(x))dx \sim 2\%$$

difficult to make connection with ordinary observables

- Contribution to the nucleon mass

$$m_s \langle N | \bar{s}s | N \rangle \sim 130 \text{ MeV}$$

- Contribution to the nucleon spin

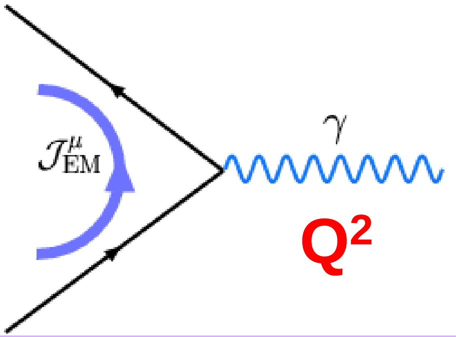
$$\langle N | \bar{s}\gamma^\mu \gamma^5 s | N \rangle = \sigma^\mu \Delta s$$

$$\Delta s \sim -0.1$$

likely 100% uncertainty

- Contributions to the nucleon charge and magnetism — strange electric and magnetic form factors: well-defined observables, results are theoretically clean.

Strange Electromagnetic Form Factors



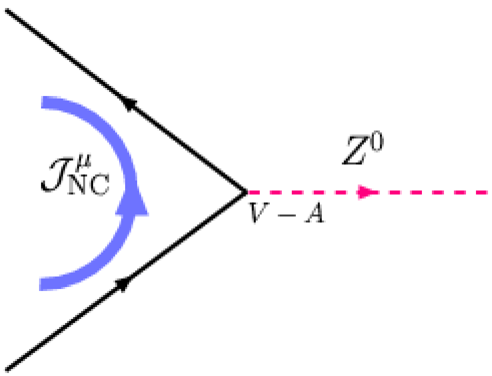
Define vector (EM) form factors:

$$\left\langle N \left| J^{\mu}_{EM} \right| N \right\rangle \Rightarrow G^{\gamma}_{E,M}$$

Distribution of nucleon's charge and magnetization.

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

$$J^{\mu}_{EM} = \sum e_q \bar{q} \gamma^{\mu} q$$



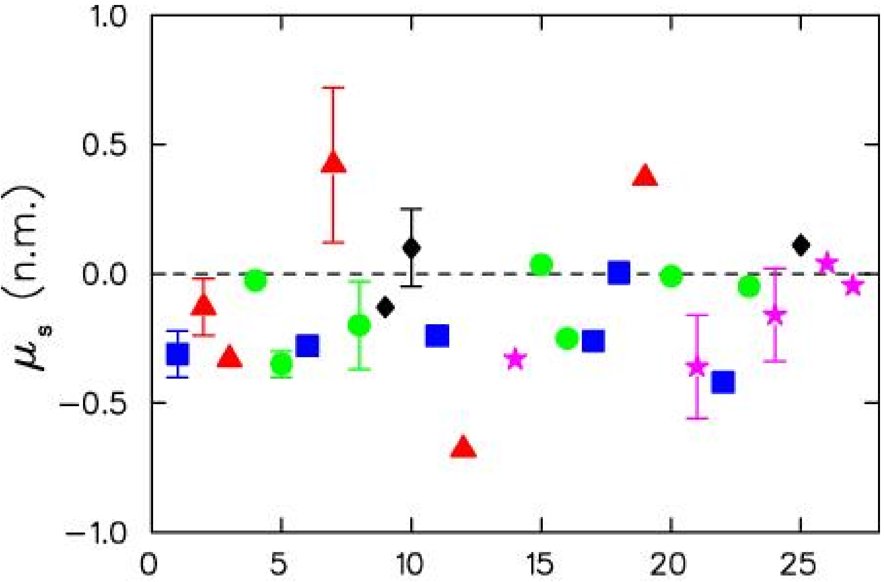
$$\left\langle N \left| J^{\mu,V}_{NC} \right| N \right\rangle \Rightarrow G^{Z}_{E,M}$$

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

$$G^{s}_{E,M} = \left(1 - 4\sin^2\theta_W\right) G^{\gamma,p}_{E,M} - G^{\gamma,n}_{E,M} - G^{Z,p}_{E,M}$$

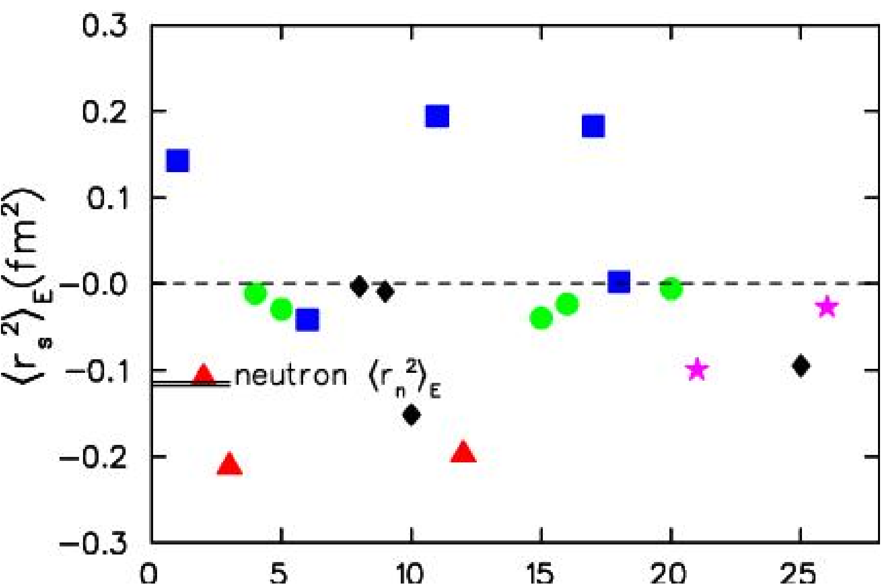
Kaplan and Manohar, 1988

Strange Form Factors Calculations at Q^2=0

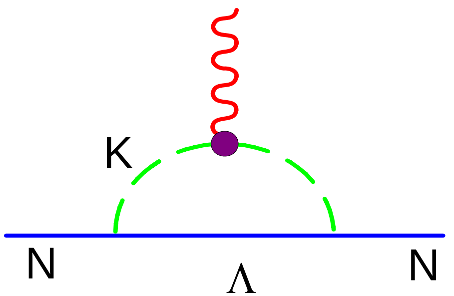


$$\mu_s = G_M^s(0)$$

$$\left\langle r_s^2 \right\rangle_E = -6 \left. \frac{dG_E^s(Q^2)}{dQ^2} \right|_{Q^2=0}$$

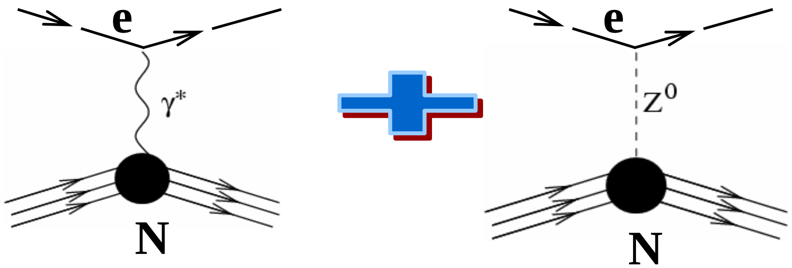


■ VMD (poles)
▲ Skyrme
● Kaon Loops
★ Lattice QCD
◆ other
QCD equalities
quark form factors
dispersion rel.
...



Measuring the NC Form Factor: Parity Violation

Elastic e-N scattering

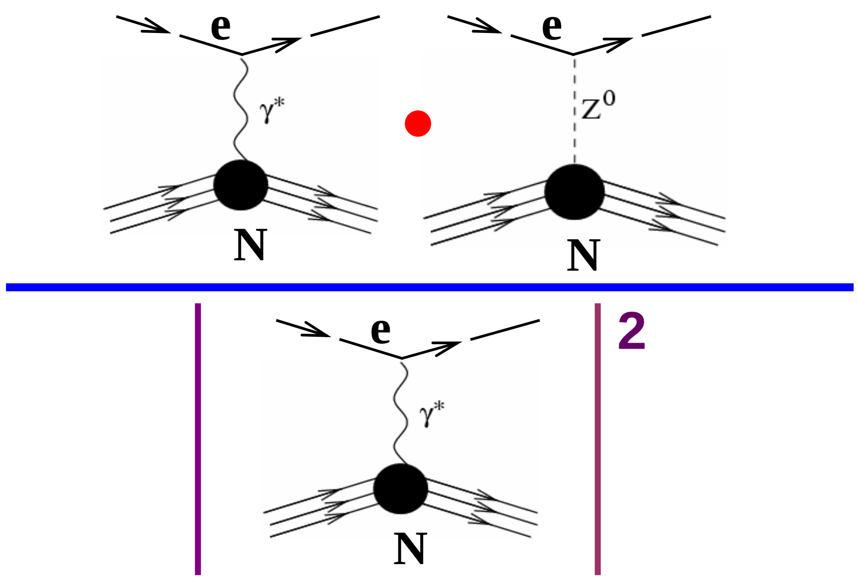


PC PV

- NC amplitude suppressed by ~10^{-4}
- Impossible to see in cross-section measurement

Parity violation in the elastic scattering → interference term → "amplify" the relative experimental sensitivity to neutralweak interaction.

A~

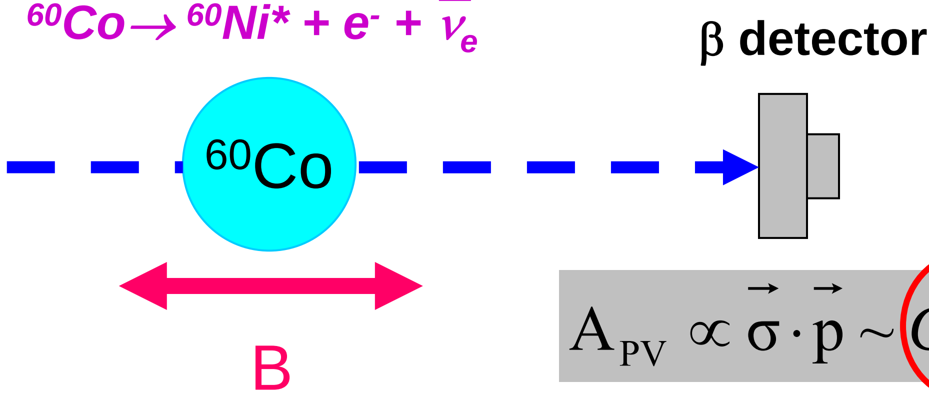


McKeown and Beck, 1989

Measurement of Parity Violation

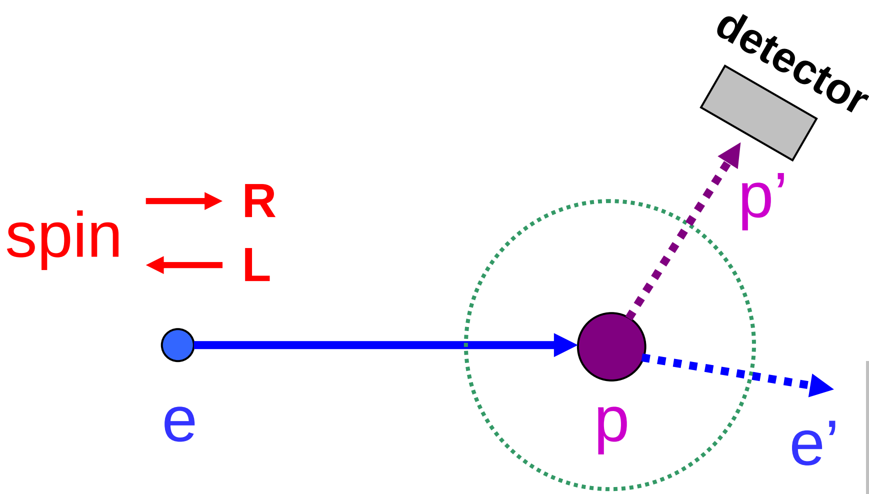
First observation of parity violation in weak interaction; Madam Wu's famous 1957 ^{60}Co beta decay experiment.

$$^{60}Co \rightarrow {}^{60}Ni^* + e^- + \bar{\nu}_e$$



$$A_{PV} \propto \vec{\sigma} \cdot \vec{p} \sim O(1)$$

C. S. Wu



In parity violating e-p scattering, the spin (helicity) of the electron is flipped back and forth.

$$A_{PV} \propto \vec{\sigma} \cdot \vec{p} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-4} Q^2$$

Parity Violating Asymmetry

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{A_E + A_M + A_A}{\varepsilon(G_E^p)^2 + \tau(G_M^p)^2}$$

$$A_E = \varepsilon(\theta)\, G_E^Z(Q^2) G_E^\gamma(Q^2) \rightarrow G_E^s$$

forward ep

$$A_M = \tau(Q^2)\, G_M^Z(Q^2) G_M^\gamma(Q^2) \rightarrow G_M^s$$

backward ep

$$A_A = -(1 - 4\sin^2\theta_W)\varepsilon' G_A^e(Q^2) G_M^\gamma(Q^2) \rightarrow G_A^e$$

backward ed

kinematic factors

$$\tau = \frac{Q^2}{4M^2}$$

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\left(\tfrac{\theta}{2}\right)\right]^{-1}$$

$$\varepsilon' = \sqrt{(1-\varepsilon^2)\tau(1+\tau)}$$

Assuming EM and axial form factors are known (with errors), each measurement yield $G_E^s + \eta G_M^s$ where $\eta = \tau G_M^p / (\varepsilon G_E^p)$

Summary of PV Electron Scattering Experiments (Spring 2006)

Experiment	Target	Q^2(GeV^2)	*Sensitivity*
SAMPLE	H_2	0.10	$G_E^s+1.67G_M^s$
HAPPEx-I	H_2	0.48	$G_E^s+0.37G_M^s$
HAPPEx-II-a	H_2	0.10	$G_E^s+0.08G_M^s$
HAPPEx-He-a	^{4}He	0.091	G_E^s
PVA4-I	H_2	0.23	$G_E^s+0.23G_M^s$
PVA4-II	H_2	0.11	$G_E^s+0.11G_M^s$
G^0	H_2	0.12-1.0	$G_E^s+0.94Q^2G_M^s$
HAPPEx-II-b	H2	0.11	$G_E^s+0.09G_M^s$
HAPPEx-He-b	^{4}He	0.08	G_E^s

The G^0 Collaboration

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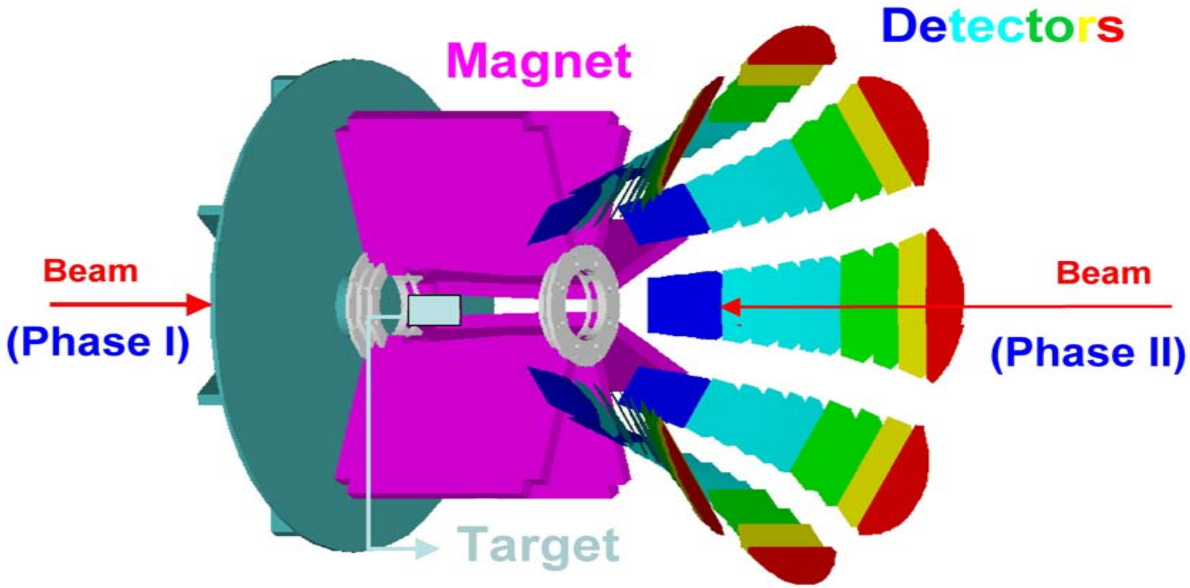
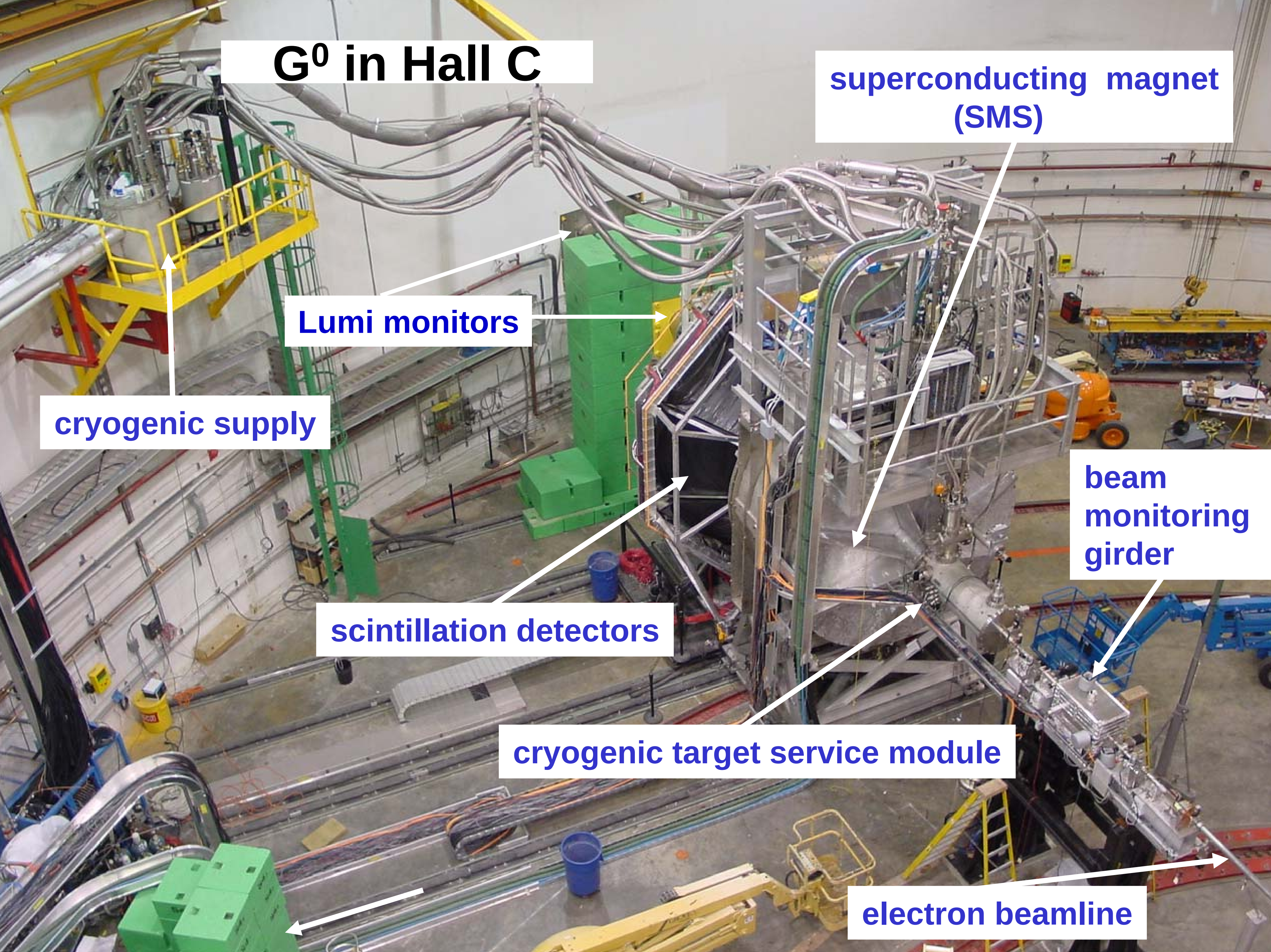
Overview of the G^0 experiment



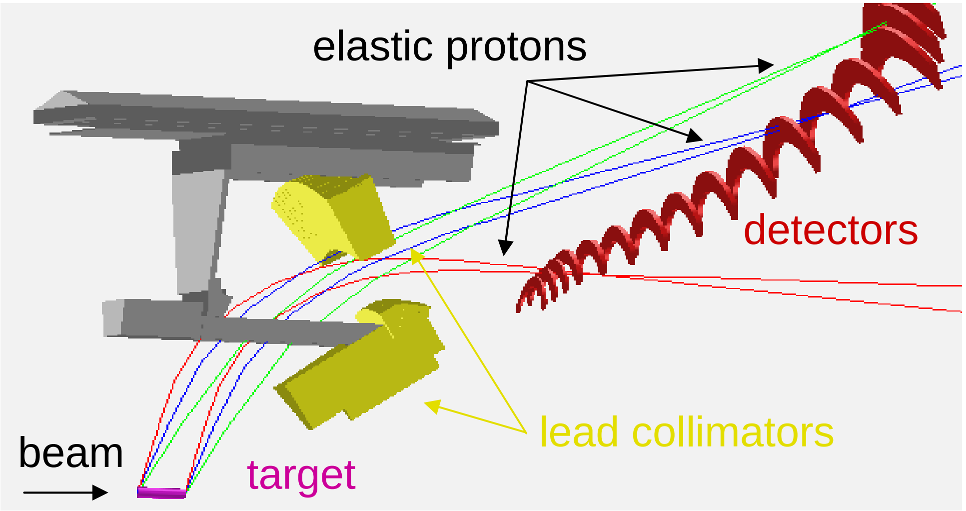
- @ Jlab Hall C. Full program: forward & backward elastic asymmetries: protons for forward, electrons for backward

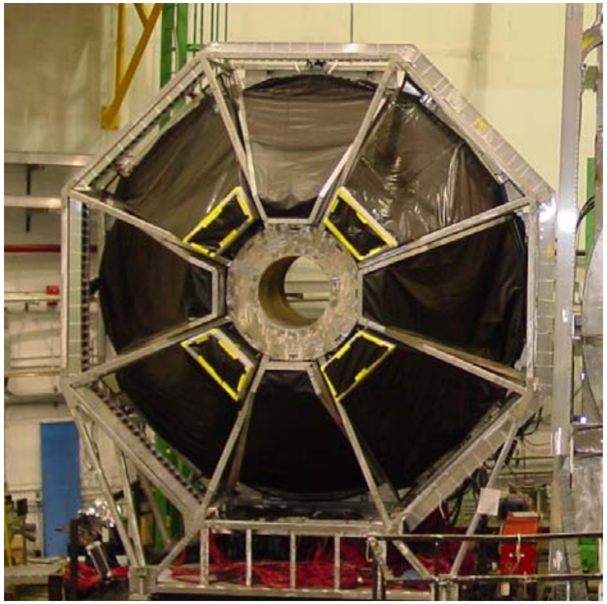
- Forward angle configuration:
  3.03 GeV beam, 40 μA, A = -1 to -50 ppm

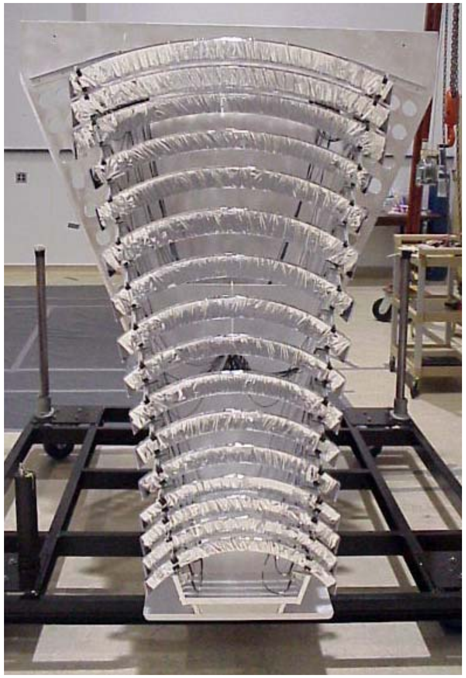

G^0 in Hall C
superconducting magnet (SMS)
Lumi monitors
cryogenic supply
beam monitoring girder
scintillation detectors
cryogenic target service module
electron beamline

Spectrometer

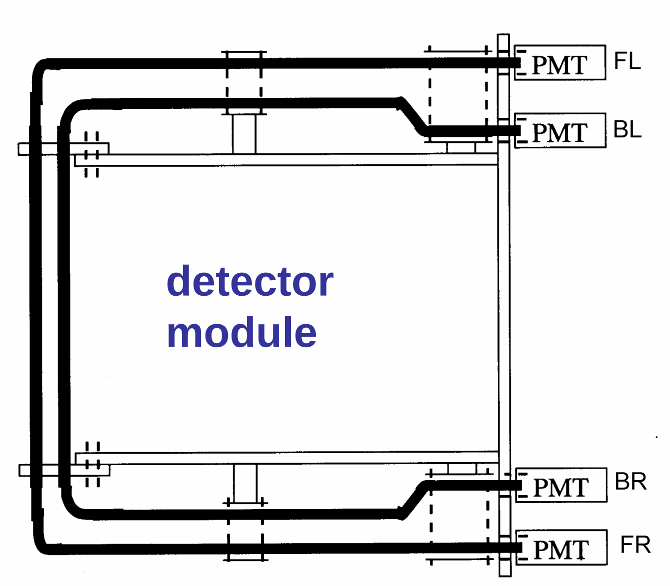
- Toroidal magnet, elastic protons dispersed in Q^2 along focal surface
- Acceptance $0.12<Q^2<1.0$ GeV^2
- 16 scintillator rings at the focal plane. 8 octants.
- Detector 15 acceptance: 0.44-0.88 GeV^2
- Detector 16: “super-elastic”, crucial to measure the background

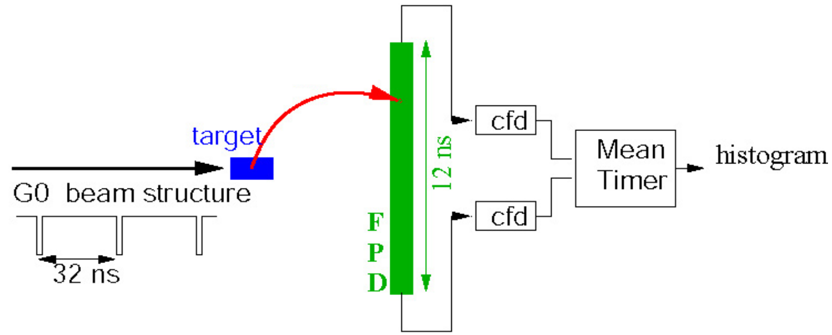


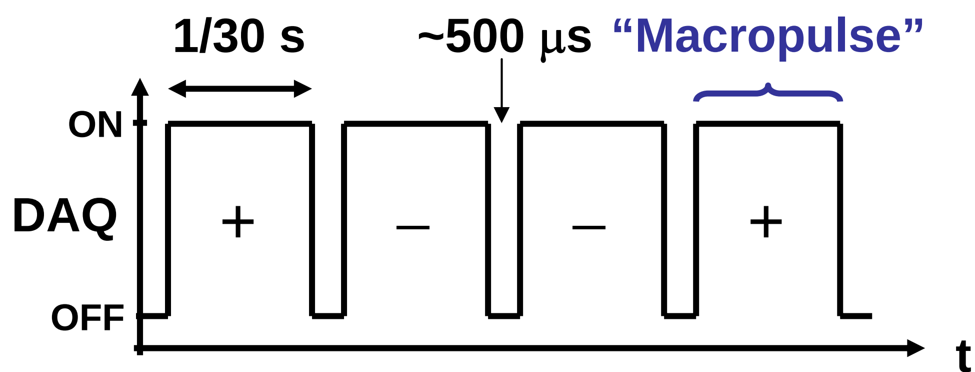




Electronics and Timing



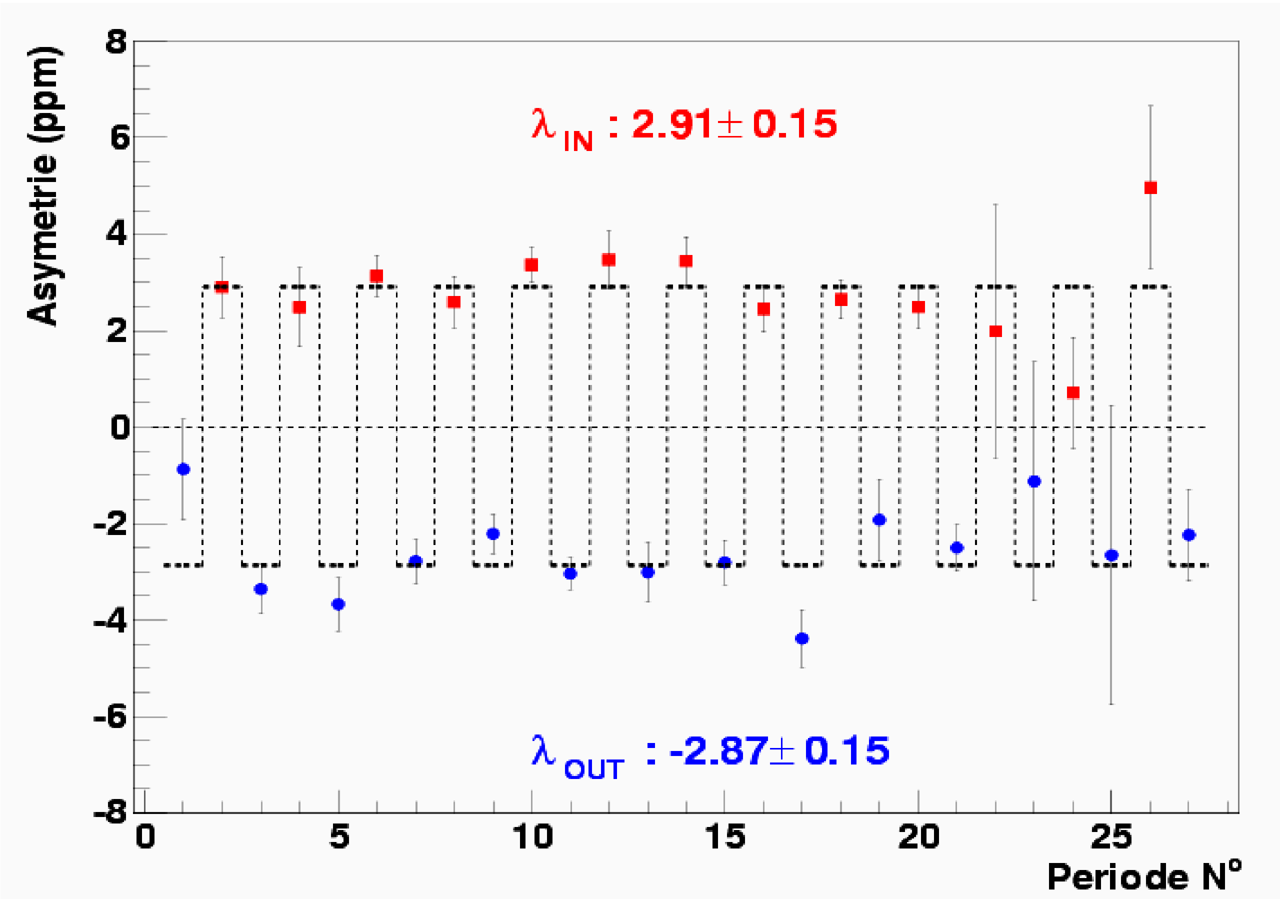


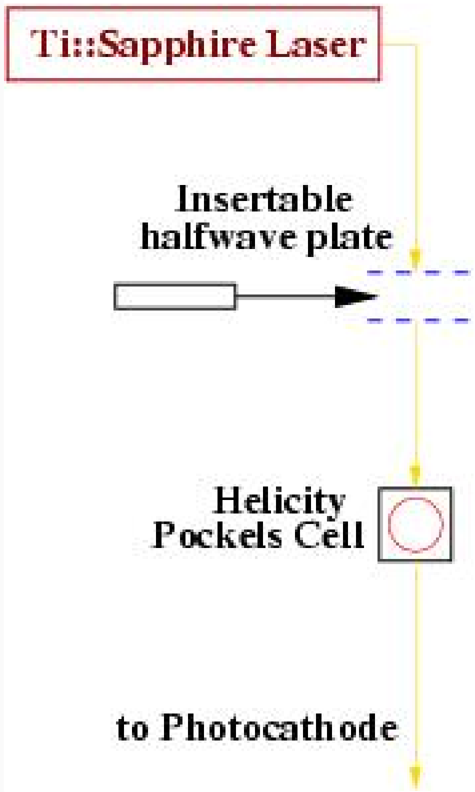


Measurement timing

- High rate counting experiment, coinc. rate ~1MHz per scintillator pair.
- Fast time encoding (ToF histogramming electronics. beam pick-off signal ⇒T=0), DAQ at 30 Hz

Measured Asymmetry upon Beam Spin Reversal



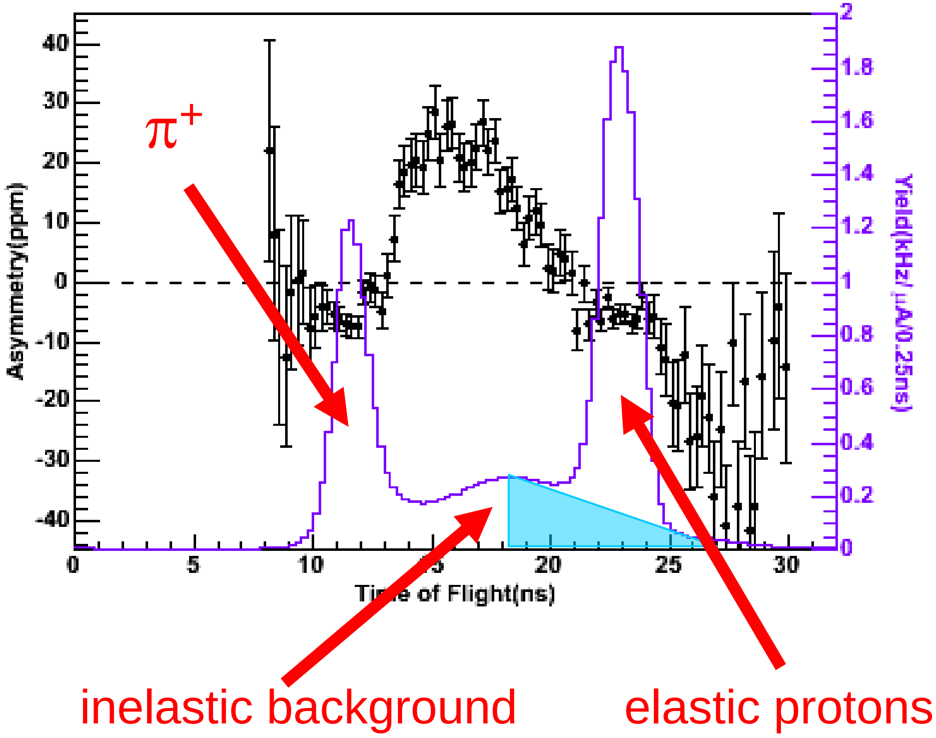


Raw Data of G^0

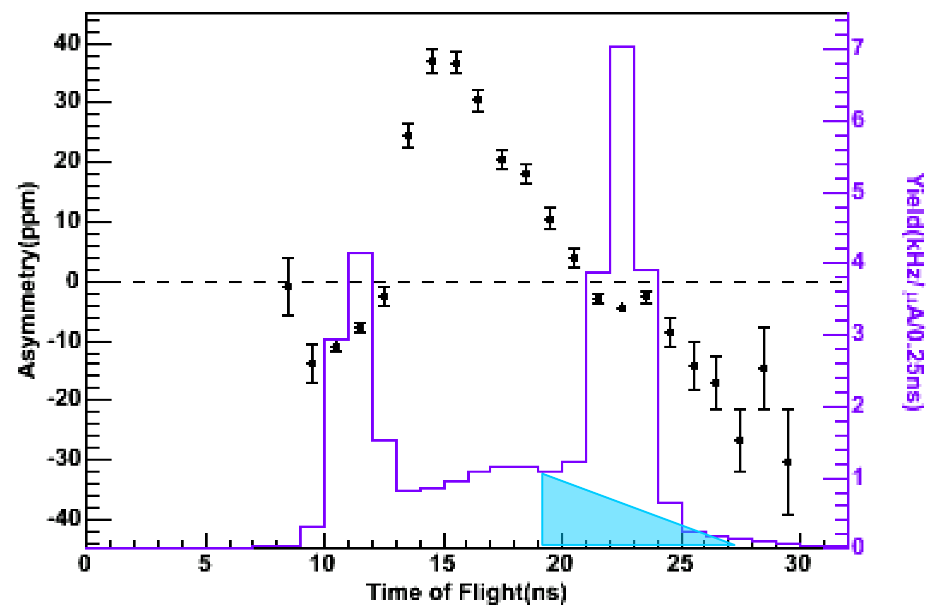
Yield and asymmetry as functions of time of flight

Two sets of electronics: French 0.25 ns/bin, NA 1 ns/bin

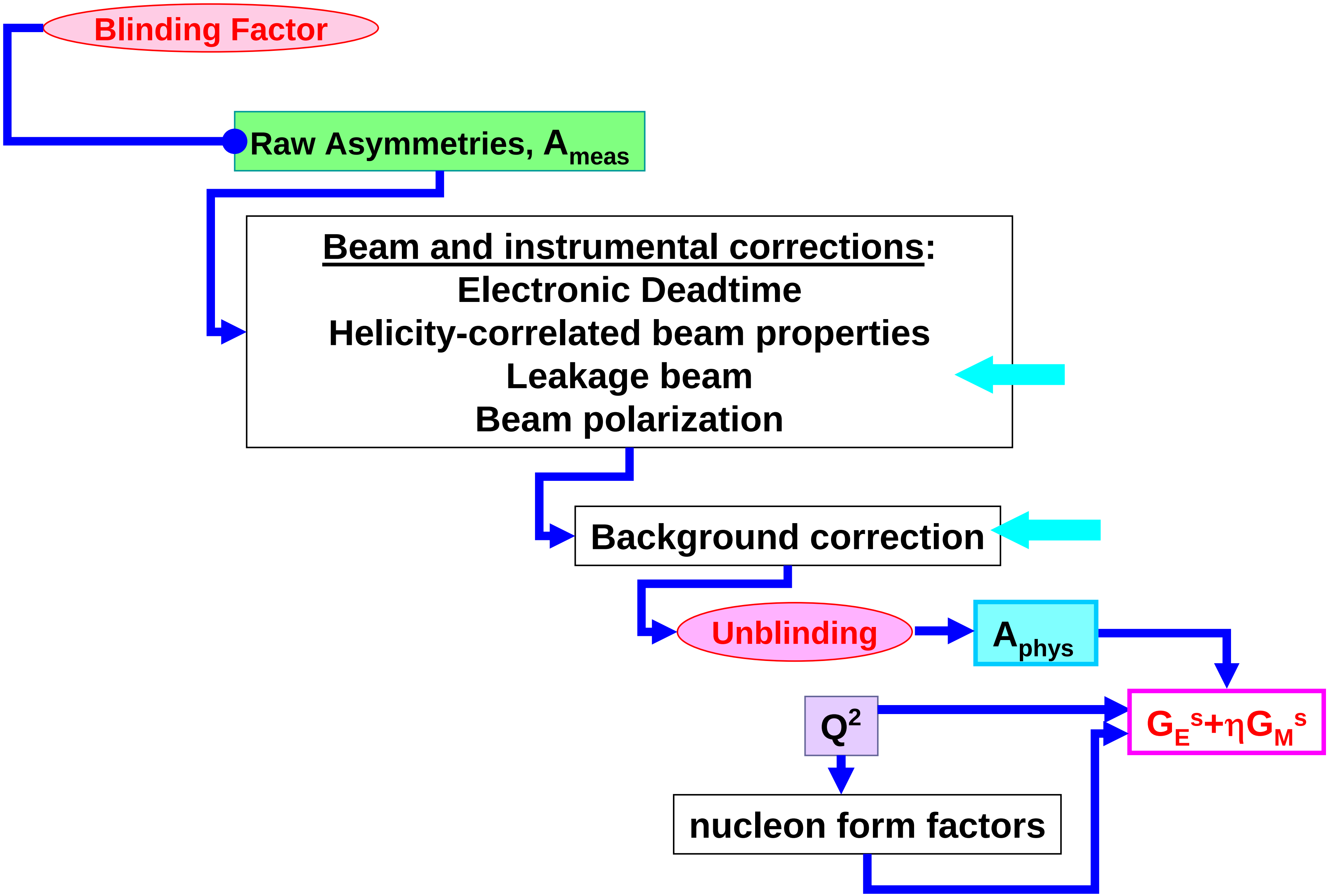
French detector 11



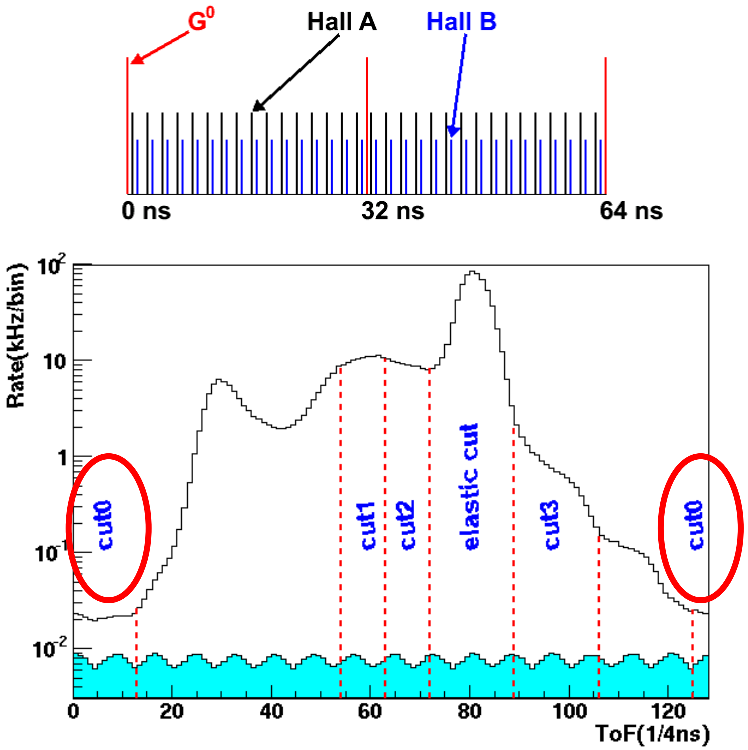
NA detector 11



Analysis Overview



Leakage Beam

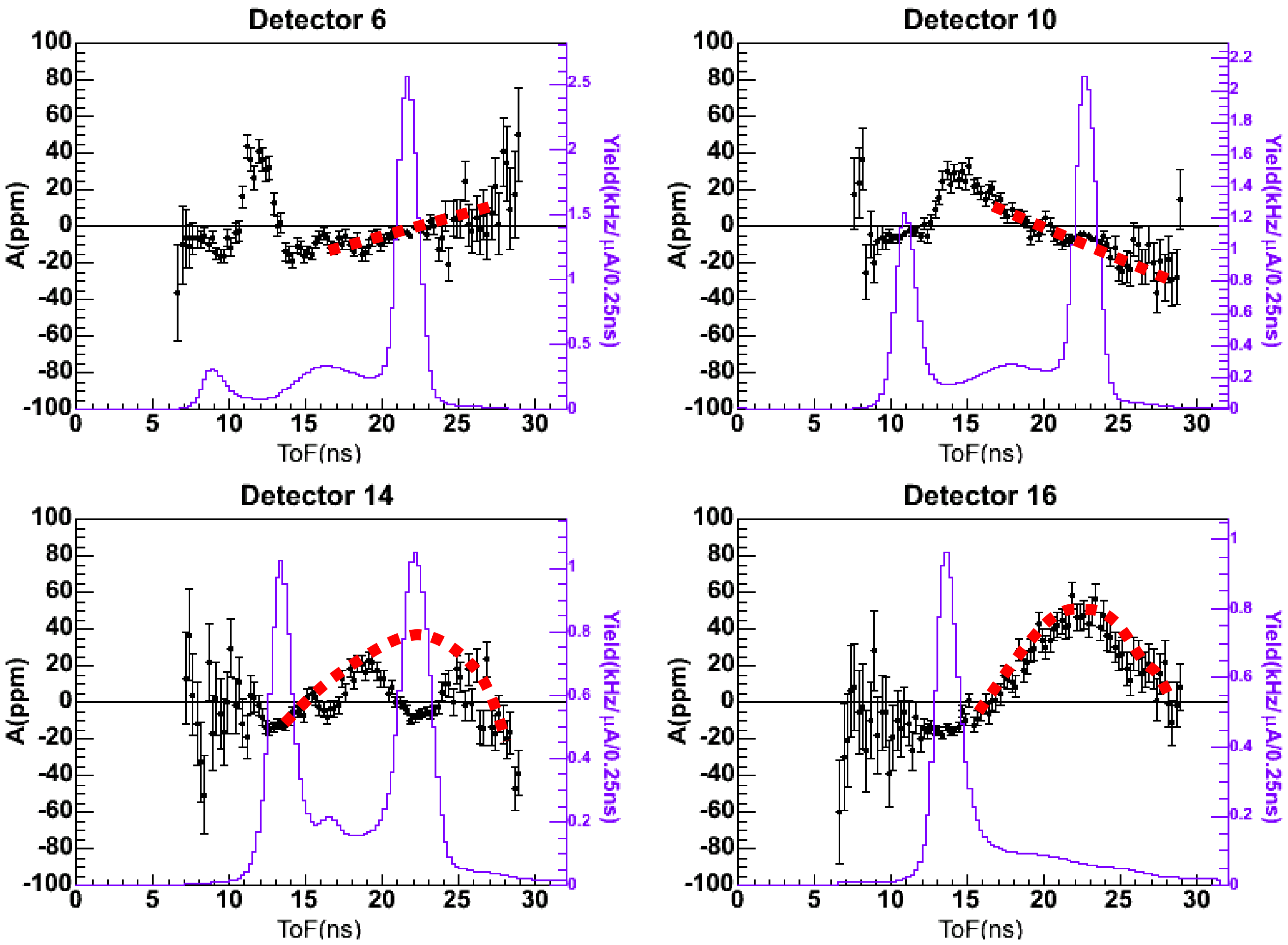


- ~ 50 nA 499 MHz beam leaks into G^0 beam (~ 40 μA)
- Leakage current has large, varying asymmetry (*A* ~ 600 ppm).
- ToF dependent false asymmetry created.
- Need to know the leakage current and asymmetry to make the correction.

- Use "cut0" region in actual data to measure leakage current and asymmetry throughout run.

ΔA_{leak} = -0.71±0.14 ppm (global uncertainty!)

Background Asymmetry



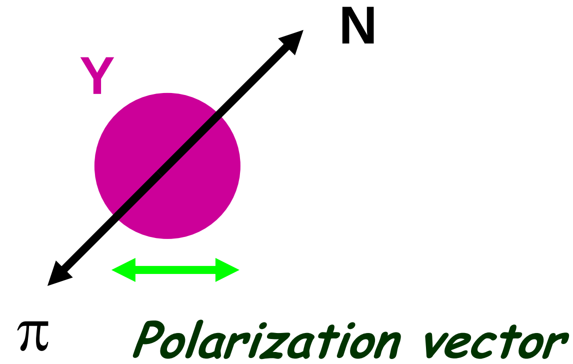
$$A_{\mathrm{m}}(t) = (1 - f_{\mathrm{b}}(t))A_{\mathrm{e}} + f_{\mathrm{b}}(t)A_{\mathrm{b}}(t)$$

Where do they come from ????

Physics Origin of the Positive Background Asymmetries

$$\vec{e} + p \rightarrow \vec{Y} + K$$

$$\vec{Y} \rightarrow N + \pi$$



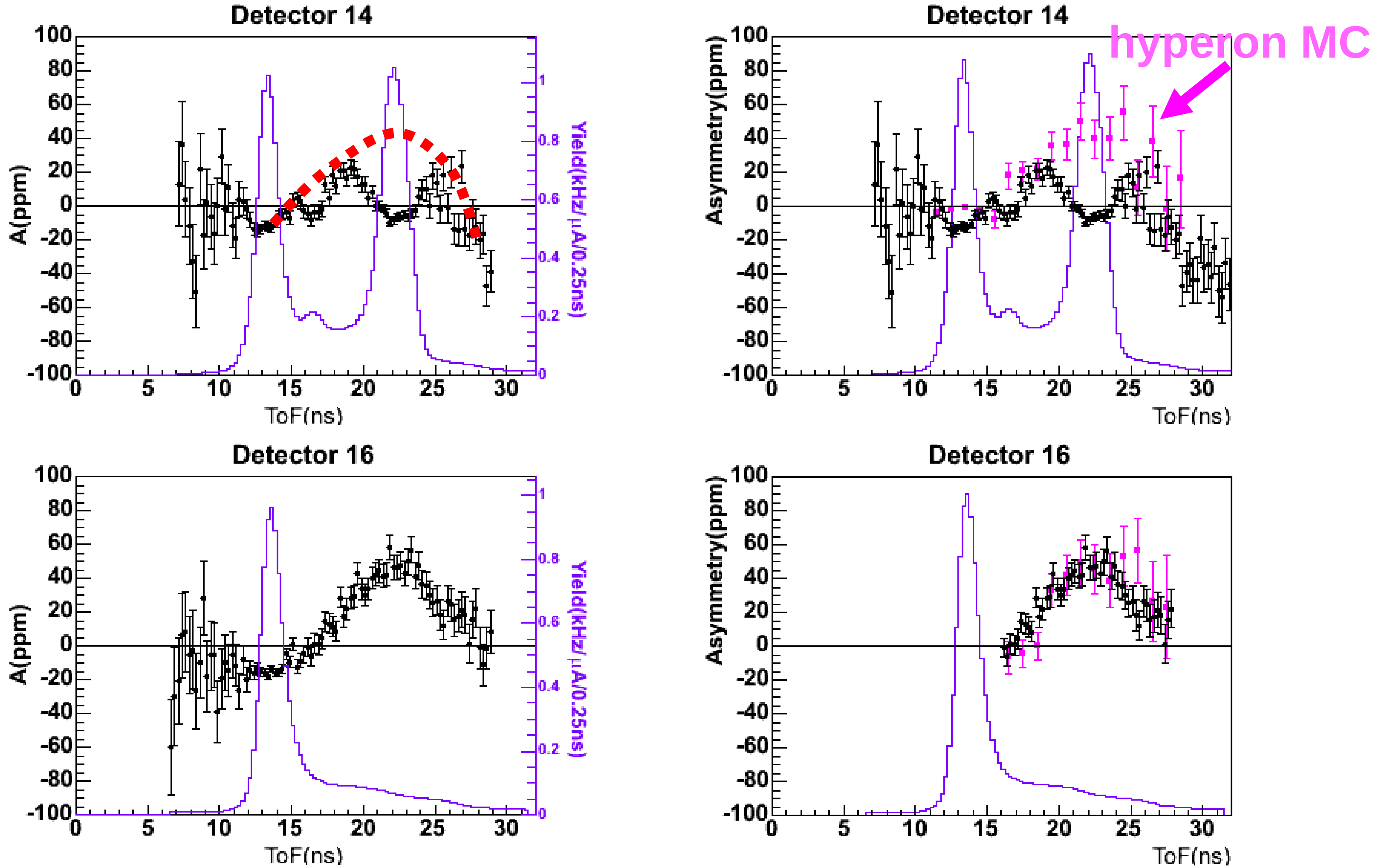
Weak decay, A ≈1 = 10^{6} ppm!!!

The decay particles of hyperons are hugely suppressed by the acceptance, but a small rate can lead to large asymmetry!

```
IF
      Y contribute to 0.001% of the rate
THEN
      A = 0.001%× 10^6 ppm = 10 ppm !
ENDIF
```

Simulated (Λ^0,Σ^+,Σ^0) production with GEANT. Decay particles <u>rescatter</u> inside the spectrometer that make it into the detector.

Results of the Hyperon Simulation

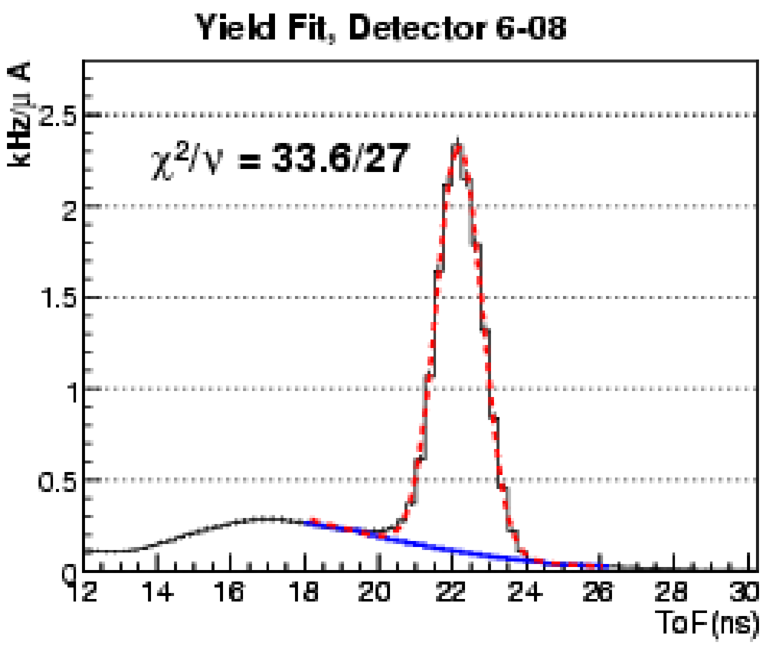


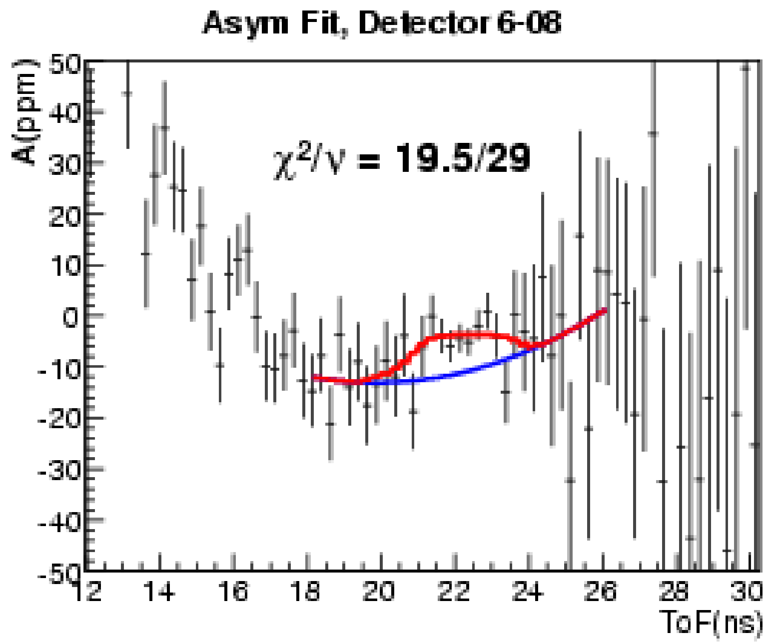
- Source explained. Background asymmetry is smooth in (FPD, ToF).
- Used measured data in the correction.

Background Correction —— Yield & Asymmetry "2-step" Fit

$$A_{\mathrm{m}}(t) = (1 - f_{\mathrm{b}}(t))A_{\mathrm{e}} + f_{\mathrm{b}}(t)A_{\mathrm{b}}(t)$$

$$f_{\mathrm{b}}(t) = \frac{Y_{\mathrm{b}}(t)}{Y_{\mathrm{e}}(t) + Y_{\mathrm{b}}(t)}$$



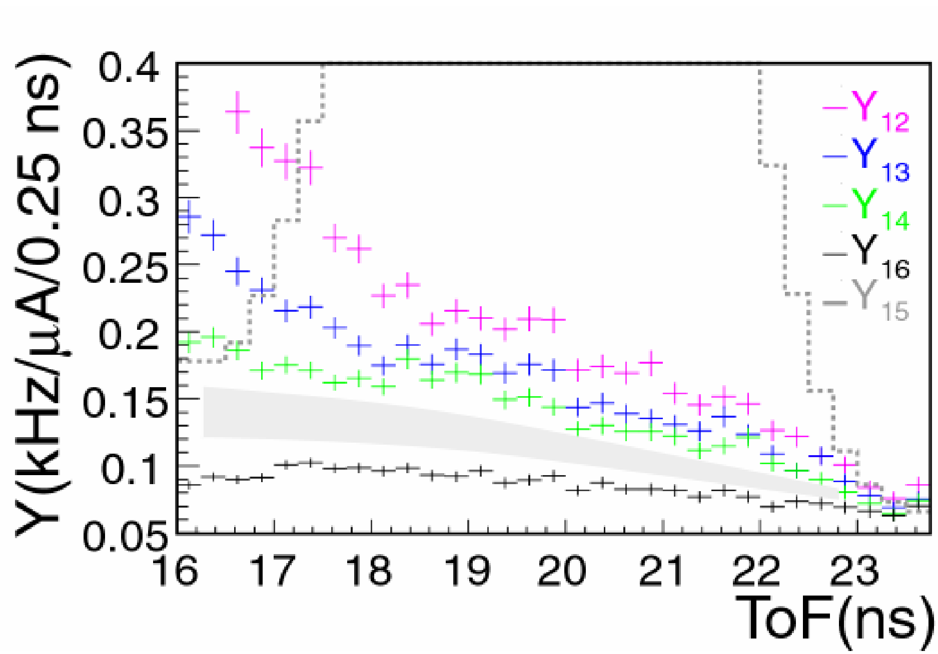


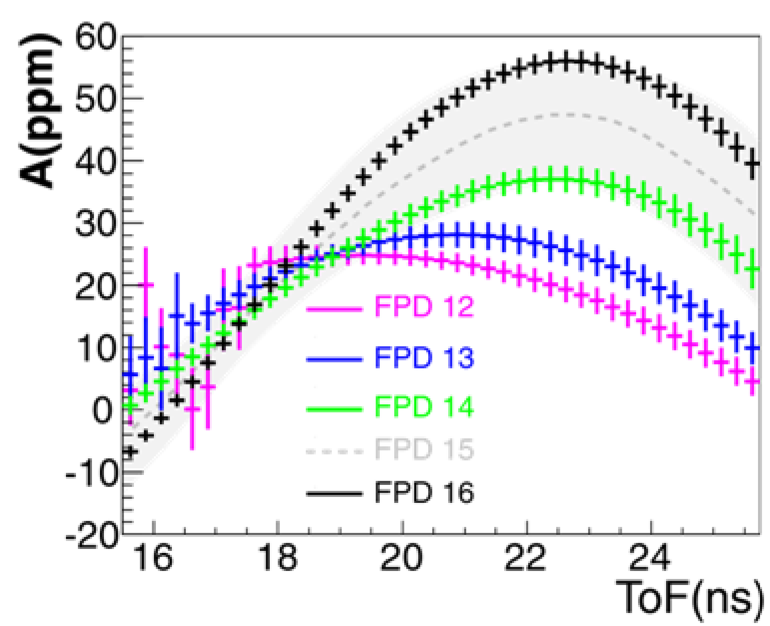
- Extract bin-by-bin background fraction $f_{\mathrm{b}}(t)$ by fitting time-of-flight spectra (gaussian elastic peak + polynomial background)
- Use results to perform asymmetry fit:

  $A_{\mathrm{e}}(t)$ = const, $A_{\mathrm{b}}(t)$ = polynomial

Det. 15 Background Determination

- Elastic peak broadened (~6 ns) because of increased Q^2 acceptance.
- Smooth variation of the background yield and over detector range 12-14, 16. So make linear interpretation over detector number to determine $Y_b(t)$.
- Similar treatment to the background asymmetry

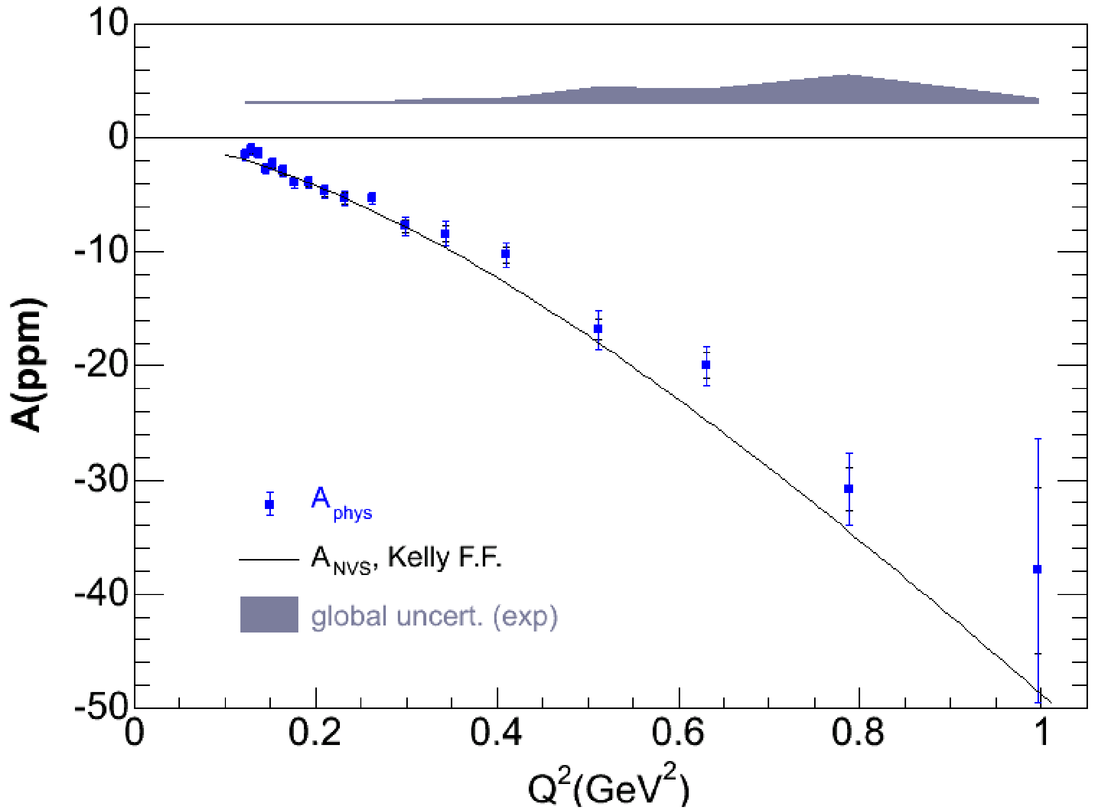




Summary of Systematic Effects

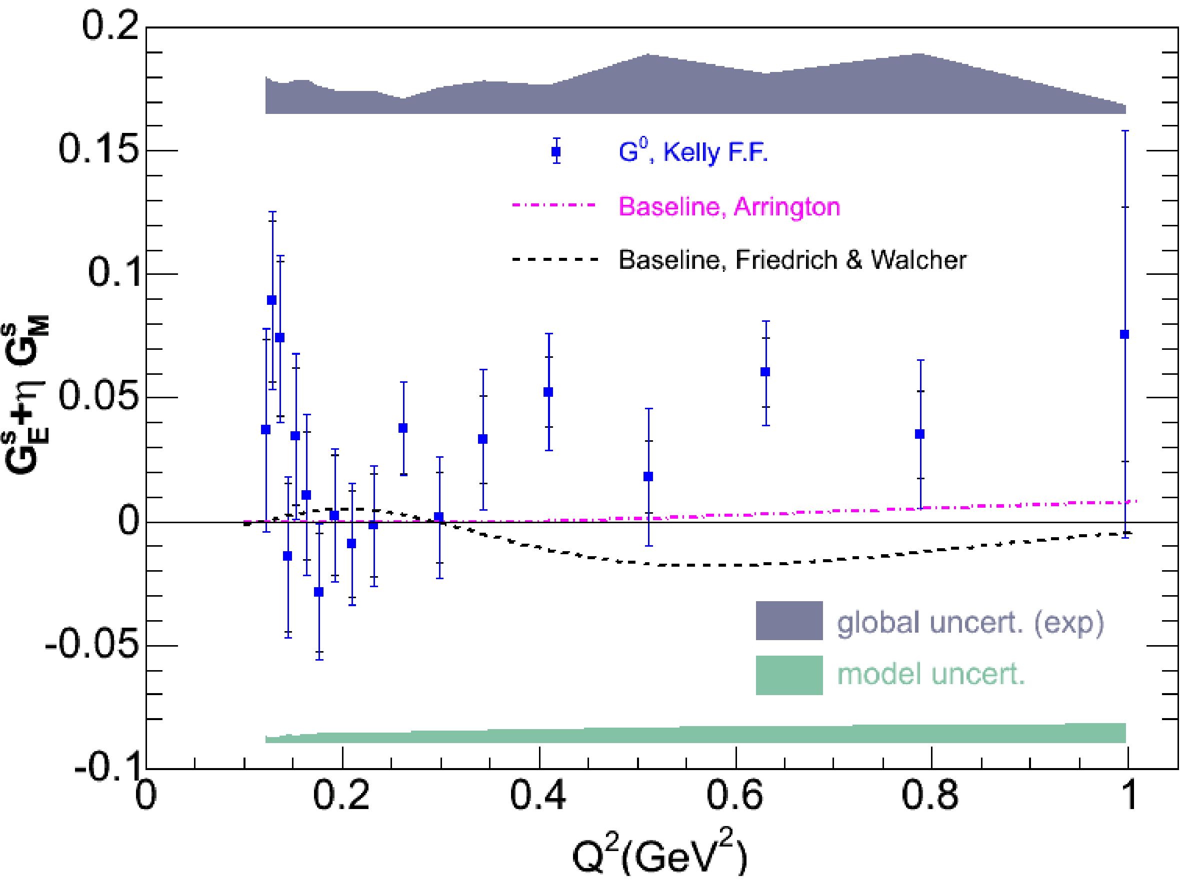
Source	*Correction*	*Uncertainty*	*global or pt-pt*
Electronics deadtime	**0.2**	**0.05 ppm**	***pt-pt***
French time bin correlation	**0**	**0.043 ppm**	***global***
Helicity-correlated differences in beam properties	**0.01**	**0.01 ppm**	***pt-pt***
Leakage beam	**0.71**	**0.14 ppm**	***global***
Beam polarization	**1.36 (frac.)**	**1 % (frac.)**	***global***
Transverse beam polarization	**0**	**0.01 ppm**	***global***
Inelastic background subtraction	**0.1-40 ppm**	**0.2-9 ppm**	***both***
Radiative corrections	**1% (frac.)**	**0.1 % (frac.)**	***pt-pt***
Detector **$\langle Q^2 \rangle$**	**0**	**1 %**	***global***

Elastic Asymmetries



- "Non-vector-strange" asymmetry, $\mathbf{A_{NVS}}$, is $\mathbf{A(G_E^s,G_M^s = 0)}$
- Nucleon EM form factors: ***Kelly PRC 70 (2004) 068202***
- Inner error bars: stat; outer: stat & pt-pt sys
- Dominating global systematic uncertainty: background & leakage

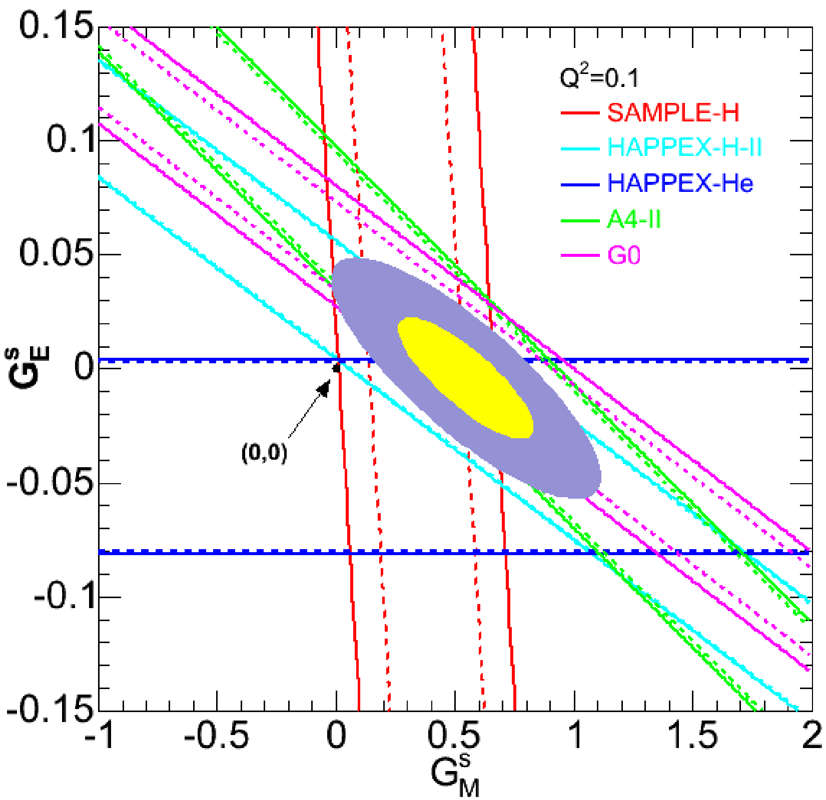
$G_E^s + \eta G_M^s$, Q^2 = 0.12-1.0 GeV^2



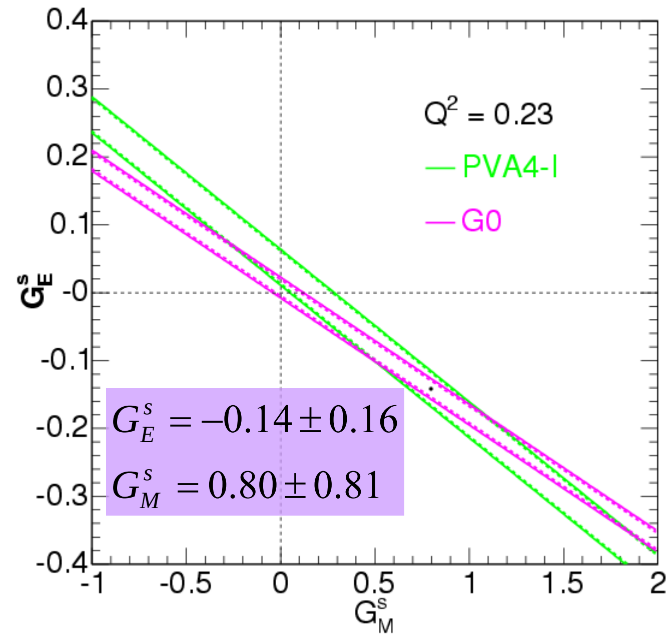
- **"Model" uncertainty: the uncertainty due to the electroweak parameters and the kinematics.**
- **3 nucleon form factor fits; spread indicate uncertainties.**

- A χ^2 test based on the random and correlated uncertainties: the "zero-line" hypothesis is disfavored at 89%.
- Data suggest that either G_E^s or G_M^s (or both) are non-zero and dependent on Q^2.

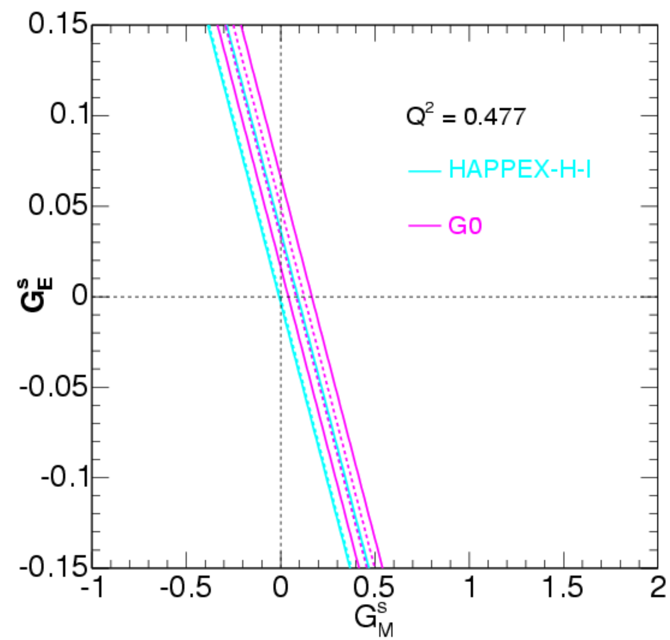
World Data with G^0 (Spring 2006)



$$G_E^s = -0.004 \pm 0.026 \pm 0.008$$
$$G_M^s = 0.55 \pm 0.28 \pm 0.14$$

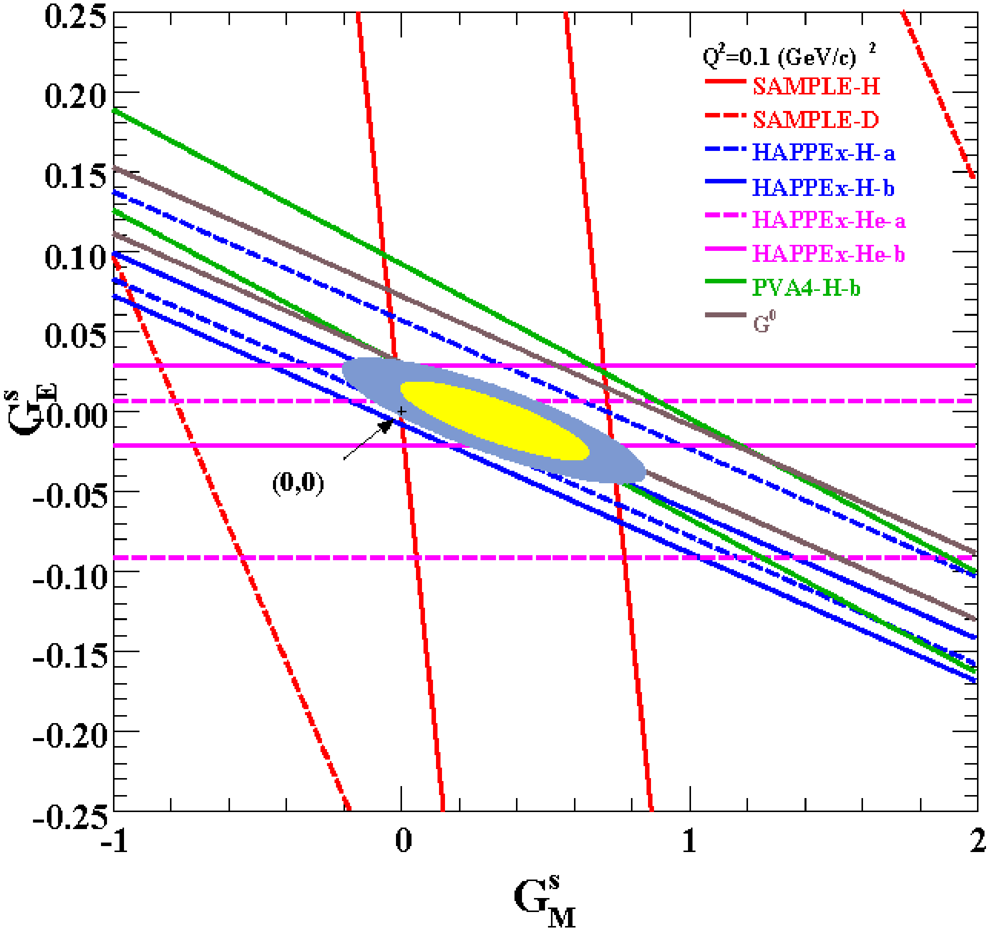


$$G_E^s = -0.14 \pm 0.16$$
$$G_M^s = 0.80 \pm 0.81$$



Most Recent Global Data Analysis

With two recent high statistics HAPPEx Runs



$$G_E^s = -0.008 \pm 0.016$$

$$G_M^s = 0.29 \pm 0.21$$

- One side confidence contour for negative G_M^s is 12.3%, so significantly negative value of G_M^s are highly disfavored.
- Strange quark contribute to μ_p at ~–4% level

nucl-ex/0706.0226

Near Future Outlook

G^0: recently completed backward angle at
Q^2 = 0.63, 0.23 GeV^2 with both LH_2 and LD_2 targets

PV-A4 backward: $\theta = 145°$
Q^2 = 0.23 GeV^2 **(underway)**
both LH_2 and LD_2 targets

HAPPEx
high precision at Q^2 = 0.6 GeV^2

Conclusion

- The G^0 forward angle experiment yields a measurement of parity violating e-p elastic asymmetries over broad Q^2 range: 0.12-1.0 GeV^2.
- Data suggest that either G_E^s or G_M^s (or both) are non-zero and Q^2-dependent.
- Fully separated G_E^s, G_M^s at various Q^2 values await the results from backward angle measurements from G^0 and PVA4.

Acknowledgements

I am so grateful that Jlab awards me the thesis prize.
But this prize is not just for myself …

I want to thank all my G^0 colleagues, particularly Betsy Beise, Doug Beck, and Julie Roche for their guidance and support throughout the years.

I also like to thank Jlab for supporting this challenging and exciting projects.

Formalism Including EW Rad. Corr.

$$A = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{1}{\varepsilon G_E^{p\,2} + \tau G_M^{p\,2}} \left\{ \left(1 - 4\sin^2\theta_W\right)\left(\varepsilon G_E^{p\,2} + \tau G_M^{p\,2}\right)\left(1 + R_V^p\right) - \left(\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n\right)\left(1 + R_V^n\right) - \varepsilon G_E^p \left(G_E^s + \eta G_M^s\right)\left(1 + R_V^{(0)}\right) - \varepsilon'\left(1 - 4\sin^2\theta_W\right) G_M^p G_A^e \right\}$$

Where $\eta \equiv \frac{\tau G_M^p}{\varepsilon G_E^p}$ and

$$G_A^e = \left[-\frac{g_A}{g_V}\left(1 + R_A^{T=1}\right) + \frac{1}{2}\left(3F - D\right)R_A^{T=0} + \Delta s\left(1 + R_A^{(0)}\right)\right] G_A^D$$

$$G_A^D = \frac{1}{(1 + Q^2/\Lambda_A^2)^2}$$

At tree level, R's are zeros.

M.J. Mosolf et al, Phys Rep. 239, No. 1(1994)
S.L Zhu et al, PRD 62,033008(2000)

- Each asymmetry measurement can be cast into a linear combination of G_E^s and G_M^s, assuming everything else is known.
- In forward angle, use theoretical value and uncertainty of G_A^e. Uncertainty dominated by the "anapole" term.

Charge Symmetry Breaking

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

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

$$G_{E,M}^{Z,p} = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G_{E,M}^{u,p} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right) G_{E,M}^{d,p} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right) G_{E,M}^{s,p}$$

$$G^{u,p} = G^{d,n} - \Delta_u ; G^{d,p} = G^{u,n} - \Delta_d ; G^{s,p} = G^{s,n} - \Delta_s$$

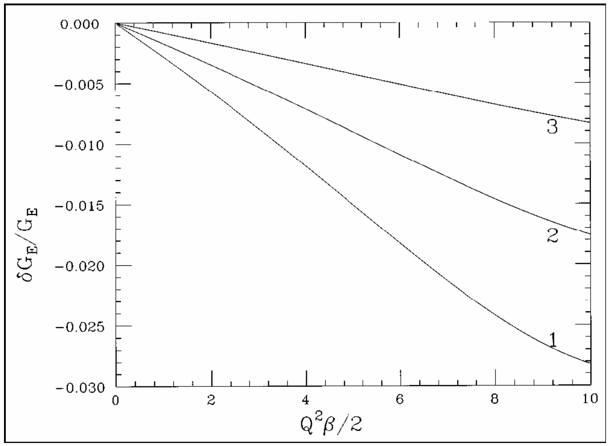
$$G_{E,M}^{s} = (1 - 4\sin^2\theta_W) G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p} + \frac{2}{3}\Delta_d - \frac{1}{3}\Delta_u - \frac{1}{3}\Delta_s$$

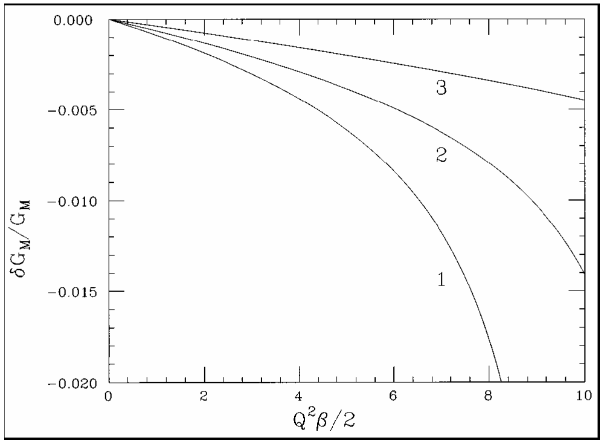
No charge symmetry breaking:

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

Ma, Phys. Lett. B 408, 387 (1997) $\delta G_M^s \approx 0.007\ n.m.$

G. Miller's (PRC 57, 1492 (1998))'s results





$\beta/2\sim0.01/\text{GeV}^2$

Loosely translated as: $\dfrac{\Delta_u}{G^{u,p}}, \dfrac{\Delta_d}{G^{d,p}}, \dfrac{\Delta_s}{G^{s,p}} < 1\%$

So $\delta G_E^s < 0.01, \delta G_M^s < 0.02$ at $Q^2\beta/2\sim4$

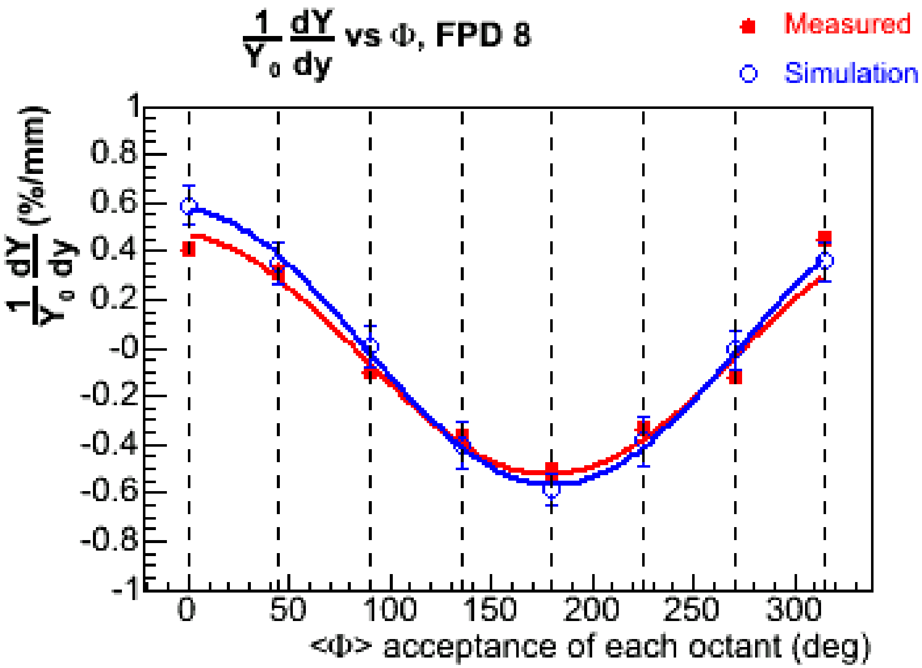
Also should be small at low Q^2

Helicity Correlated Beam Properties and Their Corrections

$$A_{\text{false}} = \sum_i \frac{1}{2\langle Y \rangle} \underline{\left(\frac{\partial Y}{\partial P_\text{i}} \right)} \underline{\underline{\Delta P_\text{i}}}$$

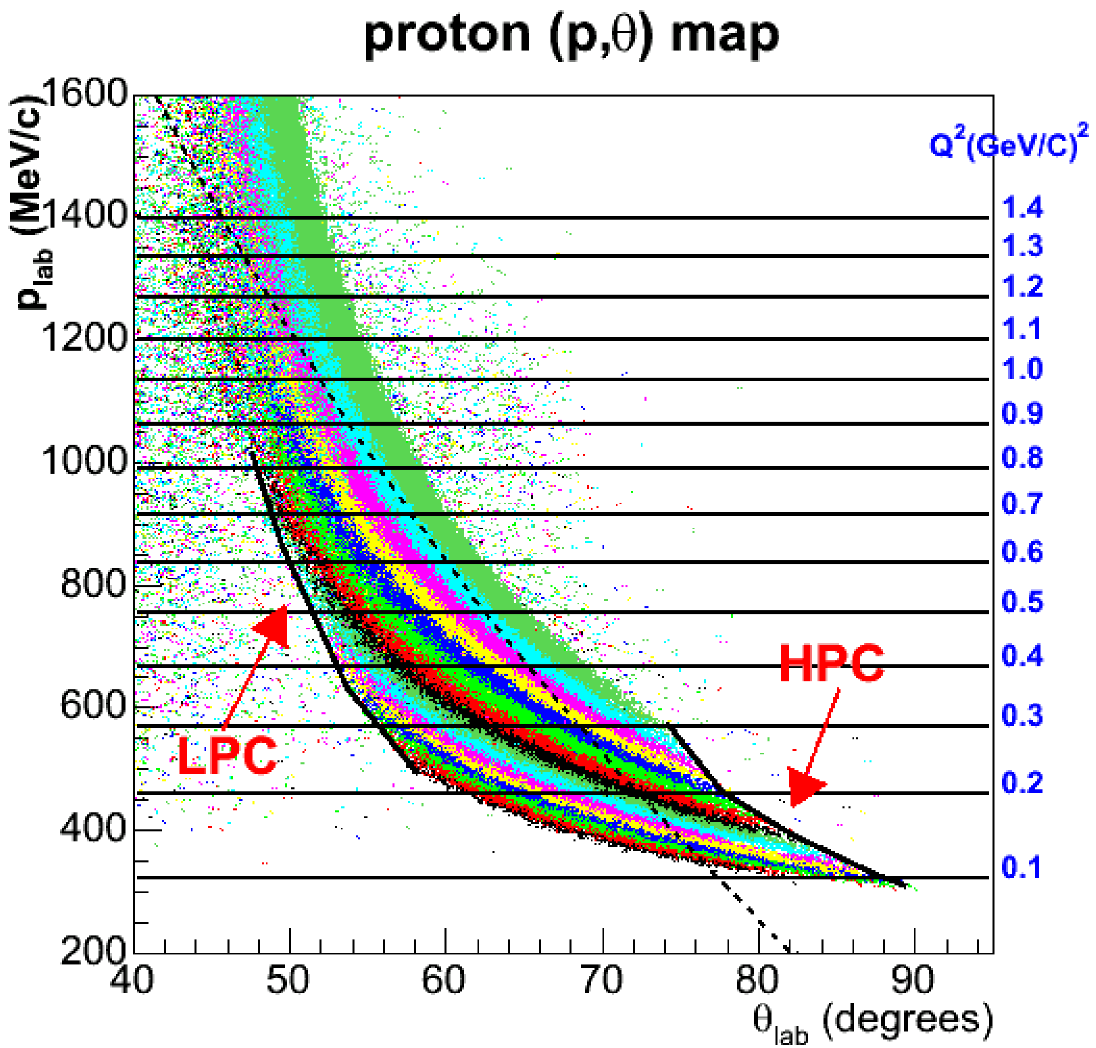
So require

- ☑ Small ΔP_i
- ☐ <u>Small sensitivity to P_i</u>



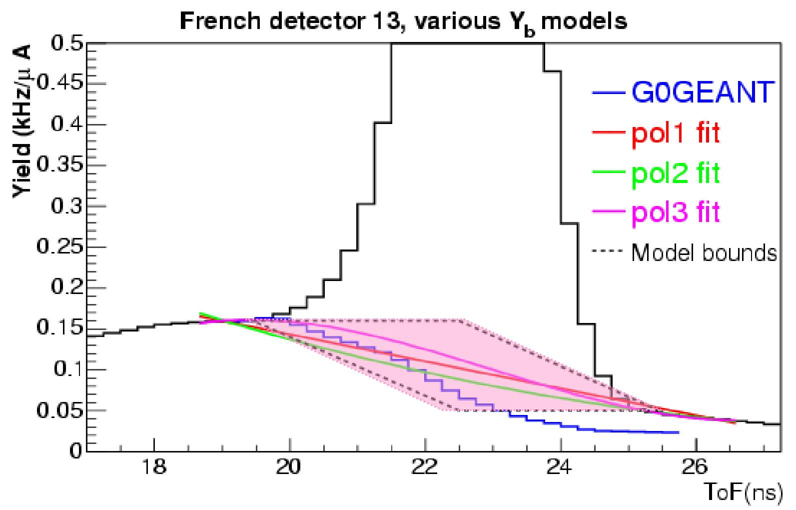
- Azimuthal symmetry ⇒ large reduction of detector sensitivity to beam positions
- Response of spectrometer to beam changes well understood
- False asymmetries (and the uncertainty) due to helicity-correlated beam parameters very small (~-0.02 ppm)

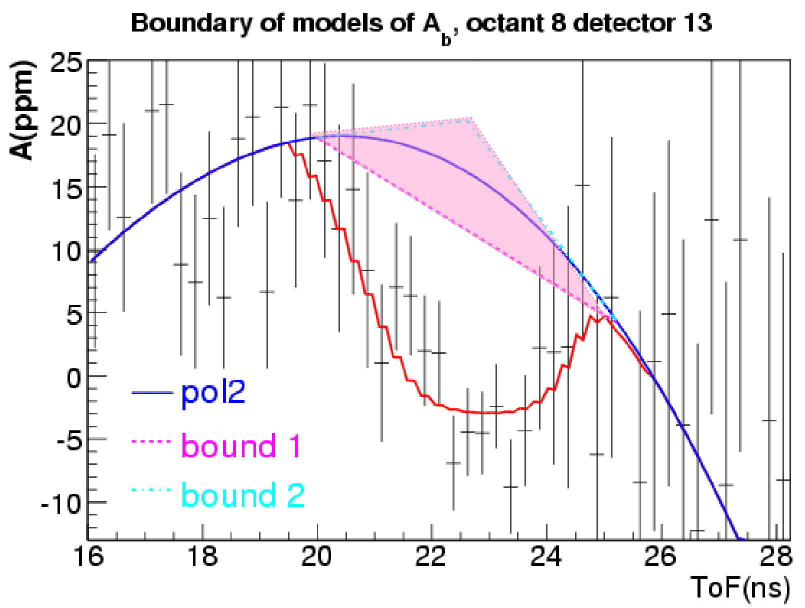
Detector Acceptance



Large and continuous acceptance for protons.

Systematic Uncertainty of the Correction



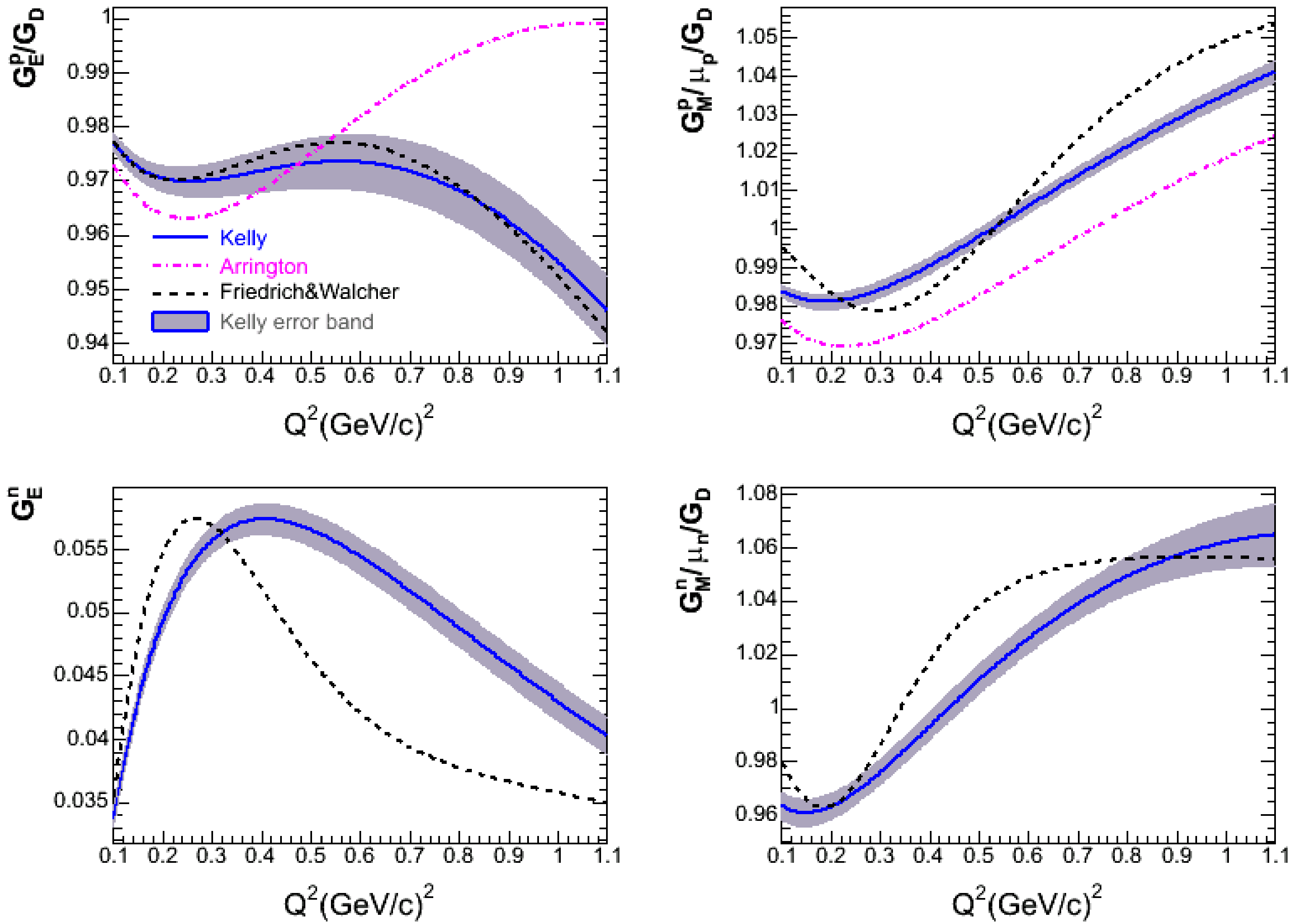


- Allowed background yield to vary within the parallelogram.
- Similar procedure for background asymmetry.
- Looking for global changes of A_e on different detectors if the background model is changed globally.

$$\sigma_{sys}^{pt-pt^2}(A_e) = \frac{3}{4}\sigma_{sys}^2(A_e)$$

$$\sigma_{sys}^{glob^2}(A_e) = \frac{1}{4}\sigma_{sys}^2(A_e)$$

Different Nucleon EM FF Parametrizations



Combining World Data

General procedure:

I. Start from the experimental asymmetries and uncertainties from different experiment
II. Use a common set of form factor and electroweak parameters
III. Calculate $\mathbf{G_E^s+\eta G_M^s}$
IV. Combine world data and separate $\mathbf{G_E^s}$ **and** $\mathbf{G_M^s}$
V. The sensitivity to nucleon form factor and electroweak parameters are evaluated separately by changing the model input globally and repeat I-IV

Interpolate G^0 Data I

Three overlapping Q^2 with other experiments:

Q^2 = 0.1(HAPPEX, SAMPLE, A4), Q^2 = 0.23 (A4), Q^2=0.48 (HAPPEX)

- $Q^2 = 0.1$

  extrapolate G^0 using A_i/Q^2_i for first 3 Q^2 points

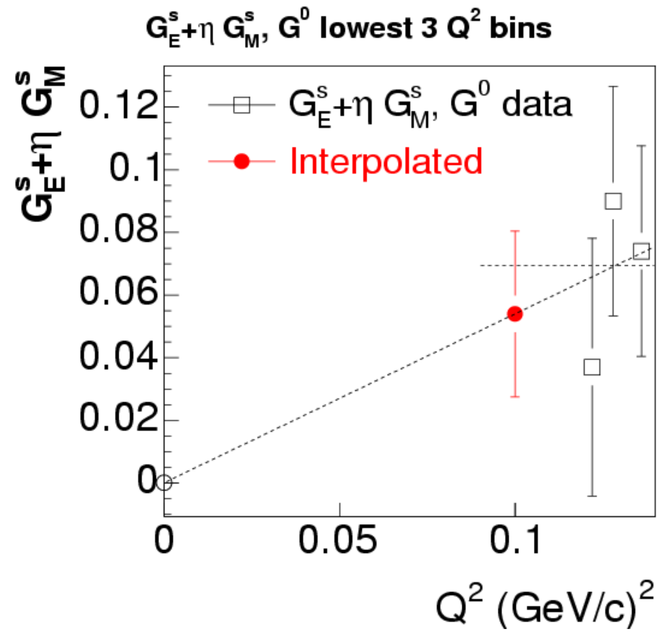
  Q^2 = {0.122, 0.128, 0.136}

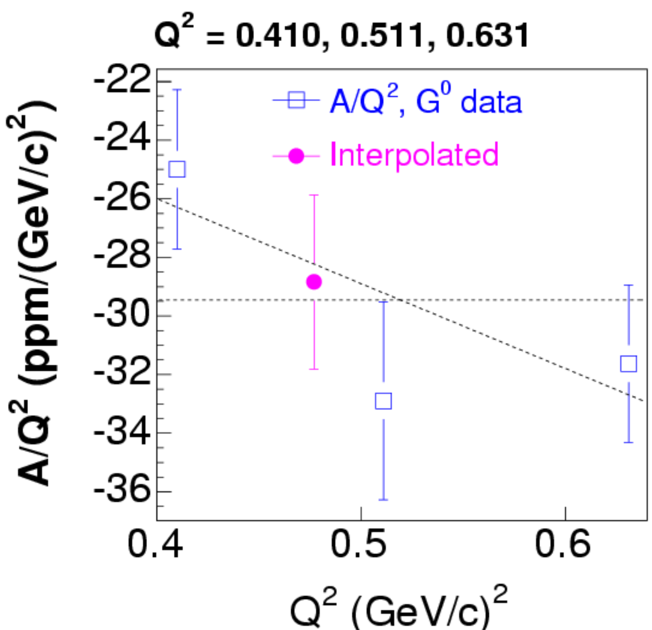
- Q^2 = 0.23 (PVA4-I), 0.477 (HAPPEX-I) GeV^2

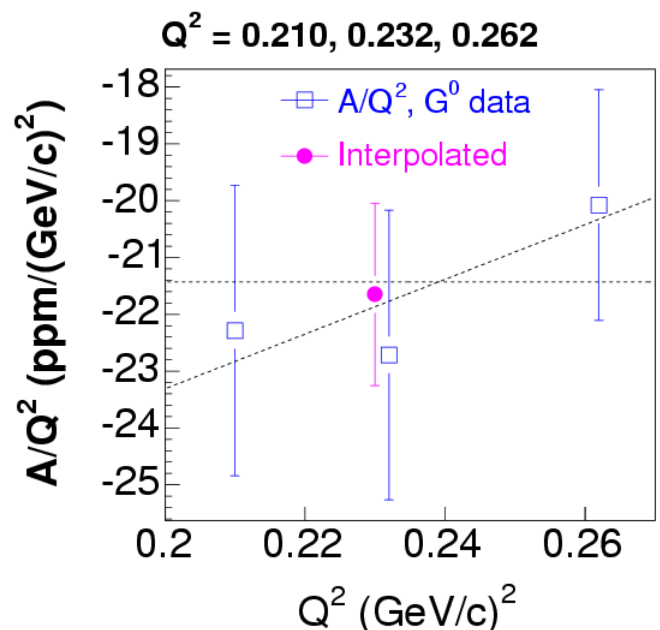
  Interpolate A_i/Q^2_i for Q^2 = {0.210, 0.232, 0.262},{0.410, 0.511, 0.631}

- Average the results of flat and linear interpolation. Use the ½ difference as an additional "model" uncertainty.

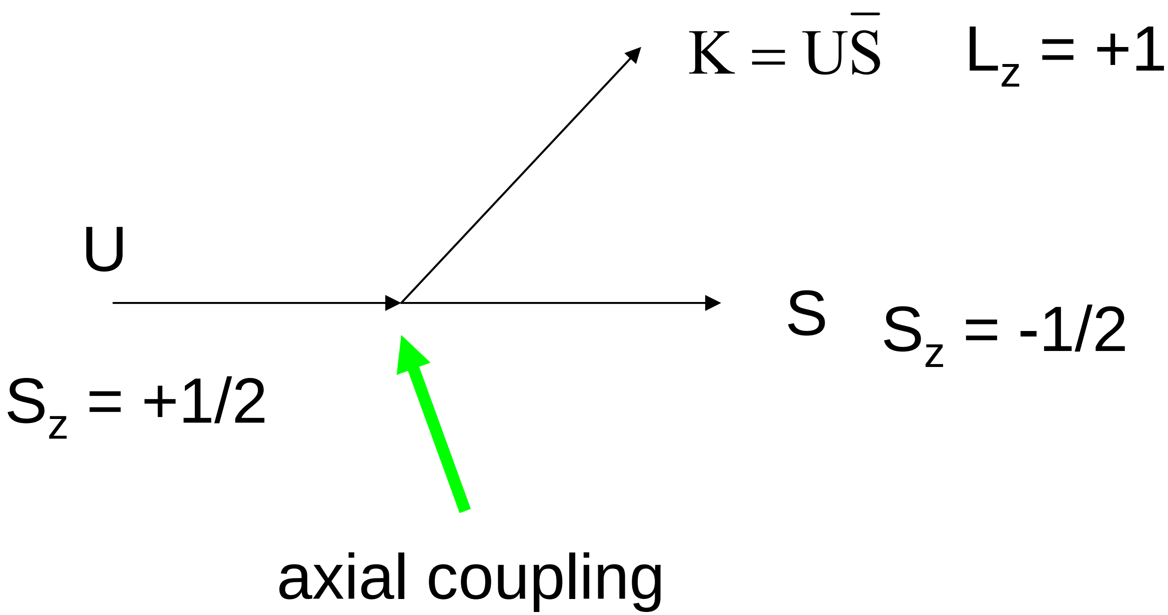
Interpolate G^0 Data II







Riska's argument for the strange magnetic moment



So both S and $\bar{S}$ contribute positive amount to proton magnetic moment $\rightarrow$ negative μ_s

^{4}He spin 0, parity even, isoscalar

$$A_{He} = \frac{G_F Q^2}{4\pi\sqrt{2}\alpha}\left(4\sin^2\theta_W + \frac{2G_E^s}{G_E^p + G_E^n}\right)$$

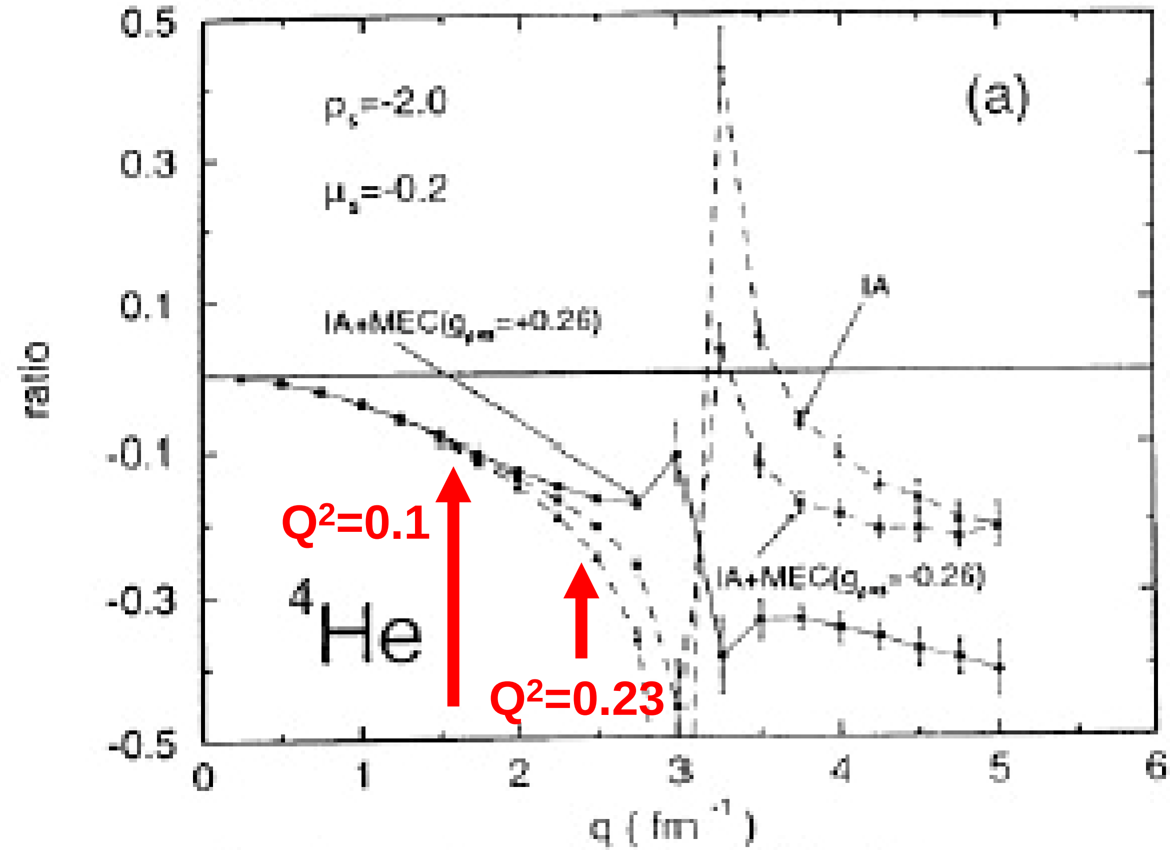


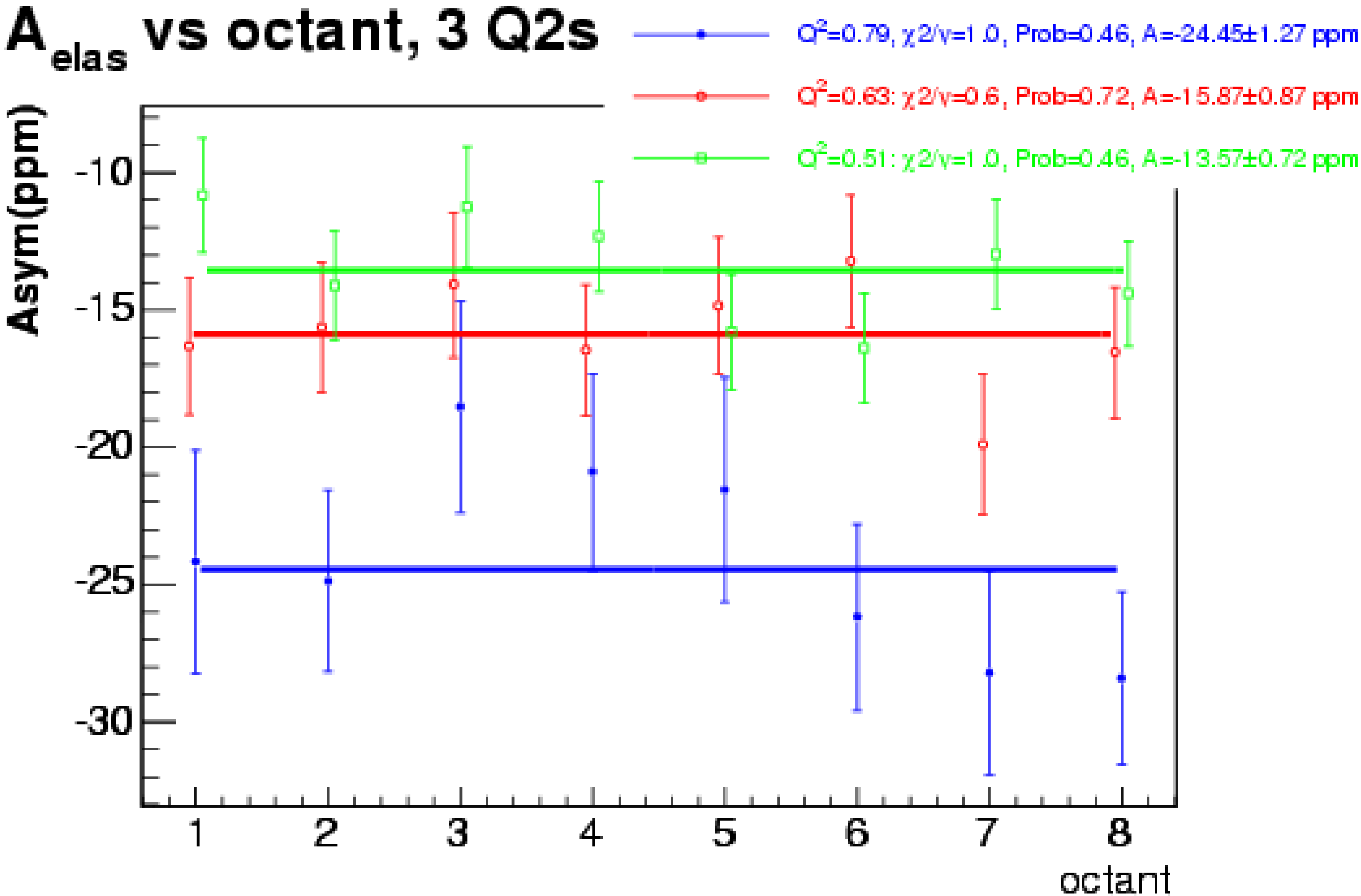
FIGURE 4. Effects of meson exchange currents (MEC) [17]. The elastic strangeness to electromagnetic form factor ratio is plotted vs. q for impulse approximation (IA) and for two choices of possible MEC contributions. At the present kinematics ($q = 1.6\,\mathrm{fm}^{-1}$), the effects of MEC are negligible.

Sensitivity of the Elastic Neutrino Scattering to the nucleon strangeness

$$\left(\frac{d\sigma}{dQ^2}\right)^{NC} = \frac{{G_F}^2}{2\pi}[\frac{1}{2}y^2(G_M^Z)^2 + (1-y-\frac{M}{2E}y)\frac{(G_E^Z)^2+\frac{E}{2M}y(G_M^Z)^2}{1+\frac{E}{2M}y}$$

$$+(\frac{1}{2}y^2+1-y+\frac{M}{2E}y)(G_A^Z)^2 + 2y(1-\frac{1}{2}y)G_M^Z G_A^Z]$$

$$y = \frac{Q^2}{2p\cdot k}$$



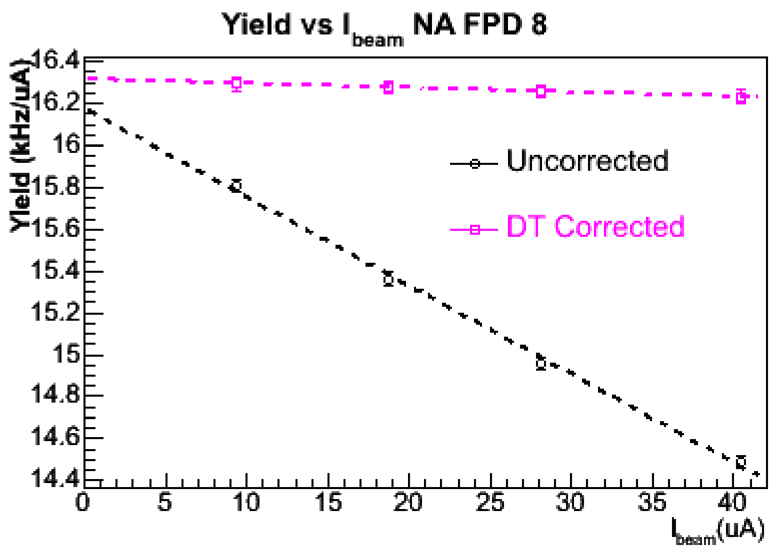
A elas vs octant, 3 Q2s
Q2=0.79, χ2/ν=1.0, Prob=0.46, A=-24.45±1.27 ppm
Q2=0.63: χ2/ν=0.6, Prob=0.72, A=-15.87±0.87 ppm
Q2=0.51: χ2/ν=1.0, Prob=0.46, A=-13.57±0.72 ppm
Asym(ppm)
-10
-15
-20
-25
-30
1
2
3
4
5
6
7
8
octant

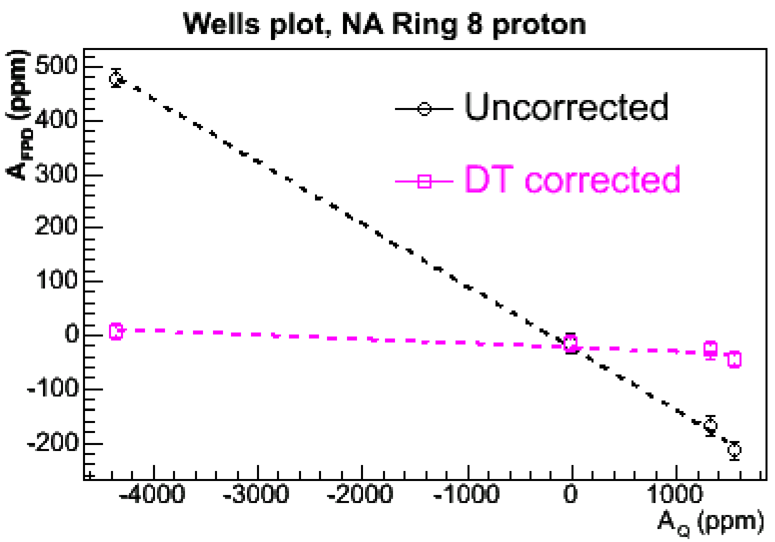
Electronic Deadtime Corrections

To the first order

$$Y_m^{\pm} = (1 - f^{\pm}(R^{\pm}))Y_t^{\pm},\ f = R\tau \sim 10\%$$

$$A_{false} = -\frac{f}{1-f}(A_Q + A_{phys})$$





- The deadtime effect is largely corrected based on the model of the electronics
- Small correction based on the measured $f_{residual}$, A_{phys}, and A_Q (~0.05±0.05 ppm).