Towards a common PVA4-SAMPLE analysis:
a first step

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1 Introduction

This is a shortened version of the report 'Evaluation of Strange Form-Factors in Parity Violating Electron Scattering'[1] where all the unnecessary formulae and Appendices have been removed. The purpose of the present report is to discuss a basic set of formulae and parameters to be used in a common analysis aiming at performing a forward/backward separation around $Q^2 = 0.1 (GeV/c)^2$. The same set of parameters could be used for G^0 .

2 Basic formulae

2.1 Asymmetry

We use the Standard Model (SM) formalism and parameters as defined in the latest Particle Data Book [8], including electroweak radiative corrections evaluated in the $\overline{MS}$ scheme. The parity violating asymmetry in ep scattering is given as a function of the SM parameters by [1]:

$$A_{LR}(\vec{e}p) = A_V + A_A + A_{ana} \tag{1}$$

$$\begin{aligned}
A_{LR}(\vec{e}p) = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \Bigg\{ & \rho'_{eq}(1 - 4\hat{\kappa}'_{eq}\hat{s}^2_Z) - 2(2\lambda_{1u} + \lambda_{1d}) \\
& -[\rho'_{eq} + 2(\lambda_{1u} + 2\lambda_{1d})] \frac{\varepsilon G^p_E G^n_E + \tau G^p_M G^n_M}{\varepsilon (G^p_E)^2 + \tau (G^p_M)^2} \Bigg\} \\
& + \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} [\rho'_{eq} + 2(\lambda_{1u} + \lambda_{1d} + \lambda_{1s})] \frac{\varepsilon G^p_E}{\varepsilon (G^p_E)^2 + \tau (G^p_M)^2} G^s_E \\
& + \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} [\rho'_{eq} + 2(\lambda_{1u} + \lambda_{1d} + \lambda_{1s})] \frac{\tau G^p_M}{\varepsilon (G^p_E)^2 + \tau (G^p_M)^2} G^s_M \\
& + \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{(1 - 4\sin^2\theta_W)\,\varepsilon' G^p_M}{\varepsilon (G^p_E)^2 + \tau (G^p_M)^2} \widetilde{G}^p_A + A_{ana}
\end{aligned} \tag{2}$$

where A_v is the vector asymmetry, A_A is the one-quark axial asymmetry an A_ana is the anapole contribution. G_F if the Fermi constant deduced from muon decay, $\sin^2\theta_W$ is taken at the Z^0 mass: $\sin^2\theta_W = \hat{s}^2_Z$. The ρ and λ parameters are taken from the PDG[8].

The axial weak form-factor is usually expressed as a function of the ξ parameters:

$$\widetilde{G}^{p}_{A}(Q^2) = \xi^{T=1}_{A} G^{(3)}_{A}(Q^2) \ + \xi^{T=0}_{A} G^{(8)}_{A}(Q^2) \ + \ \xi^{(0)}_{A} G^{s}_{A}(Q^2) \tag{3}$$

In that case the asymmetry becomes:

$$\begin{aligned} A_{LR}(\vec{e}p) = & -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left\{ \ \xi^{p}_{V} \ + \xi^{n}_{V} \ \frac{\varepsilon G^{p}_{E} G^{n}_{E} + \tau G^{p}_{M} G^{n}_{M}}{\varepsilon (G^{p}_{E})^2 + \tau (G^{p}_{M})^2} \right\} \\ & -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \xi^{(0)}_{V} \ \frac{\varepsilon G^{p}_{E}}{\varepsilon (G^{p}_{E})^2 + \tau (G^{p}_{M})^2} \ G^{s}_{E} \\ & -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \xi^{(0)}_{V} \ \frac{\tau G^{p}_{M}}{\varepsilon (G^{p}_{E})^2 + \tau (G^{p}_{M})^2} \ G^{s}_{M} \\ & +\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \ \frac{(1 - 4\sin^2\theta_W)\,\varepsilon' \, G^{p}_{M}}{\varepsilon (G^{p}_{E})^2 + \tau (G^{p}_{M})^2} \ \widetilde{G}^{p}_{A} + A_{ana} \end{aligned} \tag{4}$$

Finally it can also be written as a function of the R parameters introduced in [10] to characterize the difference between the value of the ξ parameters at tree level and at higher order:

$$\begin{aligned} A_{LR}(\vec{e}p) = & -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left\{ \ (1 - 4\sin^2\theta_W)(1 + R^{p}_{V}) - (1 + R^{n}_{V}) \frac{\varepsilon G^{p}_{E} G^{n}_{E} + \tau G^{p}_{M} G^{n}_{M}}{\varepsilon (G^{p}_{E})^2 + \tau (G^{p}_{M})^2} \right\} \\ & +\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \ (1 + R^{(0)}_{V}) \frac{\varepsilon G^{p}_{E}}{\varepsilon (G^{p}_{E})^2 + \tau (G^{p}_{M})^2} \ G^{s}_{E} \\ & +\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \ (1 + R^{(0)}_{V}) \frac{\tau G^{p}_{M}}{\varepsilon (G^{p}_{E})^2 + \tau (G^{p}_{M})^2} \ G^{s}_{M} \\ & +\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \ \frac{(1 - 4\sin^2\theta_W)\,\varepsilon' G^{p}_{M}}{\varepsilon (G^{p}_{E})^2 + \tau (G^{p}_{M})^2} \ \widetilde{G}^{p}_{A} + A_{ana} \end{aligned} \tag{5}$$

The anapole contribution A_{ana} is discussed in section 3.4 .

2.2 Relations between the different sets of electroweak radiative corrections parameters

There are the following relations between the different parameter sets:

Quantity	Standard Model Expression	
C_{1u}	$\rho'_{eq}(-\frac{1}{2} + \frac{4}{3}\hat{\kappa}'_{eq}\hat{s}^2_Z) + \lambda_{1u}$	
C_{1d}	$\rho'_{eq}(\frac{1}{2} - \frac{2}{3}\hat{\kappa}'_{eq}\hat{s}^2_Z) + \lambda_{1d}$	
C_{1s}	$\rho'_{eq}(\frac{1}{2} - \frac{2}{3}\hat{\kappa}'_{eq}\hat{s}^2_Z) + \lambda_{1s}$	
C_{2u}	$\rho_{eq}(-\frac{1}{2} + 2\hat{\kappa}_{eq}\hat{s}^2_Z) + \lambda_{2u}$	
C_{2d}	$\rho_{eq}(\frac{1}{2} - 2\hat{\kappa}_{eq}\hat{s}^2_Z) + \lambda_{2d}$	
C_{2s}	$\rho_{eq}(\frac{1}{2} - 2\hat{\kappa}_{eq}\hat{s}^2_Z) + \lambda_{2s}$	

Table 1: Electron-hadron neutral current parameters in the S.M. To first order, $\rho = \kappa = 1$, $\lambda = 0$.

In the $\overline{MS}$ -scheme[8] $\sin^2\theta_W$ is taken at the Z^0 mass: $\sin^2\theta_W = \hat{s}^2_Z$

- **Vector part**

$$\begin{aligned}
\xi_V^{T=1} &= -2C_1^u + 2C_1^d \\
&= 2\rho'_{eq}(1 - 2\hat{\kappa}'_{eq}\hat{s}_Z^2) - 2(\lambda_{1u} - \lambda_{1d}) && (6) \\
&\equiv 2(1 - 2\sin^2\theta_W)(1 + R_V^{T=1}) && (7)
\end{aligned}$$

$$\begin{aligned}
\xi_V^{T=0} &= \sqrt{3}(-2C_1^u - 2C_1^d) \\
&= -\frac{4}{\sqrt{3}}\,\rho'_{eq}\hat{\kappa}'_{eq}\hat{s}_Z^2 - 2\sqrt{3}(\lambda_{1u} + \lambda_{1d}) && (8) \\
&\equiv \frac{-4\sin^2\theta_W}{\sqrt{3}}(1 + R_V^{T=0})
\end{aligned}$$

$$\begin{aligned}
\xi_V^{(0)} &= -2(C_1^u + C_1^d + C_1^s) \\
&= -[\rho'_{eq} + 2(\lambda_{1u} + \lambda_{1d} + \lambda_{1s})] && (9) \\
&\equiv -(1 + R_V^{(0)})
\end{aligned}$$

By combining the vector and scalar part, one gets access to the neutron and proton terms:

$$\begin{aligned}
\xi_V^n &= \frac{1}{2}(-\xi_V^{T=1} + \sqrt{3}\xi_V^{T=0}) \\
&= -[\rho'_{eq} + 2(\lambda_{1u} + 2\lambda_{1d})] && (10) \\
&\equiv -(1 + R_V^n)
\end{aligned}$$

$$\begin{aligned}
\xi_V^p &= \frac{1}{2}(\xi_V^{T=1} + \sqrt{3}\xi_V^{T=0}) \\
&= \rho'_{eq}(1 - 4\hat{\kappa}'_{eq}\hat{s}_Z^2) - 2(2\lambda_{1u} + \lambda_{1d}) && (11) \\
&\equiv (1 - 4\sin^2\theta_W)(1 + R_V^p)
\end{aligned}$$

From eq.10,11, one can define:

$$R_V^p = (1 - 4\sin^2\theta_W)^{-1}\left[(1 - 2\sin^2\theta_W)R_V^{T=1} - 2\sin^2\theta_W R_V^{T=0}\right] \tag{12}$$

$$R_V^n = (1 - 2\sin^2\theta_W)R_V^{T=1} + 2\sin^2\theta_W R_V^{T=0} \tag{13}$$

- **Axial part**

$$\begin{aligned}
\xi_A^{T=1} &= \frac{1}{1 - 4\sin^2\theta_W}(2C_{2u} - 2C_{2d}) \\
&= \frac{-2}{1 - 4\sin^2\theta_W}[\rho_{eq}(1 - 4\hat{\kappa}_{eq}\hat{s}_Z^2) - (\lambda_{2u} - \lambda_{2d})] \\
&\equiv -2(1 + R_A^{T=1}) && (14)
\end{aligned}$$

$$\begin{aligned}
\xi_A^{T=0} &= \frac{\sqrt{3}}{1 - 4\sin^2\theta_W}(2C_{2u} + 2C_{2d}) \\
&= \frac{2\sqrt{3}}{1 - 4\sin^2\theta_W}(\lambda_{2u} + \lambda_{2d}) \\
&\equiv \sqrt{3}R_A^{T=0} && (15)
\end{aligned}$$

$$\begin{aligned}\xi_A^{(0)} &= \frac{2}{1-4\sin^2\theta_W}(C_{2u}+C_{2d}+C_{2s}) \\ &= \frac{1}{1-4\sin^2\theta_W}[\rho_{eq}(1-4\hat{\kappa}_{eq}\hat{s}_Z^2)+2(\lambda_{2u}+\lambda_{2d}+\lambda_{2s})] \\ &\equiv (1+R_A^{(0)}) \end{aligned} \tag{16}$$

The numerical values [8] are given in the following tables:

- Vector part

Ref.	ρ'_{eq}	$\hat{\kappa}'_{eq}$	$\hat{s}_Z^2$	λ_{1u}	λ_{1d}	λ_{1s}
[8]	0.9881000	1.0027000	0.2312000	-0.0000185	0.0000370	0.0000370
Ref.	$\xi_V^{T=1}$	$\xi_V^{T=0}$	$\xi_V^{(0)}$	$R_V^{T=1}$	$R_V^{T=0}$	$R_V^{(0)}$
[8]	1.0600489	-0.5290683	-0.9882110	-0.0140914	-0.0091121	-0.0117890

Table 2: S.M. parameters for the vector neutral current.

Ref.	ξ_V^n	ξ_V^p	R_V^n	R_V^p
[8]	-0.9882110	0.0718379	-0.0117890	-0.0447091

Table 3: S.M. parameters associated to the proton and neutron.

- Axial part

Ref.	ρ_{eq}	$\hat{\kappa}_{eq}$	$\hat{s}_Z^2$	λ_{2u}	λ_{2d}	λ_{2s}
[8]	1.0011000	1.0300000	0.2312000	-0.0121000	0.0026000	0.0026000
Ref.	$\xi_A^{T=1}$	$\xi_A^{T=0}$	$\xi_A^{(0)}$	$R_A^{T=1}$	$R_A^{T=0}$	$R_A^{(0)}$
[8]	-1.6544734	-0.4376192	0.4482474	-0.1727633	-0.2526596	-0.5517526

Table 4: S.M. electroweak parameters for the axial current.

3 Discussion of some parameters entering the asymmetry formula

3.1 Electromagnetic form-factors

The Q^2-dependence of the proton and neutron form-factors is known experimentally up to a few $(GeV/c)^2$. The precision of the neutron data is still limited and the uncertainties are mainly experimental. The precision of the proton data is much higher (as shown below) and the overall accuracy depends on the statistical error and on theoretical considerations. The data which enter the asymmetry calculations are G_E^p, G_M^p, G_E^n, G_M^n. These can be measured separately using a Rosenbluth method based on two experiments done at the same Q^2 but in different kinematical conditions (e.g. forward/backward angle

separation). This method yields large errors bars at higher Q^2 ($Q^2 > 1$ $(GeV/c)^2$) and especially for the electric form-factors as the weight of the magnetic term is proportional to Q^2 , whence the weight of the electric term decreases with Q^2 . The Rosenbluth method indicates that $\mu_p G_E/G_M \simeq 1$ over the range 0-6 $(GeV/c)^2$.
Another method measures the polarization of the recoil proton in $\vec{e}$p scattering with incident polarized electrons [36]. This methods yields directly the ratio $\mu_p G_E/G_M$ with a higher precision than the Rosenbluth method. The problem is that the polarization data are in disagreement with the Rosenbluth method above $1(GeV/c)^2$, the difference increasing rapidly by more than a factor of 2 at $Q^2 = 5$ $(GeV/c)^2$.
For $Q^2 \leq 1$ $(GeV/c)^2$, there are essentially four parametrizations which reproduce the experimental results: Galster [20], Friedrich-Walcher [21], Arrington [37] and Kelly [40]. Three of them [20, 21, 40] aim at fitting the proton and neutron form-factors. Arrington parametrization is only related to the proton data and it aims at resolving the ambiguities of the Rosenbluth/polarization methods.

3.1.1 Galster parametrization

It was published in 1971[20]. It is given by:

$$G^p_E(Q^2) = G_D(Q^2) = (1 + Q^2/0.71)^{-2} \qquad G^p_M(Q^2) = \mu_p\, G_D(Q^2) \tag{17}$$

$$G^n_E(Q^2) = -\mu_n \tau\, G_D(Q^2)/(1 + 5.6\tau) \qquad G^n_M(Q^2) = \mu_n\, G_D(Q^2) \tag{18}$$

where $\mu_p = 2.793$ and $\mu_n = -1.913$ are the proton and neutron magnetic moment respectively.
This parametrization could not use the most recent and most precise data so it is superseded by more recent analyses.

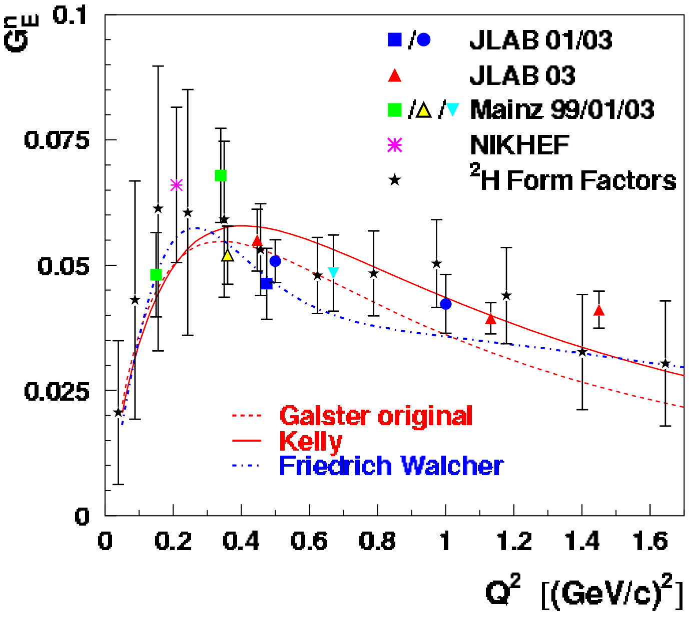

Figure 1: Comparison of the Galster, Friedrich-Walcher and Kelly parametrizations of G^n_E.

3.1.2 Friedrich-Walcher [21] parametrization

Phenomenological fits to all four form factors [polarization transfer, no Rosenbluth separation data, Q^2-range up to $2(GeV/c)^2$], can be found in [21]. They are based on a constituent quark + pion cloud model:

$$G_a(Q^2) = \frac{a_{10}}{(1+Q^2/a_{11})^2} + \frac{a_{20}}{(1+Q^2/a_{21})^2} \quad (19)$$

$$G_b(Q^2) = e^{-\frac{1}{2}(\frac{Q-Q_b}{\sigma_b})^2} + e^{-\frac{1}{2}(\frac{Q+Q_b}{\sigma_b})^2} \quad (20)$$

$$G^{p,n}_{E,M} = G_a(Q^2) + b \cdot Q^2 G_b(Q^2) \quad (21)$$

with

	a_{10}	a_{11} $(GeV/c)^2$	a_{20}	a_{21} $(GeV/c)^2$	b $(GeV/c)^{-2}$	Q_b (GeV/c)	σ_b (GeV/c)
G^p_E	1.041(40)	0.765(66)	-0.041	6.2(5.0)	-0.23(18)	0.07(88)	0.27(29)
G^p_M/μ_p (version 1)	1.002(07)	0.749(06)	-0.002	6.0(3.4)	-0.13(03)	0.35(07)	0.21(03)
G^n_E	1.04(10.7)	1.73	-1.04	1.54(1.94)	0.23(15)	0.29(17)	0.20(09)
G^n_M/μ_n	1.012(06)	0.770(10)	-0.012	6.8(3.0)	-0.28(3)	0.33(03)	0.14(02)

An example of fit to G^n_M is shown on fig.2. Since the fit is constrained, the parameters are strongly correlated and the error matrix has large non-diagonal elements. Therefore, in ref.[15], the electromagnetic form-factors were assigned an ad'hoc (experimentally motivated) error of 5 % to $G^{p,n}_M$, G^p_E and an error of 10 % to G^n_e.

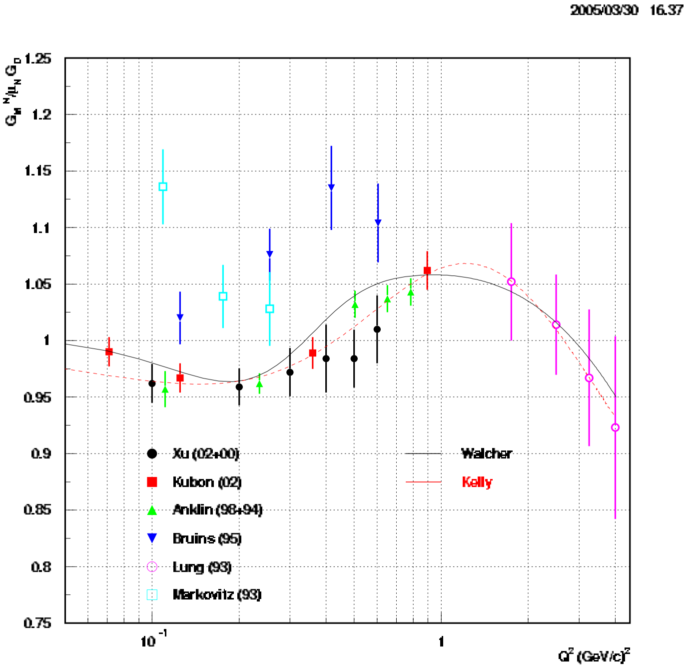

Figure 2: World data for G^n_M compared to the Friedrich-Walcher and Kelly parametrizations

3.1.3 Arrington [37] parametrization

No experimental effect has been found which could explain the differences in $\mu_p G_E/G_M$ and it has been proposed [41] that 2-γ exchange could be responsible for it. In the Born approximation, ep scattering can be characterized by two real form-factors $G^p_E(Q^2)$ and $G^p_M(Q^2)$. In the generalized case, there are 3 complex form-factors $\widetilde{G}_E(\varepsilon,Q^2)$, $\widetilde{G}_M(\varepsilon,Q^2)$ and $\widetilde{F}_3(\varepsilon,Q^2)$, which depends on Q^2 and ε. The generalized form-factors can be broken into the Born value G_E, G_M and 2-γ contributions ΔG_E and ΔG_M:

$$\widetilde{G}_E(\varepsilon, Q^2) = G_E(Q^2) + \Delta G_E(\varepsilon, Q^2) \tag{22}$$

$$\widetilde{G}_M(\varepsilon, Q^2) = G_M(Q^2) + \Delta G_M(\varepsilon, Q^2) \tag{23}$$

ΔG_E and ΔG_M are complex, but as long as they are not too large compared to G_E and G_M, only the real part has a significant effect on the observables. The third amplitude is taken as real and it can be parametrized using:

$$Y_{2\gamma} = \mathcal{R}e\left(\frac{\nu \tilde{F}_3}{M_p^2 |G_M|}\right) \tag{24}$$

Arrington has made a fit of all the existing proton data, first by fitting separately G_E^p and G_M^p using inverse polynomials functions [38]. He then did a combined fit depending on the 3 parameters ΔG_E, ΔG_M and $\tilde{F}_3$ [39] and extracted corrected G_E^p and G_M^p which can be compared to theoretical models of nucleon structure. These are also the parameters which should enter into the calculation of parity violating asymmetries. The error bars represent the statistical and systematic (theoretical) uncertainties added quadratically.
The parametrization from Friedrich-Walcher [21] is compared to Arrington[38] in fig. 3 and to Kelly in fig.4 Below 1 $(GeV/c)^2$ the difference between the 2 parametrizations is smaller than 2.5% for G_M^p and 5% for G_E^p. For the PVA4/SAMPLE combination and for G0, there are 2 choices: 1) Friedrich-Walcher who discarded the Rosenbluth data and fitted the (uncorrected for 2-γ effects) polarization data. Since the 2-γ corrections for $\mu_p G_E/G_M$ is of the order of 3.5% at 0.1 $(GeV/c)^2$ and 6.6% at 1 $(GeV/c)^2$, one should add an equivalent systematic error to the statistical uncertainty of G_E^p and G_M^p, 2) Arrington's parametrization introduces additional theoretical uncertainties but it has the virtue to reconcile polarization and Rosenbluth data in a physically motivated framework.

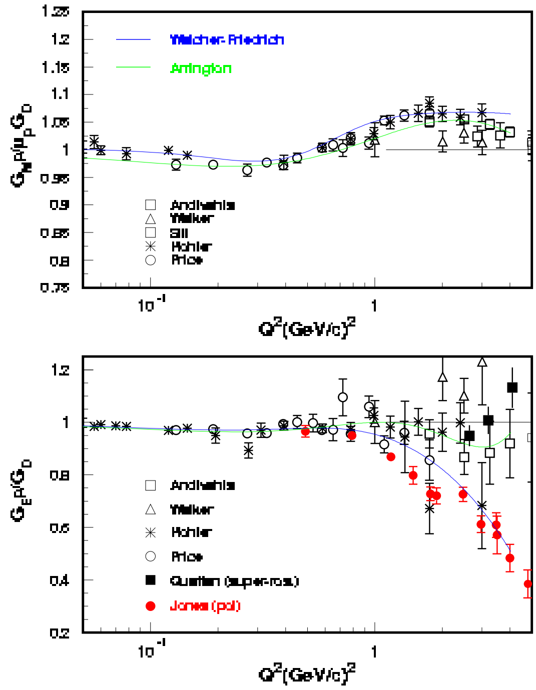

Figure 3: Comparison of the Friedrich-Walcher and Arrington parametrizations of G_E^p and G_M^p.

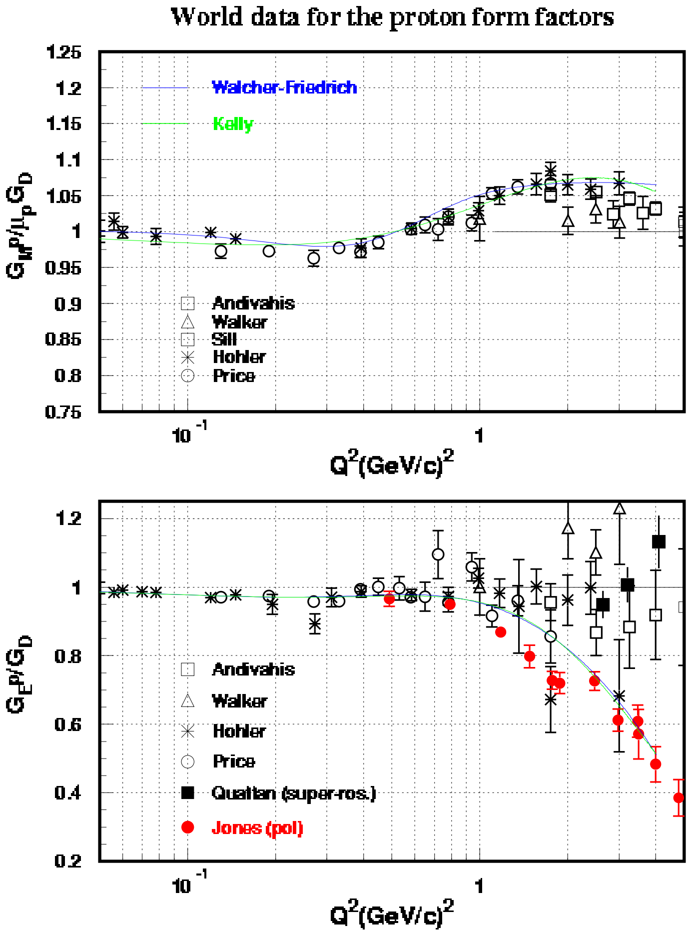

Figure 4: Comparison of the Friedrich-Walcher and Kelly parametrizations of G_E^p and G_M^p.

3.1.4 Kelly [40] parametrization

It is a parametrization of all four form factors. For G_E^p, G_M^p and G_M^n, it uses the following form:

$$G(Q^2) = \frac{\sum_{k=0}^{n} a_k \tau^k}{1 + \sum_{k=1}^{n+2} b_k \tau^k} \tag{25}$$

For G_E^n it uses a Galster parametrization with slightly different parameters (see above). The parameters being highly correlated, there is no easy way to estimate an uncertainty.

3.1.5 More on two-photon effects[43]

A recent contribution by Afanasev and Carlson [43] gives an estimate of the effect due to the exchange of 2 photons . The authors point out that 2-γ exchange not only modifies the electromagnetic form-factors (as done phenomenologically in ref.[38]), but introduces additional terms in the asymmetry. They have done calculations based on GPD estimates for Q^2 = 1-5 $(GeV/c)^2$, and found that the effect on the parity violating asymmetry is of the order of 1-2% at most. This is smaller than the corrections proposed by Arrington[38] in dealing with the form-factors only. They note that in the infra-red approximation, there would be no contribution from 2-γ exchange, due to a cancellation between diagrams. Calculations covering the range 0-1 $(GeV/c)^2$, are still missing and it would be a good case for χ-perturbation theories.

3.1.6 Summary of form-factor subsection

In order to account for the 2-γ in *ep* scattering, it is proposed to use phenomenological electromagnetic form-factors such as Kelly's with an additional uncertainty rising linearly from 0 at $Q^2 = 0$ to 1% at $Q^2 = 1.0\ (GeV/c)^2$.
The problem of the 2-γ exists also for *en* scattering but it is less acute as the statiscal error bars are larger from the start. Here again one could add a small systematic uncertainty to the statistical one.
Compared merits of form-factor parametrizations and effect on calculations of parity-violating asymmetries are discussed extensively in Julie Roche's report[42] and subsequent emails. She proposes to use Kelly's parametrization with the following uncertainties:
±18% on G^{n}_{E} mainly based on the differences between Kelly and FW
±2% on G^{n}_{M} based on the differences between Kelly and F-W
±2% on G^{p}_{M} coming from the difference between Kelly and F-W (1.5%) and between Kelly and Arrington (1.5%) added quadratically
±$(2.5 \times Q^2\ + 0.5)$% estimated in the following way: a 1% difference between Kelly and F-W (independent of Q^2) compounded with a 6% difference between Kelly and Arrington at $Q^2 = 1\ (GeV/c)^2$.

3.2 Axial form-factor

According to (eq.3):

$$\widetilde{G}^{x}_{A}(Q^2) = \xi^{T=1}_{A}\, G^{(3)}_{A}(Q^2)\ \tau_3(x)\ + \xi^{T=0}_{A}\, G^{(8)}_{A}(Q^2)\ +\ \xi^{(0)}_{A}\, G^{s}_{A}(Q^2) \tag{26}$$

Assuming that the nucleon is a good isospin doublet, at $Q^2\ = 0$ the vector axial form-factor can be related to the β-decay rate:

$$G^{(3)}_{A}(0) = \frac{1}{2}(F + D) \tag{27}$$

This approximation should be good within 1-2 % [23], which is the difference in the Coulomb corrected $^1S_0$ amplitudes in *pp* and *nn* scattering. Assuming further that the eight lowest baryons constitute an exact SU(3) octet, one can relate the octet axial form-factor to hyperon beta-decay:

$$G^{(8)}_{A}(0) = \frac{1}{2\sqrt{3}}(3F - D) \tag{28}$$

This second approximation should be good to order of $(m_\Sigma - m_N)/m_N$ or 30% [10].
The Q^2 dependence of the axial form-factors is less known. A Q^2 dipole dependence $G^{D}_{A}(Q^2)$ stems from ν-N quasi-elastic scattering [24]:

$$G^{(3)}_{A}(Q^2) = \frac{1}{2}(F + D)\, G^{D}_{A}(Q^2) \tag{29}$$

and

$$G^{(8)}_{A}(Q^2) = \frac{1}{2\sqrt{3}}(3F - D)\, G^{D}_{A}(Q^2) \tag{30}$$

with

$$G^{D}_{A}(Q^2) = \Big(1 + \frac{Q^2}{{M_A}^2}\Big)^{-2} \tag{31}$$

where M_A is the axial mass. There is no fundamental reason to take the same value for the three axial masses $M^{(0)}_{A}$, $M^{(3)}_{A}$ and $M^{(8)}_{A}$ but for small Q^2 values, this might be a reasonable assumption. Numerical values of M_A will be discussed in the next section.

The isoscalar strange axial form-factor G^s_A reduces at $Q^2 = 0$ to $G^s_A = \Delta s$ where Δs is the fraction of nucleon spin carried by the strange quarks $(s + \bar{s})$. There is little indication of the Q^2 -dependence of G^s_A (see discussion in [25]) and for convenience the same dipole dependence is assumed:

$$G^s_A(Q^2) = \Delta s \ G^D_A(Q^2) \tag{32}$$

The full expression of G^s_A is then:

$$\widetilde{G}_A(Q^2) \ = \ \frac{g_A}{2}\left[\xi_A^{T=1}\tau_3 + \frac{1}{\sqrt{3}}\,\xi_A^{T=0}\,\frac{3F/D-1}{1+F/D}\right] G^D_A(Q^2) + \xi_A^{(0)}\Delta s \ \ G^D_A(Q^2) \tag{33}$$

or alternately, using the R-parameter formalism:

$$\begin{aligned}\widetilde{G}_A(Q^2) \ &= \ -g_A\left[(1+R_A^{T=1})\tau_3 - R_A^{T=0}\,\frac{1}{2}\frac{3F/D-1}{1+F/D}\right] G^D_A(Q^2) + \xi_A^{(0)}\Delta s \ \ G^D_A(Q^2) \\ &= \ -g_A\left[(1+R_A^{T=1})\tau_3 - R_A^{T=0}\,\frac{1}{2}\frac{\tilde{a}_8}{\tilde{a}_3}\right] G^D_A(Q^2) + \xi_A^{(0)}\Delta s \ \ G^D_A(Q^2)\end{aligned} \tag{34}$$

For the proton:

$$\begin{aligned}\widetilde{G}^p_A(Q^2) = \ &-g_A\left[1+R_A^{T=1} - R_A^{T=0}\,\frac{1}{2}\frac{3F/D-1}{1+F/D}\right] G^D_A(Q^2) + \xi_A^{(0)}\Delta s \ G^D_A(Q^2) \\ = \ &-g_A\left[1+R_A^{T=1} - R_A^{T=0}\,\frac{1}{2}\frac{\tilde{a}_8}{\tilde{a}_3}\right] G^D_A(Q^2) + \xi_A^{(0)}\Delta s \ G^D_A(Q^2)\end{aligned} \tag{35}$$

where $\tilde{a}_8 = (3F - D)/\sqrt{3}$ and $\tilde{a}_3 = (F + D)/\sqrt{3}$.

3.3 Numerical estimates

- $G^D_A(Q^2) = \left(1 + \frac{Q^2}{{M_A}^2}\right)^{-2}$: Until recently the axial mass M_A used to be taken of the order of $M_A = 1.032 \pm 0.036 GeV$ [29],[30]. A recent global fit of neutrino scattering data [31] gives a lower value $M_A = 1.001 \pm 0.020 GeV$. Another recent measurement of pion electroproduction at low energy at MAMI-Mainz, resulted in $M_A = 1.068 \pm 0.015 GeV$, a value close to the one used in the 70's [32]. Thereafter it was pointed out [33] that this number should be corrected for finite pion mass effects, giving a value $M_A = 1.013 \pm 0.015 GeV$ in agreement with the value extracted from neutrino scattering. We propose to use $M_A = 1.013 \pm 0.02 GeV$.

- F and D

  Depending on the authors, $(F + D)$ is defined in two different ways:

  $(F + D) = -g_A/g_V$ [26, 27, 28, 13, 43], where g_A/g_V is a fundamental constant given in [8]

  $$g_A/g_V = -1.2695 \pm 0.0029 \tag{36}$$

  and $(F + D) = g_A$ such as in [10].

  At tree level $g_V = \xi^n_V = -1$ so that both definitions agree but at higher order $g_V = \xi^n_V = -0.988211$ and $(F+D)$ differ by 1.2% depending on the definition. Musolf (private communication) is telling us that there should be some corrections but that they have not yet been computed and he proposes that we take the uncorrected value $g_A/g_V = -1.2695$ (which is identical both at tree level and higher order) and add an uncertainty equal to the difference in the asymmetries computed with:

g_A (tree level) $= 1.2695 \pm 0.0029$

g_A (full) $= 1.2545 \pm 0.0029$

The effect has to be estimated quantitatively.

The value of $(3F - D) = \sqrt{3}\tilde{a}_8$ is less constrained. In [10], the value $F/D = 0.64$ is taken. Zhu et al [17] use $\alpha = F/(F + D) = 0.36$ or $F/D = 0.56$. An exhaustive analysis of decays of the baryon octet leads to values ranging from $F/D = 0.60$ at tree level, up to $F/D = 0.67$ at one loop (order p^3) [17]. In a NLO QCD analysis of inclusive polarized deep inelastic scattering, E. Leader et al. [13] use $a_8 = 3F - D = 0.585 \pm 0.025$ and $a_3 = F + D = 1.267 \pm 0.035$ giving $F/D = 0.58$ (note the $\sqrt{3}$ difference in definition between $\tilde{a}_3$, $\tilde{a}_8$and a_3, a_8). **We propose to use the result $3F - D = 0.585 \pm 0.025$, in connection with the latest value of $F + D = -g_A/g_V = 1.2695 \pm 0.0029$.**

- Δs

The strangeness content of the nucleon $\Delta s + \Delta\bar{s}$ (commonly written Δs) at $Q^2 = 0$ is related to the spin dependent momentum distribution of the strange quark $\Gamma_1^p \equiv \int_0^1 g_1(x)\,dx$. In first order it is related to Δu, Δd and Δs through:

$$\Gamma_1^p = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right] \tag{37}$$

By combining with $\Delta u - \Delta d = g_A = F + D$ and $\Delta u + \Delta d - 2\Delta s = 3F - D$, one can obtain the individual flavor components Δu, Δd and Δs. They can be determined experimentally or theoretically (through models) or in combining the two approaches. We will examine here a few options:

- Leading Order and phenomenological analyses

  ⋆ the most common experimental approach uses polarized DIS data. An earlier determination of Δs from the EMC data gave a value as high as $\Delta s = -0.194 \pm 0.050$ [24]. Another determination based on the SLAC E143 data in 1998 gave $\Delta s = -0.09 \pm 0.05$ [34].

  ⋆ some more recent analyses based on experiments and theoretical prejudice, yield $\Delta s = -0.12 \pm 0.03$, ref. [44] and ref.[45] gives $\Delta s = -0.06 \pm 0.05$

  ⋆ the SAMPLE collaboration used $\Delta s = -0.1 \pm 0.1$ [18]. The PVA4 collaboration took $\Delta s = -0.1 \pm 0.1$ for their $Q^2 = 0.23\ GeV/c^2$ results [15].

  ⋆ a recent semi-inclusive K-production experiment at HERMES gives a positive value $\Delta s = 0.03 \pm 0.03 \pm 0.01$ [9] compatible with 0 within one sigma.

- Non-Leading Order (NLO) analyses

  There are 3 recent NLO analyses available: Blumlein and Boettcher [11], AAC japanese group [12] and Leader et al. [13]

  1. Let's start with Leader et al. It is the most recent parton density analysis at next-to-leading order (NLO) and also the most precise. It gives $\Delta s = -0.045 \pm 0.007$ [13] . This is also the value used by the PVA4 collaboration in the analysis of their data at $Q^2 = 0.108\ GeV/c^2$ [16]. The problem is that this value is derived in the so-called JET scheme (not $\overline{MS}$) which has the nice property of being Q^2 independent. In their fig.3 they compare two of their parameters in the JET and $\overline{MS}$ scheme, just commenting briefly that their error bar overlap. They don't say in that paper how that would translate on the Δs in the $\overline{MS}$, but one can infer that, if some parameters overlap, Δs should also overlap in both schemes, but this is in contradiction with a 2002 paper by the same group [14], where they compare Δs in the 2 schemes and get:

  $\Delta s + \Delta\bar{s} = -0.13 \pm 0.04$ for $\overline{MS}$

$\Delta s + \Delta\bar{s} = -0.07 \pm 0.02$ for JET, this value being close to their most recent result $\Delta s = -0.045 \pm 0.007$.

If we believe this calculation,, we have to renormalize the latest Leader result by $0.13/0.07 = 1.86$ giving $\Delta s = -0.084 \pm 0.040$, the uncertainty being given by Leader in the $\overline{MS}$ scheme.

2. The latest japanese result [12], is $\Delta s = 2\Delta\bar{q} = -0.124 \pm 0.046$

3. Blumlein and Boettcher [11] give $\Delta\bar{q} = -0.074 \pm 0.017$ or $\Delta\bar{q} = -0.072 \pm 0.015$ depending on a set of parameters. I have not yet figured out if that is the same as Δs (in which case it would be in agreement with Leader) or if it is 1/2 Δs , in which case it would agree with the AAC analysis.

In conclusion Δs ranges from about 0.0 to -0.14 (discarding some earlier analysis), and **we propose to take $\Delta s = -0.084 \pm 0.040$ from Leader et al. renormalized in the $\overline{MS}$ scheme** .

3.4 Multiquark radiative corrections

3.4.1 Formulae

Besides the one quark corrections which can be calculated in the S.M. and which are discussed in the previous sections, there are multiquark corrections (also called hadronic corrections). They involve the exchange of a photon (similarly to the pure electromagnetic interaction), coupling to states involving weak interactions between quarks. They mostly affect the axial part [10].

In the report[1] we have shown how to calculate directly the anapole asymmetry:

$$A_{LR}^{anap}(\vec{e}N) = -2\,\mathcal{K}\,Q^2 \frac{\varepsilon' G_M^x \left(a_s F_s^{anap}(Q^2) + a_v F_v^{anap}(Q^2)\;\tau_3(x)\right)}{\varepsilon(G_E^x)^2 + \tau(G_M^x)^2} \tag{38}$$

where a_s and a_v are respectively the scalar and vector contributions to the anapole moment. The form-factors $F_s^{anap}(Q^2)$ and $F_v^{anap}(Q^2)$ are such that:

$$F_s^{anap}(Q^2=0) = F_v^{anap}(Q^2=0) = 1 \tag{39}$$

The $\mathcal{K}$ coefficient is a numerical constant which will allow to normalize the different theoretical calculations according to the lagrangians used by the authors.

3.4.2 Anapole contribution from Zhu et al[17]

They used the following anapole current [17]:

$$J^{\;anap} = \frac{1}{\Lambda_\chi^2}\,\bar{u}_{x'}\,\Big[\big(a_s F_s(Q^2) + a_v F_v(Q^2)\tau_3\big)(q^2\gamma^\mu - \not{q}\;q^\mu)\gamma_5\Big]\;u_x \tag{40}$$

from which one can calculate the anapole asymmetry:

$$A_{LR}^{anap}(\vec{e}N) = -\frac{2\,Q^2\,\varepsilon'\,G_M^x}{\varepsilon\big(G_E^x\big)^2 + \tau\big(G_M^x\big)^2}\;\frac{a_s F_s(Q^2) + a_v F_v(Q^2)\tau_3}{\Lambda_\chi^2} \tag{41}$$

where the constant $\mathcal{K} = \frac{1}{\Lambda_\chi^2}$ and $\Lambda_\chi = 4\pi f_\pi = 1.1687GeV$ with $f_\pi = 0.093GeV$.

Zhu et al. do not give a_s and a_v directly but the quantities $R_A^{(T=1)anap}$ and $R_A^{(T=0)anap}$ in relation with the R-formalism developed in the preceding sections: $R_A^{(T=1)anap} = -0.06 \pm 0.24$ et $R_A^{(T=0)anap} = 0.01 \pm 0.14$. They are related through:

$$\frac{a_s}{\Lambda_\chi^2} = \frac{g_{_A}(1-4\sin^2\theta_{_W})G_F R_{_A}^{(T=0)anap}}{8\pi\sqrt{2}\alpha} \tag{42}$$

$$\frac{a_v}{\Lambda_\chi^2} = \frac{g_{_A}(1-4\sin^2\theta_{_W})G_F R_{_A}^{(T=1)anap}}{8\pi\sqrt{2}\alpha} \tag{43}$$

where $\sin^2\theta_{_W}$ was taken in the OSR scheme. The corresponding values for a_s/Λ_χ^2 and a_v/Λ_χ^2 are given in table 5. Note that the signs of eq.42 and 43, are in agreement with the convention of ref.[10] for the currents and that they are opposite to the convention used by Zhu et al.[17]. More detailed considerations can be found in the long version of this report [1].

3.4.3 Anapole contribution from Maekawa et al.[48]

Similar calculations including specific form-factors have been proposed in ref.[48]. The anapole current is taken as:

$$J^{anap} = \frac{1}{M_{_N}^2}\,\bar{u}_{x'}\,\Big[\big(a_s F_s(Q^2) + a_v F_v(Q^2)\tau_3\big)(q^2\gamma^\mu - \not{q}\, q^\mu)\gamma_5\Big]\,u_x \tag{44}$$

for which the asymmetry becomes:

$$A_{_{LR}}^{anap}(\vec{e}N) = -\frac{2\,Q^2\,\varepsilon'\,G_{_M}^x}{\varepsilon(G_{_E}^x)^2 + \tau(G_{_M}^x)^2}\;\frac{a_s F_s(Q^2) + a_v F_v(Q^2)\tau_3}{M_{_N}^2} \tag{45}$$

where now ($\mathcal{K} = 1/M_{_N}^2$). Maekawa et al. do not give any numerical values for a_s and a_v, but they claim that their calculations are in agreement with Zhu et al.[17] for both terms. The main interest of their paper is the consideration of analytical form-factors for a_s and a_v, obtained in chiral perturbation theory in LO and NLO, although the theory allows for a wide range of models. We show in fig.5, the variation as a function of Q^2 for for the following set of parameters: $a_s(\Lambda_\chi) = a_v(\Lambda_\chi) = 0$ and values for $r = \sqrt{2}m_n h_A^1/3g_A f_\pi h_{\pi NN}^{(1)} = \pm 1/3$, the most probable value being around 1/3 as estimated by Maekawa et al. We do not represent here the most extreme values $r = \pm 2$. The anapole contributions are normalized to 1 at $Q^2 = 0$.

3.4.4 Anapole contribution from Riska [47]

D.O. Riska[47] uses the following definition of the current:

$$J^{anap} = \frac{1}{M_{_N}^2}\,\bar{u}_{x'}\,\left[(a_s F_s + a_v F_v\tau_3)(q^2\gamma^\mu - 2M_{_N} q^\mu)\gamma_5\right]\,u_x \tag{46}$$

which leads to the following asymmetry (with $\mathcal{K} = 1/M_{_N}^2$):

$$A_{_{LR}}^{anap}(\vec{e}N) = -\frac{2\,Q^2\,\varepsilon'\,G_{_M}^x}{\varepsilon(G_{_E}^x)^2 + \tau(G_{_M}^x)^2}\;\frac{a_s F_s(Q^2) + a_v F_v(Q^2)\tau_3}{M_{_N}^2} \tag{47}$$

Riska gives: $a_p = a_s + a_v = -0.90 \times 10^{-8}$ for the proton anapole moment and $a_n = a_s - a_v = 0.68 \times 10^{-8}$ for the neutron, from which one gets:

$$a_s = \frac{a_p + a_n}{2} = -0.11 \times 10^{-8} \qquad\qquad a_v = \frac{a_p - a_n}{2} = -0.79 \times 10^{-8} \tag{48}$$

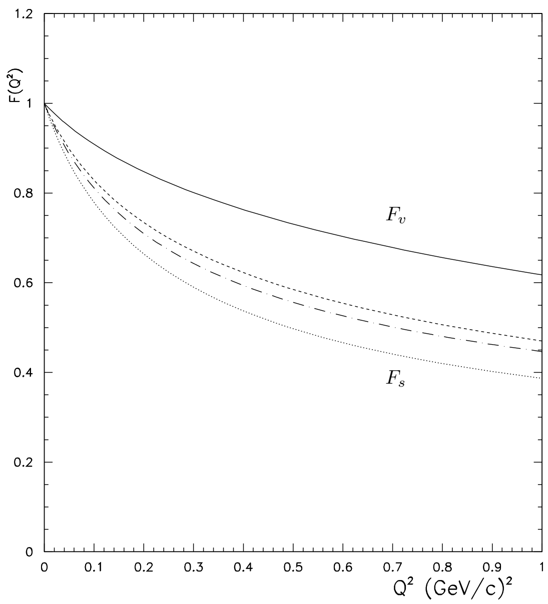

Figure 5: Variation of the axial isoscalar F_s and isovector F_v anapole form factors with Q^2 according to Maekawa et al. [48]. For the isoscalar term F_s the 3 curves correspond to the dominant term (LO) (dashed curve) and NLO with values of the r-parameter r = 1/3 (points) and r = -1/3 (dot-dashed)[48].

and:

$$\frac{a_s}{M_{_N}^2} = -0.125\,10^{-8} \pm 0.125\,10^{-8} \qquad\qquad \frac{a_v}{M_{_N}^2} = -0.897\,10^{-8} \pm 0.897\,10^{-8} \tag{49}$$

where the uncertainty is ±100% as estimated in ref.[47]. The values of the parameters $\mathcal{K}\,a_s$ and $\mathcal{K}\,a_v$ (which enter linearly in the asymmetry calculation) from Zhu-Maekawa and from Riska are compared in table 5. They are much smaller in absolute value in Riska than in Zhu et al. and Maekawa et al., but still compatible due to the large uncertainties in Zhu's parameters. Note that the sign of the isovector contribution is positive in both calculations, but it differs for the (much smaller) isoscalar part.

Ref.	$\mathcal{K}$	$\mathcal{K}\,a_s$			$\mathcal{K}\,a_v$		
		Min.	Central	Max.	Min.	Central	Max.
Zhu/Maekawa	$1/\Lambda_\chi^2$	$-8.00\,10^{-7}$	$6.153\,10^{-8}$	$9.23\,10^{-7}$	$-1.85\,10^{-6}$	$-3.692\,10^{-7}$	$1.11\,10^{-6}$
Riska	$1/M_{_N}^2$	$-0.250\,10^{-8}$	$-0.125\,10^{-8}$	0.00	$-1.80\,10^{-7}$	$-0.897\,10^{-8}$	0.00

Table 5: Central and limit values of the isoscalar and isovector contributions to the anapole moment for Zhu[17], Maekawa[48] and Riska[47]

The proton and neutron anapole form factors of Riska can be parametrized with the following functions:

$$F_x(Q^2) = \begin{cases} \alpha_x\, Q^2 + \beta_x + e^{(\alpha'_x Q^2 + \beta'_x)} & Q^2 < 0.4 (GeV/c)^2 \\ \alpha_x\, Q^2 + \beta_x & Q^2 \geq 0.4\ (GeV/c)^2 \end{cases} \tag{50}$$

with:

$$
\begin{array}{llll}
\alpha_n = -0.11\,10^{-8}\ (GeV/c)^{-2} & \beta_n = \ \ 0.276\,10^{-8} & \alpha'_n = -12.0895\ (GeV/c)^{-2} & \beta'_n = -19.327 \\
\alpha_p = \ \ 0.20\,10^{-8}\ (GeV/c)^{-2} & \beta_p = -0.159\,10^{-7} & \alpha'_p = \ \ -9.493\ \ (GeV/c)^{-2} & \beta'_p = -18.792
\end{array}
\tag{51}
$$

The Q^2-variation of the isoscalar and isovector form-factors, normalized at $Q^2 = 0$ are compared in fig. 6 and 7 respectively. Note that the Q^2-dependence of Riska form-factors between $Q^2 = 0.1 - 1.0$ $(GeV/c)^2$ is rather flat as compared to Maekawa.

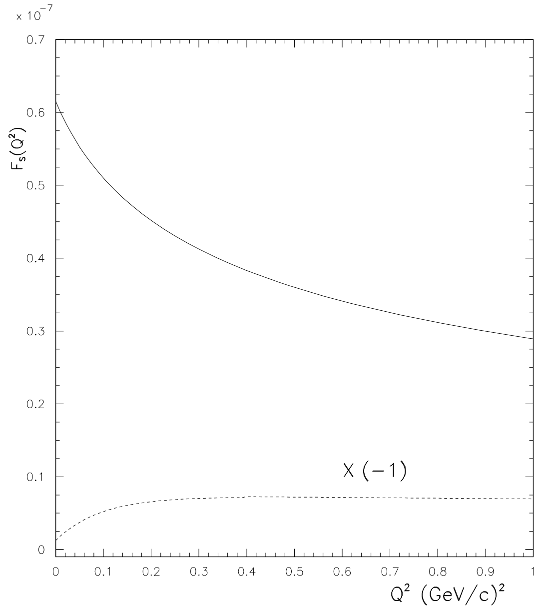

Figure 6: Variation with Q^2 of the axial isoscalar form-factor $F_s(Q^2)$. The calculation of Maekawa at leading order is represented by the continuous line and the values of Riska (with sign inverted) are shown as a dotted curve.

3.4.5 Estimates of the anapole asymmetry

Taking Zhu's central values $\mathcal{K}a_s = 6.15310^{-8}$ and $\mathcal{K}a_v = -3.69210^{-7}$ and assuming no Q^2 -dependence, the following asymmetries are calculated:

- **PVA4:** $\theta = 35^o, E = 0.570GeV, Q^2 = 0.106$

$$A_V = -1.74 \times 10^{-6}, A_A = -2.22 \times 10^{-7}, A_{ana} = 2.22 \times 10^{-8} \pm 9.0 \times 10^{-8}$$

$$A_{tot} = -1.94 \times 10^{-6}$$

to be compared to $A_{tot}(Q^2 averaged) = -2.06 \times 10^{-6}$ [16].

$$\frac{A_{ana}}{A_V} = -0.0127, \frac{A_{ana}}{A_A} = -0.100$$

- **SAMPLE:** $\theta = 146^o, E = 0.194GeV, Q^2 = 0.105$

$$A_V = -6.00 \times 10^{-6}, A_A = -1.52 \times 10^{-6}, A_{ana} = 1.512 \times 10^{-7} \pm 6.0 \times 10^{-7}$$

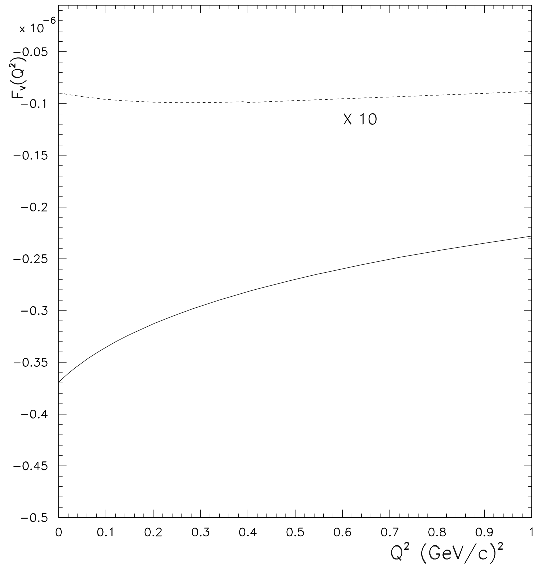

Figure 7: Same as fig.6 for $F_v(Q^2)$. The Riska curve has been multiplied by 10 for convenience.

$$A_{tot} = -7.37 \times 10^{-6}$$

to be compared to $A_{tot} = -7.84$ as calculated in [18].

$$\frac{A_{ana}}{A_V} = -0.0252, \frac{A_{ana}}{A_A} = -0.099$$

The difference between the present calculations and ref. [16],[18]comes from the fact that we do not take into account any Q^2 averaging and from the use of different parameters (electroweak corrections, form-factors). We have taken the PDG2004 values for the one-quark parameters:
$\sin^2\theta_W = 0.2312$
$g_A = 1.2545$
$G_F = 1.16637 \times 10^{-5}$
$R_V^{T=1}$ = -0.0140914, $R_V^{T=0}$ = -0.0091121, $R_V^{(0)}$ = -0.011789
$R_A^{T=1}$ = -0.1727633, $R_A^{T=0}$ = -0.2526596, $R_A^{(0)}$ = -0.5517526.
All strangeness dependent parameters are set to zero: $G_E^s = G_M^s = G_A^s = 0$,
we used $F/D = 0.58$ [13] and $M_A = 1.013$ GeV [33].
Since Maekawa gives a wide spectrum of parameters (see table 5) this induces uncertainties on the anapole asymmetry which are 4-5 times the central value, changing even its sign. Moreover, if one takes into account the uncertainties on the Q^2-dependence we arrive at uncertainties which are as large as the axial asymmetry itself and of the order of 10% of the total asymmetry.
These seem to be unreasonably large values and it is proposed to take Zhu parameters together with a standard dipole Q^2 dependence with $M_A = 1.013 \pm 0.02 GeV$, ignoring for the moment the Maekawa and Riska conflicting calculations. This choice should have essentially negligible effects on the SAMPLE/PVA4 comparisons and on G^0 forward angles. It will be reassessed once the G^0 backward angles data will be available.

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