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## Moments of the spin structure functions $g(1)(p)$ and $g(1)(d)$ for $0.05 < Q(2) < 3.0 \text{ GeV}^2$

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## Moments of the spin structure functions $g_1^p$ and $g_1^d$ for $0.05 < Q^2 < 3.0 \text{ GeV}^2$

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## ABSTRACT

The spin structure functions  $g_1$  for the proton and the deuteron have been measured over a wide kinematic range in  $x$  and  $Q^2$  using 1.6 and 5.7 GeV longitudinally polarized electrons incident upon polarized  $\text{NH}_3$  and  $\text{ND}_3$  targets at Jefferson Lab. Scattered electrons were detected in the CEBAF Large Acceptance Spectrometer, for  $0.05 < Q^2 < 5 \text{ GeV}^2$  and  $W < 3 \text{ GeV}$ . The first moments of  $g_1$  for the proton and deuteron are presented – both have a negative slope at low  $Q^2$ , as predicted by the extended Gerasimov–Drell–Hearn sum rule. The first extraction of the generalized forward spin polarizability of the proton  $\gamma_0^p$  is also reported. This quantity shows strong  $Q^2$  dependence at low  $Q^2$ . Our analysis of the  $Q^2$  evolution of the first moment of  $g_1$  shows agreement in leading order with Heavy Baryon Chiral Perturbation Theory. However, a significant discrepancy is observed between the  $\gamma_0^p$  data and Chiral Perturbation calculations for  $\gamma_0^p$ , even at the lowest  $Q^2$ .

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Fundamental to our understanding of nuclear matter is a complete picture of the spin structure of the nucleon. The spin of the nucleon arises from the spin and orbital angular momenta of both the quarks and gluons. One way to access the quark spins in lepton scattering is through measurements of the spin structure functions  $g_1$  and  $g_2$  [1], which are not well known at low momentum transfer to the target nucleon ( $Q^2 < 2 \text{ GeV}^2$ ). At larger momentum transfer,  $g_1(x, Q^2) = \frac{1}{2} \sum e_i^2 \Delta q_i(x)$  (in the parton picture), where  $\Delta q_i/q_i$  is the net helicity of quarks of flavor  $i$  in the direction of the (longitudinally polarized) nucleon spin,  $q_i$  is the probability of finding a quark of flavor  $i$  with momentum fraction  $x$ , and  $e_i$  is the quark charge. (The Bjorken scaling variable  $x = \frac{Q^2}{2M\nu}$  in the lab frame,  $M$  is the nucleon mass and  $\nu$  is the energy transferred from the electron to the target nucleon.) At sufficiently small  $Q^2$ ,  $g_1$  and its moments can be more economically described by hadronic degrees of freedom and effective low-energy approximations to QCD, like Chiral Perturbation Theory ( $\chi$ PT).

There is particular interest in the first moment of  $g_1$ ,  $\Gamma_1(Q^2) = \int_0^{x_0} g_1(x, Q^2) dx$ , which is related to the fraction of the nucleon spin carried by quark spins. The upper limit of the integral,  $x_0$ , corresponds to pion production threshold. This limit excludes elastic scattering, which otherwise dominates the low  $Q^2$  behavior of the integral.  $\Gamma_1$  is constrained as  $Q^2 \rightarrow 0$  by the Gerasimov–Drell–Hearn (GDH) sum rule [2,3] to be  $-\frac{\kappa^2}{8M^2} Q^2$ , where  $\kappa$  is the anomalous magnetic moment of the nucleon. At high  $Q^2$ ,  $\Gamma_1$  has been measured in deep inelastic scattering (DIS) experiments at SLAC [4,5], CERN [6–8] and DESY [9]. Ji and Osborne [10] have shown that the GDH sum rule can be generalized to all  $Q^2$  via

$$\Gamma_1(Q^2) = \frac{Q^2}{8} S_1(\nu=0, Q^2) - \Gamma_1^{\text{el}}(Q^2), \quad (1)$$

where  $S_1(\nu, Q^2)$  is the spin-dependent virtual photon Compton amplitude and  $\Gamma_1^{\text{el}}$  is the contribution to the integral from elastic scattering. At high  $Q^2$ ,  $S_1$  can be calculated using the operator product expansion (OPE). By comparing the OPE twist series with  $\Gamma_1$ , one can extract higher twist parameters [11–15], which are sensitive to quark–gluon and quark–quark correlations in the nucleon at moderate  $Q^2$ . Lattice QCD calculations may eventually

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be available in the moderate  $Q^2$  region below the range of applicability of the OPE. At low  $Q^2$ ,  $S_1$  can be calculated in  $\chi$ PT, a model-independent effective field theory [16], but it is not clear how high in  $Q^2$  these calculations can be applied [17,18]. Thus  $\Gamma_1$  presents a calculable observable that spans the entire energy range from fundamental degrees of freedom (quarks and gluons) to effective ones (hadrons).

Higher moments of  $g_1$  are interesting as well. In our kinematic domain, these moments emphasize the resonance region over DIS kinematics because of extra factors of  $x$  in the integrand. The fundamental generalized forward spin polarizability of the nucleon is given by [19]

$$\gamma_0(Q^2) = C(Q^2) \int_0^{x_0} x^2 \left\{ g_1(x, Q^2) - \frac{4M^2}{Q^2} x^2 g_2(x, Q^2) \right\} dx, \quad (2)$$

where the kinematic factor  $C(Q^2) = 16\alpha M^2/Q^6$  and  $\alpha$  is the fine structure constant. At high  $Q^2$  one would expect  $g_2$  to diminish significantly and  $g_1$  to vary logarithmically with  $Q^2$ , thus  $\gamma_0$  weighted by  $Q^6$  should be largely independent of  $Q^2$  [1,19,20]. A measurement of  $\gamma_0$  on the neutron indicates no evidence for such “scaling” below  $Q^2 = 1 \text{ GeV}^2$ , and furthermore the data barely agree with  $\chi$ PT calculations at low  $Q^2$  [21]. No measurement of  $\gamma_0$  on the proton has been reported so far.

In order to advance our theoretical understanding of the nucleon spin, it is essential to have data on the spin structure functions at low  $Q^2$  and in the resonance region, as well as at DIS kinematics. Data in the resonance region are necessary to calculate moments, especially at low and moderate  $Q^2$ . Until recently, data in the resonance region were quite scarce [22], but new measurements of spin structure functions in the resonance region have now been reported on proton [23,24], deuteron [25] and  $^3\text{He}$  targets [26,27] from Jefferson Lab. Testing  $\chi$ PT at low  $Q^2$  has increasingly been a focus of new spin structure experiments [28–30].

The EG1 experiment of the CLAS Collaboration has collected new data using longitudinally polarized 1.6 and 5.7 GeV electrons on proton ( $\text{NH}_3$ ) and deuteron ( $\text{ND}_3$ ) targets [31]. These data cover a wide kinematic range that includes invariant mass  $W^2 = M^2 + 2M\nu - Q^2$  from elastic scattering (quasielastic for the deuteron) up to 9  $\text{GeV}^2$  [32,33]. First results for the generalized forward spin polarizability of the proton and new results for the first moments of  $g_1^p$  and  $g_1^d$  at low and intermediate  $Q^2$  in the range  $0.05 < Q^2 < 3 \text{ GeV}^2$  are reported in this Letter.

In the EG1 experiment, the beam was produced from a strained GaAs wafer and had an average polarization of 70% as measured by Moller polarimetry [34]. The polarization of the electrons was flipped at 30 Hz pseudo-randomly. The beam was rastered over the face of the target cell to avoid heating and depolarization. The current varied from 0.3 nA to 10 nA depending on the beam conditions and target.

The product of the beam and target polarizations  $P_b P_t$  was determined from the data through comparison with the known elastic scattering asymmetry and ranged from 0.50 to 0.60 for the  $\text{NH}_3$  target and from 0.12 to 0.23 for the  $\text{ND}_3$  target. Data were also taken with  $^{12}\text{C}$ ,  $^4\text{He}$  and frozen  $^{15}\text{N}$  to determine the dilution from unpolarized materials [35].

Scattered electrons were detected in the CEBAF Large Acceptance Spectrometer (CLAS) in Hall B [34], covering a range in polar angle from  $8^\circ$  to  $45^\circ$  in the efficient region of the detector. Data acquisition was triggered by a coincidence between the Čerenkov detector and the calorimeter in any one of the six sectors. Only electrons detected in a region of the Čerenkov detector with an efficiency greater than 80% were used in the analysis. Additional details about the experiment can be found in Refs. [25,32].

We measured the raw inclusive double spin asymmetry with longitudinally polarized beam and target in each  $Q^2$  and  $W$  bin. This raw asymmetry was then corrected for the difference in accumulated charge in the two beam polarization states,  $e^+e^-$  pair production and pion contamination. Polarization and dilution factors were divided out and radiative corrections applied. The resulting asymmetry,  $A_{\parallel}$ , is proportional to a linear combination of the two virtual photon asymmetries  $A_1$  and  $A_2$  [25]. Using a parameterization of the world data to model  $A_2$  [25], the unpolarized structure function  $F_1$  [36,37], and the ratio of transverse to longitudinal structure functions  $R$  [36],  $A_1$  and  $g_1$  were extracted using:

$$A_1(x, Q^2) = \frac{1}{D} A_{\parallel} - \eta A_2, \quad (3)$$

$$g_1(x, Q^2) = \frac{F_1}{1 + \gamma^2} (A_1 + \gamma A_2), \quad (4)$$

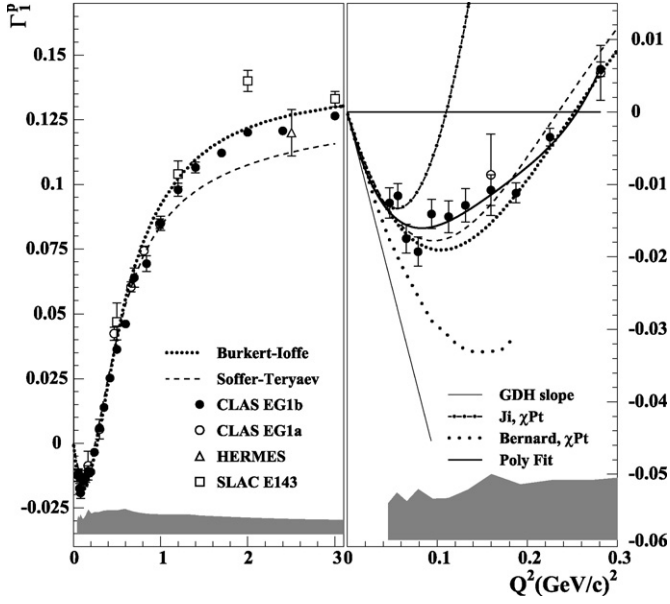
where the depolarization factor  $D$  depends on  $R$ ,  $\eta$  is a kinematical factor and  $\gamma^2 = \frac{Q^2}{\nu^2}$ . The generalized forward spin polarizability for the proton was calculated from the data for  $A_1$  and the  $F_1$  parameterization using  $\gamma_0(Q^2) = C \int_0^{x_0} A_1 F_1 x^2 dx$ , which is equivalent to Eq. (2).

The total systematic error on  $g_1$  varies greatly depending on the kinematic bin; for the proton it is roughly 10% and for the deuteron it is typically 15% for the 1.6 GeV data and 20% for the high energy data. The systematic error is dominated by model uncertainties on  $A_2$ ,  $F_1$  and  $R$ , which are estimated by using different parameterizations of the world data. For the deuteron data the uncertainty in  $P_b P_t$  also contributes substantially to the systematic error.

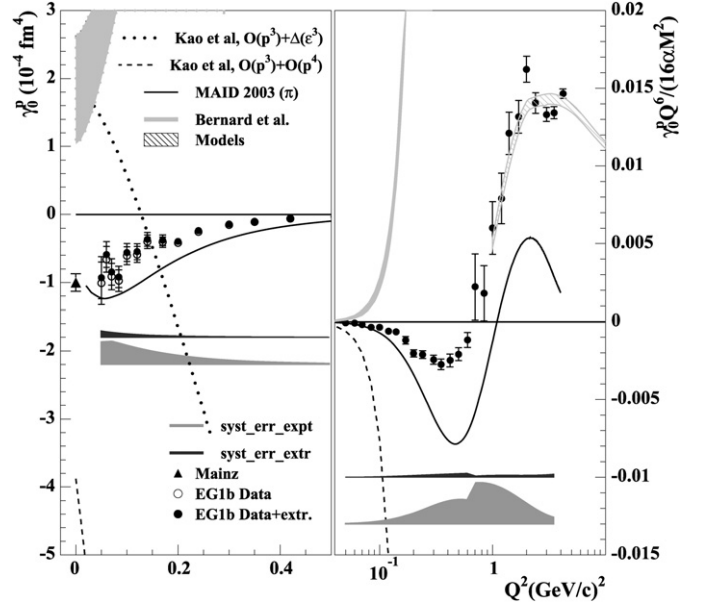
The values of  $g_1^p$  and  $g_1^d$  were extracted for  $Q^2$  from 0.05 to 5  $\text{GeV}^2$  and for  $x$  greater than 0.1; all results are available from the CLAS database [38]. At low  $Q^2$ , the  $\Delta(1232)$  resonance is quite prominent, with a negative asymmetry as expected for this transition. It decreases steadily in strength as  $Q^2$  increases. In the mass region above the  $\Delta(1232)$  resonance,  $g_1$  increases from nearly zero to large positive values as  $Q^2$  increases. In the  $\Delta(1232)$  region and at low  $Q^2$ ,  $g_1^d/2$  is consistent with  $g_1^p$ , as expected for a transition to an isospin  $\frac{3}{2}$  state. However, at high  $Q^2$ ,  $g_1^p$  is significantly larger than  $g_1^d/2$ , indicating a negative contribution from the neutron.

The first moments of  $g_1^p$  and  $g_1^d$  are shown in Figs. 1 and 2, respectively. The parameterization of world data [38] is used to include the unmeasured contribution to the integral down to  $x = 0.001$ . The systematic uncertainty (shown by the grey bands) includes the model uncertainty from the extrapolation to the unmeasured region. Only the  $Q^2$  bins in which the measured part (summed absolute value of the integrand) constitutes at least 50% of the total integral are shown. For the proton, the parameterization is also used at high  $x$  (in the range  $1.09 < W < 1.14$  (1.15) GeV for the 1.6 (5.7) GeV data). For the deuteron, the integration is carried out up to the nucleon pion production threshold at high  $x$ , excluding the quasi-elastic and electro-disintegration contributions. Our low  $Q^2$  coverage allows us to observe, for the first time, the slope changing sign at low  $Q^2$ , consistent with the expectation of a negative slope given by the GDH sum rule at very low  $Q^2$ . In general the data are well described by the phenomenological models of Burkert and Ioffe [39,40] and Soffer and Teryaev [41].

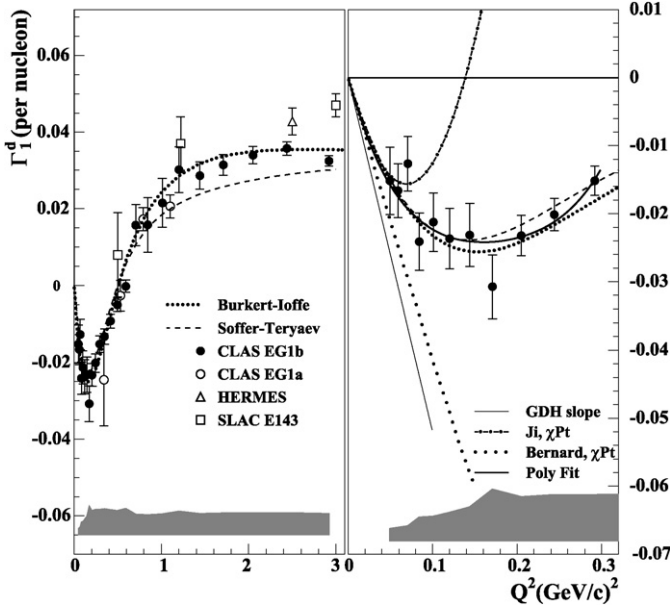
The low  $Q^2$   $\Gamma_1$  data are shown in more detail in the right-hand panels of Figs. 1 and 2. It is possible to make a quantitative comparison between our results for  $\Gamma_1^p$  and  $\Gamma_1^d$  at low  $Q^2$  and the next-to-leading order  $\chi$ PT calculation by Ji et al. [18], who find  $\Gamma_1^p(Q^2) = -\frac{\kappa_p^2}{8M^2} Q^2 + 3.89 Q^4 + \dots$  and  $\Gamma_1^n(Q^2) = -\frac{\kappa_n^2}{8M^2} Q^2 + 3.15 Q^4 + \dots$ . Treating the deuteron as the incoherent sum of a



**Fig. 1.**  $\Gamma_1^p$  as a function of  $Q^2$ . The data reported here (EG1b) are shown as the solid circles, along with the earlier EG1 data (EG1a) [23], SLAC [22] and Hermes data [9], shown for comparison. The filled circles represent the present data, including an extrapolation over the unmeasured part of the  $x$  spectrum using a model of world data. Phenomenological models of Burkert and Ioffe [39,40] and Soffer and Teryaev [41] are represented by solid and dashed lines, respectively. The grey band represents the systematic error. In the right plot, the scales are expanded and  $\chi$ PT calculations from Bernard [17] and Ji [18] are included.



**Fig. 3.** Generalized forward spin polarizability  $\gamma_0^p$  as a function of  $Q^2$  for the full integral (closed circles), the measured portion of the integral (open circles) and  $Q^2 = 0$  [44] (triangle). The systematic error on the measured (grey) and unmeasured (dark) contributions are indicated by bands.  $\chi$ PT calculations [17,45] are shown along with MAID 2003 [46]. The data shown on the right are weighted by  $Q^6/(16\alpha M^2)$ . Our parameterization of world data is also shown at moderate to high  $Q^2$ .



**Fig. 2.**  $\Gamma_1^d/2$  as a function of  $Q^2$ . The symbols and curves are the same as for Fig. 1.

proton and a neutron, and correcting for the  $D$ -state as discussed in Ref. [42],

$$\Gamma_1^d(Q^2) = \frac{1}{2}(1 - 1.5\omega_D)\{\Gamma_1^p(Q^2) + \Gamma_1^n(Q^2)\}, \quad (5)$$

where  $\omega_D = 0.056$  is the weight of the  $D$ -wave in the deuteron, one finds that  $\Gamma_1^d(Q^2) = -0.451Q^2 + 3.26Q^4$ . In the range of  $Q^2$  from 0 to 0.3  $\text{GeV}^2$ , we fit  $\Gamma_1^p$  and  $\Gamma_1^d$  to a function of the form  $aQ^2 + bQ^4 + cQ^6 + dQ^8$ , where  $a$  is fixed at  $-0.456$  (proton) and  $-0.451$  (deuteron) by the GDH sum rule. Note that the GDH sum rule on the deuteron here excludes the two-body breakup part, which otherwise nearly cancels the inelastic contribution [43]. The

fit results for the proton,  $b = 4.31 \pm 0.31(\text{stat}) \pm 1.36(\text{syst})$ , and for the deuteron,  $b = 3.19 \pm 0.44(\text{stat}) \pm 0.68(\text{syst})$ , are both consistent with the  $Q^4$  term predicted by Ji et al. [18]. The fit (labelled “Poly Fit”) is shown in the right-hand panels of Figs. 1 and 2 along with Ji’s prediction. Clearly the  $Q^6$  term becomes important even below  $Q^2 = 0.1 \text{ GeV}^2$  and this term needs to be included in the  $\chi$ PT calculations in order to extend the range of their validity beyond roughly  $Q^2 = 0.06 \text{ GeV}^2$ . The  $\chi$ PT 4th order (one-loop), relativistic calculation by Bernard et al. [17] is also shown in Figs. 1 and 2. Not shown is the result from Bernard et al. that includes an estimate of the  $\Delta(1232)$  and vector meson degrees of freedom, which are important at low  $Q^2$ . That result has large uncertainties and is consistent with our data.

Fig. 3 shows the result for the generalized forward spin polarizability of the proton  $\gamma_0^p(Q^2)$ . Since  $\gamma_0$  is weighted by an additional factor of  $x^2$  compared to  $\Gamma_1$ , the integral is mostly saturated by the  $\Delta(1232)$  resonance and uncertainties due to the low- $x$  extrapolation are greatly reduced. The MAID 2003 [46] model follows the trend of the data but lies systematically below them. The MAID model is consistent with our data for  $A_1$  in the  $\Delta$  resonance region, but MAID includes only single-pion production channels, which leads to an underestimation of the unpolarized structure function  $F_1$  entering the definition of  $\gamma_0$ .

Unlike  $\Gamma_1$ ,  $\gamma_0$  is not constrained at  $Q^2 = 0$  and is therefore a more stringent test of Chiral Perturbation calculations. The leading order heavy baryon  $\chi$ PT calculation by Kao et al. [45], shown by the dotted line in Fig. 3, includes the  $\Delta$  resonance contribution. Their 4th order calculation (dashed line) is of opposite sign and shows no sign of convergence; neither calculation reproduces the trend or magnitude of the data. The relativistic  $\chi$ PT calculation of Bernard et al. converges better at 4th order [17]. That calculation, including the resonance contribution, is represented by the grey band in Fig. 3, and is also in serious disagreement with the data. The  $\Delta(1232)$  and vector meson contribution is negative (around  $-2 \times 10^{-4} \text{ fm}^4$ ) and is consistent with the calculation by Kao et al.

at  $Q^2 = 0$ , suggesting that the discrepancy at low  $Q^2$  is mainly due to the non-resonance terms [47].

In the right-hand panel of Fig. 3,  $\gamma_0^p$  is weighted by a factor of  $Q^6/(16\alpha M^2)$ . In the limit of very large  $Q^2$ , this expression converges to the third moment of  $g_1$ ,  $a_2$ , which is expected to scale approximately in the framework of OPE. Our data seem to be leveling off above  $Q^2 = 1.5 \text{ GeV}^2$ , but do not go high enough in  $Q^2$  to confirm scaling behavior. We also show an evaluation of  $\int_0^{x_0} A_1 F_1 x^2 dx$  (shaded band) based on our model for  $F_1$  and a fit to the world data for  $A_1$  (mostly from SLAC, SMC, and HERMES in addition to our own data). The width of the shaded band indicates the combined one-sigma uncertainty of the models of  $F_1$  and  $A_1$ . Our model confirms the leveling-off around  $Q^2 = 2 \text{ GeV}^2$  and shows a logarithmic fall-off at higher  $Q^2$ .

In summary,  $g_1(x, Q^2)$  for the proton and the deuteron have been measured over a vastly expanded kinematic range at low and intermediate momentum transfer, which includes the entire resonance region and part of the DIS regime. These measurements enable us to evaluate moments of  $g_1$  over a wider range in  $Q^2$ , decreasing extrapolation uncertainties. The first extraction of  $\gamma_0^p$  has been reported along with a new precise mapping of  $\Gamma_1^p$  and  $\Gamma_1^d$  down to lower  $Q^2$  than previously available. At moderately high  $Q^2$  our data for  $Q^6\gamma_0^p$  seem to level off, in agreement with models and QCD expectations, and we see the expected trend toward DIS results in  $\Gamma_1$ . It will be interesting to extend these measurements to higher  $Q^2$  once the upgraded beam energy is available at Jefferson Lab. At low  $Q^2$ , the first moments of  $g_1^p$  and  $g_1^d$  exhibit a change in the sign of the slope, to match the negative slope constraint from the generalized GDH sum rule, and are consistent with  $\chi$ PT calculations for momentum transfer values up to about  $0.06 \text{ GeV}^2$ . It is important to note, however, that these  $\chi$ PT calculations also assume the validity of the GDH sum rule; a more sensitive test of  $\chi$ PT calculations is  $\gamma_0(Q^2)$ . We observe that  $\chi$ PT calculations fail to describe our results for  $\gamma_0^p$ , even for  $Q^2$  as low as  $0.05 \text{ GeV}^2$ . The  $\chi$ PT calculations are increasingly being used to extract results from lattice QCD and it is critical to understand their range of applicability [16]. Data for the isoscalar quantity  $\gamma_0^p - \gamma_0^n$  have also been published by our collaboration and may give additional guidance to future theoretical work in this area [48]. We also look forward to results from new experiments at Jefferson Lab, in which spin structure functions down to  $Q^2 = 0.01 \text{ GeV}^2$  will provide a more stringent test of  $\chi$ PT [28–30].

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