

# Unveiling the Tensor Charge of the Nucleon at Jefferson Lab

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We present detailed estimates of how well future Jefferson Lab 12 experiments, in particular CLAS and SOLID, could constrain transversity distribution and tensor charge of the nucleon. Our study is performed based on the global QCD extraction of transversity from available experimental data and on a robust Bayesian re-weighting technique that allows to use realistic pseudo-data generated for future measurements of Jefferson Lab.

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## I. INTRODUCTION

Nucleon tensor charge is one of the fundamental properties of the proton and its determination is among the main goals of existing and future experimental facilities [? ? ? ? ?]. It also plays an important role in constraining the nuclear physics aspects for probing new physics beyond the standard model, and has been an active subject from lattice QCD calculations [? ?]. In terms of the partonic structure of the nucleon, the tensor charge,  $\delta q$ , for a particular quark type  $q$  is constructed from the quark transversity distribution,  $h_1(x, Q^2)$ , one of the three leading-twist quark distributions that de-

scribe completely spin-1/2 nucleon [? ? ? ?]:

$$\delta q(Q^2) \equiv \int_0^1 dx (h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)) . \quad (1)$$

However, the experimental exploration of the quark transversity distribution in high energy scattering is difficult because of its odd chirality [? ].

It is extremely important to extend the experimental study of the quark transversity distribution to both large and small  $x_B$  to constrain the total tensor charge contributions. The Jefferson Lab 12 GeV program [? ] is going to explore the region of relatively high- $x$  dominated by valence quarks. The planned Electron Ion Collider [? ? ? ] is going to extend the range of explored  $x$  to lower values and thus provide a possibility to study anti-quark transversity.

In this paper we will present a detailed analysis of impact of future Jefferson Lab 12 data and in particular the data from CLAS and SOLID to determination of tensor charge and transversity distributions.

We will base our studies on a QCD global fit of the available Semi-Inclusive Deep Inelastic Scattering (SIDIS) data and  $e^+e^-$  annihilation into hadron pairs performed in Ref. [? ]. Using the best fit of transver-

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sity distributions of Ref. [?] we will generate pseu-data for SOLID and CLAS experiments and estimate experimental uncertainties of future data assuming transversity distributions of Ref. [?].

The current available experimental data suggest that anti-quark transversity is very small and does not constrain anti-quark transversity. In this study we will assume that anti-quark transversity are negligible and does not contribute to tensor charge. The analysis of impact of future data including anti-quark transversity and data from future Electron-Ion Collider will be published elsewhere.

In order to analyze the impact of future data we will utilize Bayesian reweighting technique method [?] that will allow us to reliably estimate impact of Jefferson Lab 12 data on both quark transversity and its contribution to tensor charge.

This study will also provide information on contribution of tensor charge from kinematical region of Jefferson Lab 12 and will serve as guidance to planning of future experiments.

## II. PRESENT STATUS OF EXTRACTION OF TRANSVERSITY FROM EXPERIMENTAL DATA

An important channel to investigate the quark transversity distribution is to measure the Collins azimuthal spin asymmetries in semi-inclusive hadron production in deep inelastic scattering (SIDIS) [?]. Measurements have been made by the HERMES Collaboration [?], the COMPASS Collaboration [?], and JLab HALL A [?] experiments. However, the extraction of the quark transversity distributions requires the knowledge of the Collins fragmentation functions [?], which are different from the usual unpolarized fragmentation functions. It was further suggested to measure the Collins fragmentation functions from the azimuthal angular asymmetries of two back-to-back hadron productions in  $e^+e^-$  annihilations [?]. Recently both BELLE and BABAR Collaborations have studied these asymmetries at the B-factories at center of mass energy around  $\sqrt{s} \simeq 10.6$  GeV [?]. Analogous data [?], newly released by the BESIII collaboration, on  $e^+e^-$  annihilations into pion pair at the much lower  $\sqrt{s} \simeq 3.6$  GeV, offer the ideal ground for a study on the sensitivity of these azimuthal correlations on TMD evolution effects.

The data from two processes, SIDIS and  $e^+e^-$ , can be combined in global QCD analysis due to the universality of the Collins fragmentation functions [?]. The effort to extract the transversity distributions and Collins fragmentation functions has been carried out by the Torino-Cagliari-JLab group extensively in the last few years [?]. Transversity coupled to the so-called dihadron interference fragmentation functions is employed to study transversity in its collinear version in Ref. [?].

These results have demonstrated the powerful capability of the Collins asymmetry measurements in constrain-

ing the quark transversity distributions and hence the nucleon tensor charge in high energy scattering experiments.

The first extraction of the transversity distribution and Collins fragmentation functions with TMD evolution was performed in Ref. [?]. It was demonstrated that the TMD evolution can describe the experimental data and constrain the nucleon tensor charge with improved theoretical accuracy. To achieve that, the most recent developments from both theory and phenomenology sides [? ? ? ? ? ? ? ? ? ?] were used, and the TMD evolution at NLL order within the Collins-Soper-Sterman (CSS) [? ? ?] formalism was applied to the data.

As our study is dedicated to Jefferson Lab 12 that will utilize SIDIS for experimental studies, let us discuss the origin of Collins asymmetries in SIDIS.

Collins asymmetries in SIDIS are generated by the convolution of the transversity function  $h_1$  and the Collins TMD FF  $H_1^\perp$ .

The relevant contributions to the SIDIS cross-sections are

$$\frac{d^5\sigma(S_\perp)}{dx_B dy dz_h d^2P_{h\perp}} = \sigma_0(x_B, y, Q^2) \left[ F_{UU} + \sin(\phi_h + \phi_s) \frac{2(1-y)}{1+(1-y)^2} F_{UT}^{\sin(\phi_h + \phi_s)} + \dots \right]. \quad (2)$$

The polarized structure function  $F_{UT}^{\sin(\phi_h + \phi_s)}$  contains the convolution of transversity with the Collins function,  $h_1 \otimes H_1^\perp$ .

Experimentally measured Collins asymmetry is then

$$A_{UT}^{\sin(\phi_h + \phi_s)}(x_B, y, z_h, P_{h\perp}) = \frac{2(1-y)}{1+(1-y)^2} \frac{F_{UT}^{\sin(\phi_h + \phi_s)}}{F_{UU}} \quad (3)$$

Applying the TMD evolution,  $F_{UU}$  and  $F_{UT}^{\sin(\phi_h + \phi_s)}$  can be written as [? ? ? ?]

$$\begin{aligned} F_{UU} &= \frac{1}{z_h^2} \int \frac{db b}{2\pi} J_0\left(\frac{P_{h\perp} b}{z_h}\right) e^{-S_{\text{PT}}(Q, b_*) - S_{\text{NP}}^{(\text{SIDIS})}(Q, b)} \\ &\quad \times C_{q \leftarrow i} \otimes f_1^i(x_B, \mu_b) \hat{C}_{j \leftarrow q}^{(\text{SIDIS})} \otimes \hat{D}_{h/j}(z_h, \mu_b), \\ F_{UT}^{\sin(\phi_h + \phi_s)} &= -\frac{1}{2z_h^3} \int \frac{db b^2}{2\pi} J_1\left(\frac{P_{h\perp} b}{z_h}\right) e^{-S_{\text{PT}}(Q, b_*) - S_{\text{NP coll}}^{(\text{SIDIS})}(Q, b)} \\ &\quad \times \delta C_{q \leftarrow i} \otimes h_1^i(x_B, \mu_b) \delta \hat{C}_{j \leftarrow q}^{(\text{SIDIS})} \otimes \hat{H}_{h/j}^{(3)}(z_h, \mu_b), \end{aligned} \quad (4)$$

where  $b$  is the Fourier conjugate variable to the measured final hadron momentum  $P_{h\perp}$ ,  $J_1$  is the Bessel function,  $\mu_b = c_0/b_*$  with  $c_0 \simeq 1.12$ , and the symbol  $\otimes$  represents the usual convolution in momentum fractions. The sum over quark flavors  $q$  weighted with quark charge,  $\sum_q e_q^2$ , and the sum over  $i, j = q, \bar{q}, g$ , are implicit in all formulas for the structure functions.  $C, \hat{C}$  and  $\delta C, \delta \hat{C}$  are the coefficient functions for the unpolarized distribution and

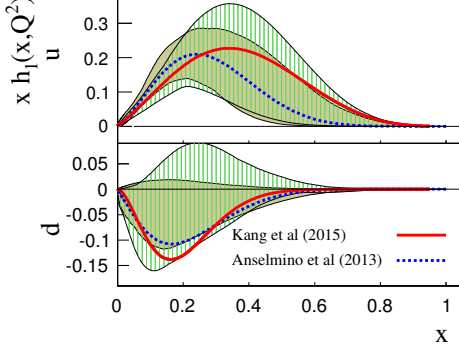


FIG. 1: [color online] Transversity distribution for up and down quarks comparison of extraction in Ref. [?] and [?]. The band corresponds to the uncertainty of the extraction.

fragmentation functions, and for transversity and Collins FF, that can be calculated perturbatively. The usual  $b_*$ -prescription that allows for smooth transition from perturbative to non perturbative physics was used in Ref. [?].  $S_{\text{NP}}^{(\text{SIDIS})}$  and  $S_{\text{NP coll}}^{(\text{SIDIS})}$  are non perturbative factors contain information on the initial conditions of evolution:

$$S_{\text{NP}}^{(\text{SIDIS})} = g_2 \ln \left( \frac{b}{b_*} \right) \ln \left( \frac{Q}{Q_0} \right) + \left( g_q + \frac{g_h}{z_h^2} \right) b^2, \quad (6)$$

$$S_{\text{NP coll}}^{\text{SIDIS}} = g_2 \ln \left( \frac{b}{b_*} \right) \ln \left( \frac{Q}{Q_0} \right) + \left( g_q + \frac{g_h - g_c}{z_h^2} \right) b^2, \quad (7)$$

where  $Q_0^2 = 2.4 \text{ GeV}^2$ , for the spin-averaged contribution. In the above parameterization, the parameters  $g_q = g_1/2 = 0.106$ ,  $g_2 = 0.84$ ,  $g_h = 0.042 \text{ (GeV}^2\text{)}$  have been determined from the analysis of SIDIS and Drell-Yan processes in Ref. [?].

The existing experimental data does not allow to determine precisely shapes of all polarised distributions in coordinate space, the parameter  $g_c$  allowed for the Collins fragmentation function to modify its shape with respect to unpolarised fragmentation distributions.

The Collins fragmentation function  $H_{1h/j}^\perp(z_h, p_\perp)$  [?] at small values of  $b$  can be related to the so called twist-three fragmentation function  $\hat{H}_{h/q}^{(3)}(z_h)$  [?] via Operator Product Expansion (OPE).

Three important ingredients have to be included to achieve the NLL formalism for the above structure functions and asymmetries. First of all, the perturbative Sudakov form factor [?],

$$S_{\text{PT}}(Q, b_*) = \int_{\mu_b^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[ A \ln \frac{Q^2}{\mu^2} + B \right], \quad (8)$$

with perturbative coefficients  $A^{(1,2)} \sim \alpha_s^{(1,2)}$  and  $B^{(1)} \sim \alpha_s^1$  [?]. Then, the scale evolutions of the quark transversity distribution and of the Collins fragmentation functions up to the scale of  $\mu_b$ .

The global fit of SIDIS and  $e^+e^-$  was performed in Ref. [?]. The quark transversity distributions was parametrized as as

$$h_1^q(x, Q_0) = N_q^h x^{a_q} (1-x)^{b_q} \frac{(a_q + b_q)^{a_q + b_q}}{a_q^{a_q} b_q^{b_q}} \times \frac{1}{2} (f_1^q(x, Q_0) + g_1^q(x, Q_0)), \quad (9)$$

at the initial scale  $Q_0$ , for up and down quarks  $q = u, d$ , respectively, where  $f_1^q$  are the unpolarized CT10 NLO quark distributions [?] and  $g_1^q$  are the NLO DSSV quark helicity distributions [?]. The available SIDIS data does not allow for extraction of anti-quark transversity distributions and anti-quark transversity was assumed to be zero,  $h_1^{\bar{q}} = 0$ .

Twist-3 Collins fragmentation functions were parametrized in terms of the unpolarized fragmentation functions,

$$\hat{H}_{fav}^{(3)}(z, Q_0) = N_u^c z^{\alpha_u} (1-z)^{\beta_u} D_{\pi^+/u}(z, Q_0), \quad (10)$$

$$\hat{H}_{unf}^{(3)}(z, Q_0) = N_d^c z^{\alpha_d} (1-z)^{\beta_d} D_{\pi^+/d}(z, Q_0), \quad (11)$$

which correspond to the favored and unfavored Collins fragmentation functions, respectively. The newest NLO extraction of fragmentation functions [?] was used for unpolarised FF,  $D$ .

Therefore, Ref. [?] introduced total of 13 parameters in the global fit:  $N_u^h, N_d^h, a_u, a_d, b_u, b_d, N_u^c, N_d^c, \alpha_u, \alpha_d, \beta_d, \beta_u, g_c$  ( $\text{GeV}^2$ ).

The global fit of SIDIS and  $e^+e^-$  data resulted in the total  $\chi^2 = 218.407$ ,  $n_{d.o.f.} = 249$ , and  $\chi^2/n_{d.o.f.} = 0.88$ . The description of the data was equally good for SIDIS and  $e^+e^-$ :  $\chi_{SIDIS}^2/n_{SIDIS} = 0.93$ ,  $\chi_{e^+e^-}^2/n_{e^+e^-} = 0.72$ .

The resulting parameters of Ref. [?] after minimization procedure are presented in Table I.

$N_u^h = 0.85 \pm 0.09$	$a_u = 0.69 \pm 0.04$	$b_u = 0.05 \pm 0.04$
$N_d^h = -1.0 \pm 0.13$	$a_d = 1.79 \pm 0.32$	$b_d = 7.00 \pm 2.65$
$N_u^c = -0.262 \pm 0.025$	$\alpha_u = 1.69 \pm 0.01$	$\beta_u = 0.00 \pm 0.54$
$N_d^c = 0.195 \pm 0.007$	$\alpha_d = 0.32 \pm 0.04$	$\beta_d = 0.00 \pm 0.79$
$g_c = 0.0236 \pm 0.0007$	$(\text{GeV}^2)$	

$$\chi_{min}^2 = 218.407 \quad \chi_{min}^2/n_{d.o.f.} = 0.88$$

TABLE I: Fitted parameters of the transversity quark distributions for  $u$  and  $d$  and Collins fragmentation functions.

Fig. 1 shows transversity distributions for  $u$  and  $d$  quarks results obtained in Ref. [?] and compared to results of Ref. [?].

Since the experimental data has only probed the limited region  $0.0065 < x_B < 0.35$ , the following partial contribution to the tensor charge was defined

$$\delta q^{[x_{\min}, x_{\max}]}(Q^2) \equiv \int_{x_{\min}}^{x_{\max}} dx h_1^q(x, Q^2). \quad (12)$$

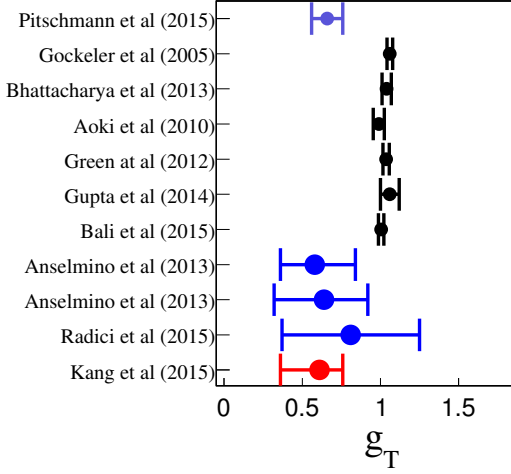


FIG. 2: [color online] Comparison of the isovector nucleon tensor charge  $g_T$  from this paper at 68% C.L. (Kang et al 2015) at  $Q^2 = 10 \text{ GeV}^2$  and result from Ref. [?] (Radici et al 2015) at 68% CL and  $Q^2 = 4 \text{ GeV}^2$ , and Ref. [?] at 95% CL standard and polynomial fit (Anselmino et al 2013) at  $Q^2 = 0.8 \text{ GeV}^2$ . Other points are lattice computation at  $Q^2 = 4 \text{ GeV}^2$  of Bali et al Ref. [?], Gupta et al Ref. [?], Green et al Ref. [?], Aoki et al Ref. [?], Bhattacharya et al ref. [?], Gockeler et al Ref. [?]. Pitschmann et al is DSE calculation at  $Q^2 = 4 \text{ GeV}^2$  Ref. [?].

and the following partial tensor charges were calculated [?]

$$\delta u^{[0.0065, 0.35]} = +0.30^{+0.08}_{-0.12}, \quad (13)$$

$$\delta d^{[0.0065, 0.35]} = -0.20^{+0.28}_{-0.11}, \quad (14)$$

at 90% C.L. at  $Q^2 = 10 \text{ GeV}^2$ .

The tensor charge calculated over the whole kinematical region  $\delta q^{[0,1]}$  is:

$$\delta u^{[0,1]} = +0.39^{+0.16}_{-0.20}, \quad (15)$$

$$\delta d^{[0,1]} = -0.22^{+0.31}_{-0.10}, \quad (16)$$

at 90% C.L.

One can see that the kinematical region not covered by experimental data can potentially give  $\sim 25\%$  contribution to the tensor charge.

Apart from that the assumption that anti-quark transversity is exactly equal to zero may not be true in future and maximal contribution from sea quarks can be .... for  $\bar{u}$  and  $\bar{d}$  quarks respectively.

The isoscalar nucleon tensor charge  $g_T^0 = \delta u + \delta d$  is

$$g_T^0 = +0.17^{+0.47}_{-0.30}, \quad (17)$$

at 90% C.L. at  $Q^2 = 10 \text{ GeV}^2$ .

The isoscalar tensor charge is presented in Fig. 2. One can see that lattice QCD calculations have much better precision compared to extractions from experimental data.

Future Jefferson Lab 12 data is going to allow for much more precise extraction of tensor charge that will compete with ab-initio calculations.

### III. BAYESIAN RE-WEIGHTING TECHNIQUE

Nobuo, could you write description of the re-weighting procedure, please? Bayes theorem allows to incorporate information from new data by applying re-weighting of probability densities for model parameters. The details of application of re-weighting are explained in Ref. [?].

Probability density function for model parameters  $\alpha$ ,  $\mathcal{P}(\alpha)$ , is going to be modified in presence of new data and the Bayes theorem states that

$$\mathcal{P}(\alpha|D) = \frac{\mathcal{P}(D|\alpha)\mathcal{P}(\alpha)}{\mathcal{P}(D)}, \quad (18)$$

where  $\mathcal{P}(\alpha|D)$  is the so-called *posterior* density, is the updated pdf from the *prior* density  $\mathcal{P}(\alpha)$ .

The quantity  $\mathcal{P}(D|\alpha)$  called the *likelihood* function, represents the conditional probability for a data set  $D$  given the parameters  $\alpha$  of the model. The quantity  $\mathcal{P}(D)$  ensures the normalization of the posterior density to unity.

For a particular observable  $\mathcal{O}$  one can write the expectation value with the new data as,

$$\begin{aligned} \mathbb{E}[\mathcal{O}] &= \int d^n \alpha \mathcal{P}(\alpha|D) \mathcal{O}(\alpha) \\ &= \int d^n \alpha \frac{\mathcal{P}(D|\alpha)}{\mathcal{P}(D)} \mathcal{P}(\alpha) \mathcal{O}(\alpha) \\ &= \frac{1}{N} \sum_k w_k \mathcal{O}(\alpha_k). \end{aligned} \quad (19)$$

In the last line a Monte Carlo approximation of the integral is used. Similarly, the variance of observable  $\mathcal{O}$  is given by

$$\text{Var}[\mathcal{O}] = \frac{1}{N} \sum_k w_k (\mathcal{O}(\alpha_k) - \mathbb{E}[\mathcal{O}])^2. \quad (20)$$

The quantities  $\{w_k\}$  are called *weights* and are proportional to  $\mathcal{P}(D|\alpha_k)$ . Their normalization is fixed by demanding  $\mathbb{E}[1] = 1$ , that is,  $\sum_k w_k = N$ .

The reweighting procedure depends on the form assumed for the likelihood function. We use  $\chi^2$  minimization in the fits and thus weights have the following form:

$$w_k \propto \exp\left(-\frac{1}{2}\chi^2\right), \quad (21)$$

### IV. SIMULATED DATA FOR SOLID

Several SIDIS experiments have been approved at Jefferson Lab to take advantage of the newly updated

12 GeV electron beam with longitudinal polarization and measure the asymmetries of proton and neutron target at both the transversed and longitudinally polarized directions. The E12-09-018 experiment in Hall A [?] will measure the semi-inclusive electroproduction of pions and kaons on a transversely polarized  $^3\text{He}$  target using the Super-BigBite and BigBite spectrometers. This experiment will more focus on the high- $x$  region and provide the single spin-asymmetries as functions of the kinematic variables,  $x$ ,  $p_T$  and  $z$  at two different  $Q^2$  values. The CLAS12 conditional approved experiment, C12-11-111 [?], will collect high precision data of the single- and double-spin asymmetries on a transversely polarized proton target. The large acceptance feature of the CLAS12 provides very wide kinematic coverage which allows one to study leading-twist TMDs in multiple-dimensional binning of  $Q^2$ ,  $x$ ,  $p_T$  and  $z$ .

Three other Hall A experiments, E12-10-006 [?] (90 days), E12-11-007 [?] (35 days) and E12-11-108 [?] (120 days), will be run on a high intensity and large acceptance device, named SoLID [?], and measure both the target-spin and double-spin asymmetries on proton and  $^3\text{He}$  ("neutron") targets at both transversely and longitudinally polarize directions. These experiments can provide a complete SIDIS data set with very high accuracy at extensive kinematic coverage. They aim to extract all leading twist TMDs in the valance quark region and perform a four dimensional binning in  $Q^2$ ,  $z$ ,  $p_T$  and  $x$ . In this article, we will study the prospective improvement of the tensor charge measurement with the SoLID SIDIS experiments.

The pseudo-data was generated based on the kinematic settings presented in the proposals of these experiments. The electron beam energy is set at two different values, 8.8 GeV and 11 GeV. The momentum of detected electrons and hadrons can go as low as 1 GeV/c. The SoLID configuration dedicated to the SIDIS measurements provides a full  $2\pi$  coverage in azimuthal angle and a coverage of the polar angle from  $8^\circ$  up to  $24^\circ$ . The overall luminosities of the proton target and the  $^3\text{He}$  target are  $1 \times 10^{35\text{cm}^{-2}\text{s}^{-1}}$  and  $1 \times 10^{36\text{cm}^{-2}\text{s}^{-1}}$ , respectively. The polarization and dilution factor of the proton target ( $^3\text{He}$  target) are 65% (70%) and 0.3 (0.13), respectively.

Table II summarizes the kinetically limits of SoLID used in this study. There are totally 1014 bins for

$^3\text{He}(e,e')\pi^+$ , 879 bins for  $^3\text{He}(e,e')\pi^-$ , 617 bins for  $p(e,e')\pi^-$ , and 492 bins for  $p(e,e')\pi^-$ , respectively. The total statistics in a 4-dimensional bin is weighted by the SIDIS cross sections event-by-event, and the average values of  $Q^2$ ,  $z$ ,  $p_T$  and  $x$  are recorded. These binning data are provided to generate the pseudo-data with the model given in Section II. The global fit to the existing data provides best values of these 13 parameters together with their associated errors given in a co-variant matrix. One assumes a Gaussian distribution for each parameter with its best fit value as the central value and its error as the width. For each pseudo-data set, one generates a group of these 13 parameters which are chose randomly from their Gaussian distributions, and then calculates the transversity, Collins fragmentation function, unpolarized cross section and the asymmetry value for each data bin. Analogously, to get more sets of pseudo-data, one keeps generates more random values of these 13 parameters and calculates physics quantities for individual bins. One can continuously add more data-set until the statistical fluctuation is well controlled.

Variable	Min	Max	Bin Size	Comments
$Q^2$	1.0 GeV <sup>2</sup>	8.0 GeV <sup>2</sup>	1.0 GeV <sup>2a</sup>	6 bins
$z$	0.3 GeV <sup>2</sup>	0.7 GeV <sup>2</sup>	0.05 GeV <sup>2</sup>	8 bins
$p_T$	0.0 GeV	1.6 GeV	0.2 GeV <sup>b</sup>	$\leq 8$ bins
$x$	0.	1.0	N/A <sup>c</sup>	$\leq 8$ bins

<sup>a</sup>last bin from 6 to 8 GeV<sup>2</sup>

<sup>b</sup>double the bin-size when total events  $< 5 \times 10^6$

<sup>c</sup>bin size varies to keep events in one bin  $\sim 10^6$

TABLE II: Kinematic limits of SoLID.

FIG. 3: [color online] Kinematical plane with SoLID data.

## V. TENSOR CHARGE AND TRANSVERSITY FROM SOLID

## VI. SUMMARY AND CONCLUSIONS

### Acknowledgments

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