Spin and Polarization in QCD

1. What carries the spin of a nucleon?
2. Polarized parton distributions
   — Spin in DIS
3. Skewed parton distributions
   — Deep Virtual Compton Scattering (DVCS)
4. Multiparton Correlation functions
5. Chiral odd parton distributions
6. Spin at RHIC
7. Conclusions

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CTEQ Summer School
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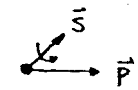
1. What carries the spin of a nucleon?

- Nucleon :



Mass : $m_N \sim 1\,\text{GeV}$, Spin : $S_N = \frac{1}{2}$, Composite par

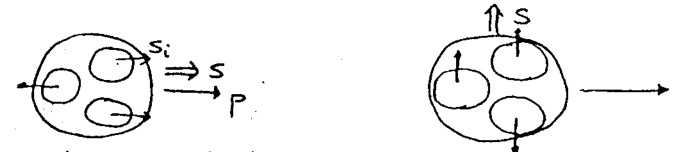
[Magnetic moment : $\left(\frac{\mu(n)}{\mu(p)}\right)_{exp} \sim -0.68 \neq 0$, ...

$\Rightarrow$ P, n Not point-like]

- Naive quark model picture ($|\vec{P}| \ll m_N$):

* 3 Constituent quarks : $s_i = \frac{1}{2}$, $\mu_i = Q_i\left(\frac{e}{2m_i}\right)$, i=

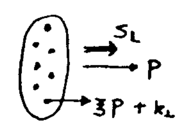
$\Rightarrow$ give correct nucleon spin, $\frac{\mu(n)}{\mu(p)}$, ...



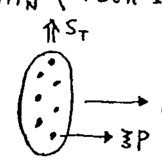
* Longitudinally polarized — NRQM Rotation — Transversely pol

- Parton model picture ($|\vec{P}| \to \infty$):

* "boost" from the state at $|\vec{P}| \ll m_N$ (Many multipa
Fock states t
import



$0 < \xi < 1$
$k_\perp \sim 0$
Partons

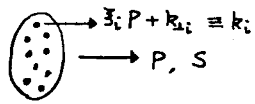


* Relation between nucleon's spin and parton's spin ?

* Relation between Longitudinal and transverse spin sta

⋮

· QCD Picture ($|\vec{P}| \gg m_N$):



* Momentum Sum Rule: $P = \sum_i k_i \approx (\sum_i \xi_i) P$ Large # ! Not a Large #

* Angular momentum Sum Rule: $S = \sum_i \langle P, \tfrac{1}{2} | \hat{J}_i^z | P, \tfrac{1}{2} \rangle = \tfrac{1}{2}$

QCD angular momentum operator: $J^i_{QCD} = \frac{1}{2} \epsilon^{ijk} \int d^3x\, M^{0jk}_{QCD}$

$M^{\alpha\mu\nu}_{QCD} = T^{\alpha\nu}_{QCD} x^\mu - T^{\alpha\mu}_{QCD} x^\nu$ angular momentum density

energy-momentum tensor

— quark field: $\vec{J}_q = \int d^3x \left[\psi_q^\dagger \vec{\gamma} \gamma_5 \psi_q + \psi_q^\dagger (\vec{x} \times (-i\vec{D})) \psi_q \right]$

— gluon field: $\vec{J}_g = \int d^3x \left[\vec{x} \times (\vec{E} \times \vec{B}) \right]$

— Nucleon Spin: $J_{q,g}(\mu^2)\, 2\vec{S} \equiv \langle PS | \vec{J}_{q,g}(\mu^2) | PS \rangle$

$$\Rightarrow \frac{1}{2} = \overbrace{\frac{1}{2} \Sigma(\mu^2) + L_q(\mu^2)}^{J_q(\mu^2)} + J_g(\mu^2)$$

quark spin — quark orbital — total gluon angular momentum — Renormalization scale

* Scale dependence of $J_q(\mu^2)$ and $J_g(\mu^2)$: X. Ji '97

$$\frac{\partial}{\partial \ln\mu^2} \begin{pmatrix} J_q \\ J_g \end{pmatrix} = \frac{\alpha_s}{2\pi} \frac{1}{9} \begin{pmatrix} -16 & 3n_f \\ 16 & -3n_f \end{pmatrix} \begin{pmatrix} J_q \\ J_g \end{pmatrix} \underset{\mu^2 \to \infty}{\Rightarrow} \begin{pmatrix} J_q(\infty) \\ J_g(\infty) \end{pmatrix} = \frac{1}{2} \frac{1}{16 + 3n_f} \begin{pmatrix} 3n_f \\ 16 \end{pmatrix}$$

$$\approx \frac{1}{2} \begin{pmatrix} 0.53 \\ 0.47 \end{pmatrix} \text{ for } n_f = 6$$

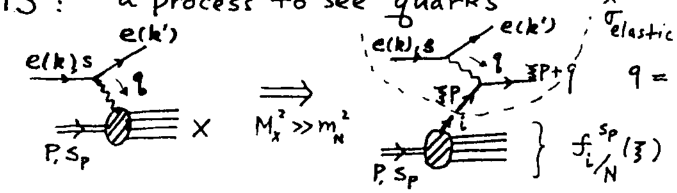
* Test of QCD (Spin Sector):

— independent measurement of $\Sigma(\mu^2)$, $L_q(\mu^2)$, $J_g(\mu^2)$

— Distributions of quarks and gluons inside a polarized nucleon

2. Polarized Parton Distributions:

● DIS : a process to "see" quarks



$q = k - k'$

$Q^2 = -q^2$

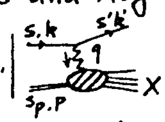
$x = \frac{Q^2}{2P \cdot q}$

$$\Rightarrow d\sigma^{(eN \to eX)}_{s S_p} \approx \sum_i \int_x^1 d\xi \left[d\hat{\sigma}^{(ei \to ex')}_{elastic} \right] \cdot \left[f^{S_p}_{i/N}(\xi) \right]$$

general parton model formula

elastic : $(\xi P + q)^2 = 0 \Rightarrow \xi = -\frac{q^2}{2P \cdot q} = x$

● Structure functions and Asymmetries :



$$k' \frac{d^3\sigma}{d^3k'} \sim \frac{1}{2S} \sum_{X, s'} \left| \cdots \right|^2 = \frac{1}{2SQ^4} L^{\mu\nu} W_{\mu\nu}$$

$$L^{\mu\nu} \sim \sum_{s'} (\ \gamma_\mu \ )(\ \gamma_\nu \ )^*$$

$\sim L^{\mu\nu}_{unpol} + 2 i m_e \epsilon^{\mu\nu\alpha\beta} q_\alpha S_\beta$ ← known from QED

Spin of the incoming lepton.

$$W_{\mu\nu} \sim W^{unpol}_{\mu\nu} + m_p \frac{4\pi i}{P \cdot q} \epsilon_{\mu\nu\lambda\sigma} q^\lambda \left[S_p^\sigma g_1(x, Q^2) + (S_p^\sigma - \frac{S_p \cdot q}{P \cdot q} P^\sigma) g_2(x, Q^2) \right]$$

— Structure functions : $g_1(x, Q^2)$, $g_2(x, Q^2)$

— Asymmetrices : $A_{LL} \equiv \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}}$, $A_{LN} \equiv \frac{\sigma_{\uparrow\rightarrow} - \sigma_{\uparrow\leftarrow}}{\sigma_{\uparrow\rightarrow} + \sigma_{\uparrow\leftarrow}}$

$g_1(x, Q^2) \simeq A_{LL} \left(\frac{F_1(x, Q^2)}{1 + R} \right)$ $R = \frac{\sigma_L}{\sigma_T}$ See E.W. Hughes, R. Voss '9

$g_2(x, Q^2)$ in terms of A_{LN} and A_{LL}.

5

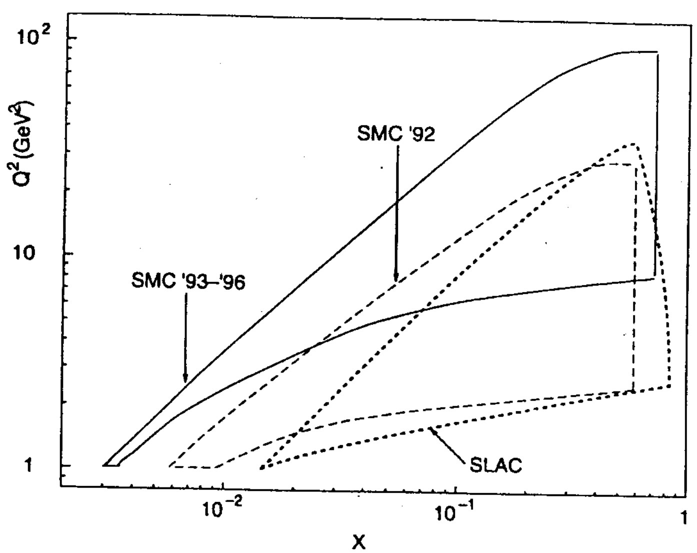


Figure 7 Kinematic domains of recent measurements of $g_1(x, Q^2)$. For the Spin Muon Collaboration, there are two different regions because different beam energies were used in 1992 (100 GeV) and in 1993–1996 (190 GeV). The SLAC curve indicates the combined domain covered by experiments E142, E143, E154, and E155. The HERMES domain is roughly similar to SLAC's but starts at $x = 0.03$.

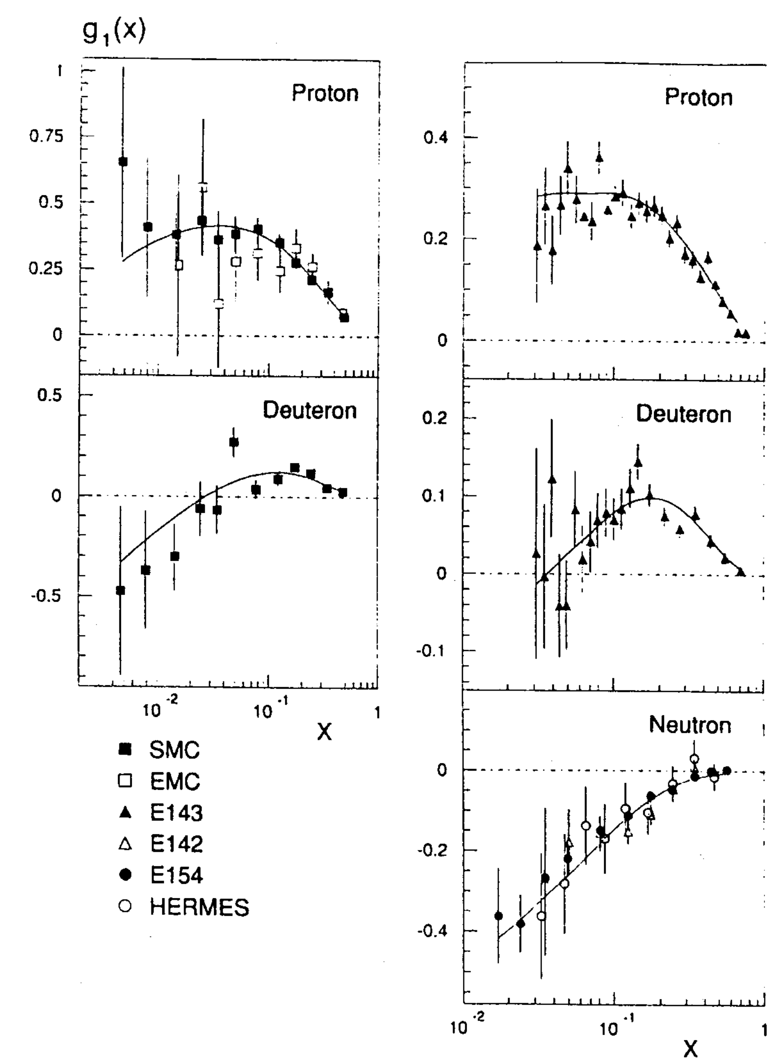


Figure 8 The structure function g_1 of the proton, the deuteron, and the neutron, as a function of x, from the CERN muon-scattering experiments (*left*) and the SLAC and DESY electron-scattering experiments (*right*). Only statistical errors are shown. Solid lines show a next-to-leading order QCD fit, discussed in Section 5.

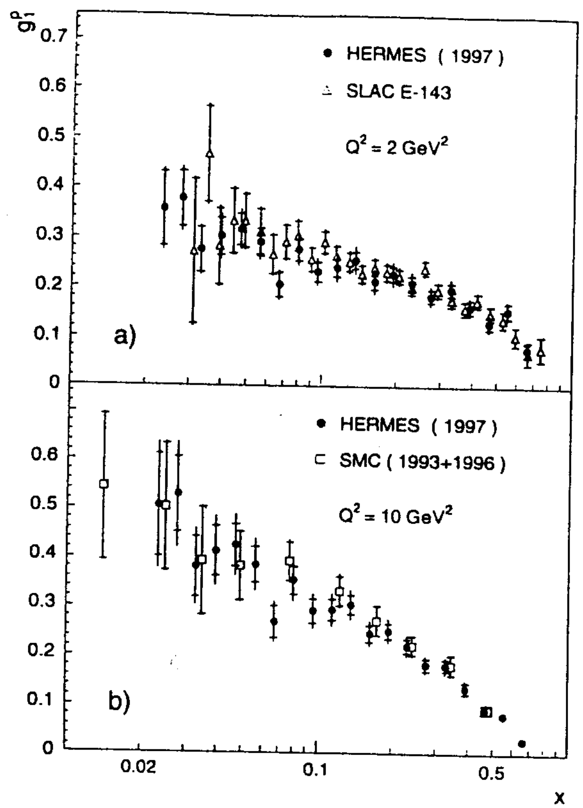


Figure 9 Recent data on the spin structure function g_1^p from the HERMES experiment at (*a*) $Q^2 = 2$ GeV^2 and (*b*) $Q^2 = 10$ GeV^2, compared with data from the SMC and SLAC E143 experiment. Inner error bars represent statistical error only; outer error bars are statistical and systematic errors combined in quadrature.

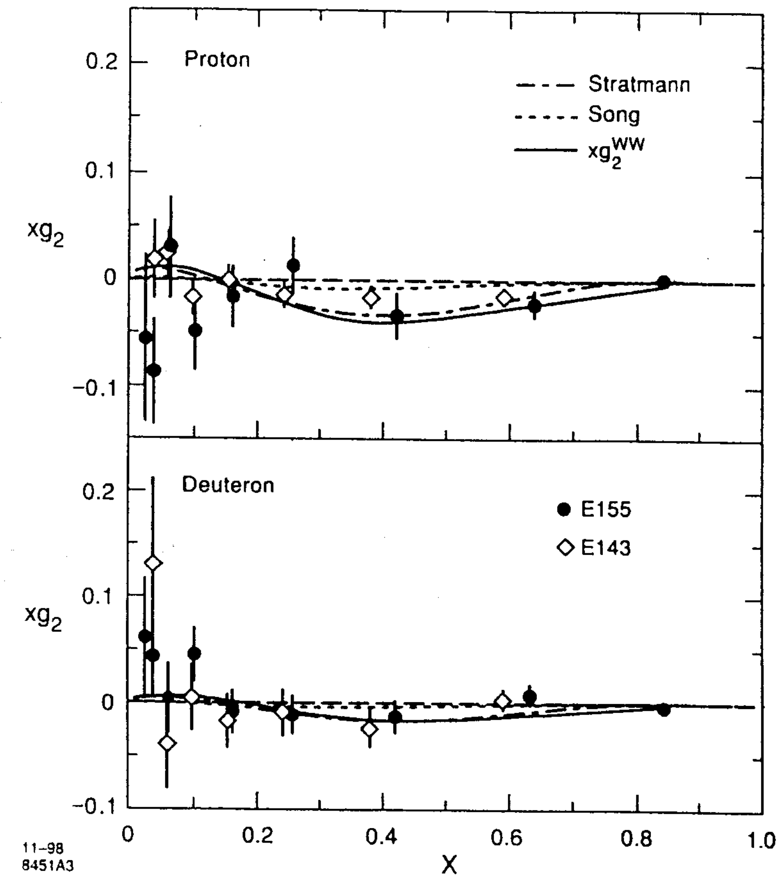


Figure 10 The spin-dependent structure function xg_2 as a function of x, measured by SLAC experiments E143 and E155, for the proton and the deuteron. Only statistical errors are shown; the systematic errors are much smaller. The solid curve shows a twist-2 calculation of g_2^{WW}. Also shown are bag model calculations at $Q^2 = 5.0$ GeV^2 by Stratmann (70) and Song (71).

- Parton Model for $g_1(x, Q^2)$:

$$W_N^{\mu\nu}(x, P, S) = \sum_{q, s_q} \int_x^1 d\xi \; W_q^{\mu\nu}(\xi P, s_q)\; q_N^{s_q}(\xi)$$

← spin dependent quark distribution

$W_q^{\mu\nu}(\xi P, s_q)$ from $\left| \; q, \; \xi P, s_q \rightarrow \xi P + q \; \right|^2 \propto \delta(\xi - x)$

$$\Rightarrow \; g_1^N(x, Q^2) = \frac{1}{2} \sum_q Q_q^2 \, \Delta q_N(x)$$

Scaling (indep. of Q^2)

$\Delta q_N(x) = \underbrace{q_N^{\uparrow}(x)}_{\text{parallel}} - \underbrace{q_N^{\downarrow}(x)}_{\text{antiparal.}}$

- Parton Model $\longrightarrow$ QCD:

$$W_q^{\mu\nu}(\xi P, s_q) \longrightarrow \underbrace{W_{q(0)}^{\mu\nu}}_{\text{Born or PM term.}} + \alpha_s W_{q(1)}^{\mu\nu} + \alpha_s^2 W_{q(2)}^{\mu\nu} + \cdots$$

$\Delta q_N(x) \longrightarrow \Delta q_N(x, Q^2)$ ← renormalization Scale

Polarized parton distribution

= Quantum Mechanical Matrix element in N state

Number operator

$$\Delta q_N(x, Q^2) \sim \int^{Q^2} dk_\perp^2 \, \langle N | \, b_q^{\dagger} b_q(xP, k_\perp) - b_{\downarrow}^{\dagger} b_{\downarrow}(xP, k_\perp) \, | N \rangle$$

$$\sim \int \frac{dy}{4\pi} e^{-ixP\cdot n y} \langle N | \bar{\psi}_q(yn) \, \gamma \cdot n \, \gamma_5 \, \psi_q(0) | N \rangle$$

Similar definition for polarized gluon distribution. $n \cdot A = 0$ gauge.

$$\Rightarrow \; g_1^N(x, Q^2) = \frac{1}{2}\Big[\sum_q Q_q^2 \, \Delta C_q(x/\xi, \alpha_s) \otimes \Delta q_N(\xi, Q^2) + \Delta C_g(\tfrac{x}{\xi}, \alpha_s) \otimes \Delta G_N(\xi, Q^2) \Big]$$

Power series in α_s.

* Measure g_1^N, extract informations on $\Delta q_N(x, Q^2)$ & $\Delta G_N(x, Q^2)$

* But, too many unknown distributions!

- The Sum Rules for the Moments:

* 1^{st} moment : $\int_0^1 dx \, \Delta q_N(x, Q^2) = \frac{n_\mu}{2P\cdot n} \langle N | \underbrace{\bar{\psi}_q(0) \gamma^\mu \gamma_5 \psi_q(0)}_{\text{Axial vector current.}} | N \rangle$

$\equiv \Delta q$

(a basic current in the Standar model, Couples to $W^{\pm}, Z$)

* Leading order approximation:

$$\Gamma_1^P \equiv \int_0^1 dx \, g_1^P(x, Q^2) \approx \frac{1}{2}\left[\frac{4}{9} \Delta u_p + \frac{1}{9} \Delta d_p + \frac{1}{9} \Delta s_p \right] + O(\alpha_s)$$

* u, d isospin symmetry: $\bar{u} \gamma^\mu \gamma_5 u \longleftrightarrow \bar{u} \gamma^\mu \gamma_5 d$

(exact in QCD)

* u, d, s, SU(3) flavor Sym.: $\bar{u} \gamma^\mu \gamma_5 u \longleftrightarrow \bar{u} \gamma^\mu \gamma_5 s$

(Approximate in QCD)

* Isospin: $\Delta u_p - \Delta d_p \propto \langle p | \bar{u} \gamma^\mu \gamma_5 d | n \rangle$

$\propto (g_A/g_V)_{np}$ from $n \to p e \bar{\nu}_e$

* Bjorken Sum Rule (Isospin Sym.):

$$\Gamma_1^P - \Gamma_1^n = \frac{1}{6}[\Delta u_p - \Delta d_p] + O(\alpha_s)$$

$$= \frac{1}{6}[g_A/g_V]\left[1 - \frac{\alpha_s}{\pi} + \cdots\right]$$

* Ellis - Jaffe Sum Rule (SU(3) flavor Sym. + $\Delta S = 0$):

$a_0 = \Delta u + \Delta d + \Delta S \equiv \Delta\Sigma$

$a_3 = \Delta u - \Delta d = |\frac{g_A}{g_V}| = F + D$

$a_8 = \Delta u + \Delta d - 2\Delta S = 3F - D$

F and D are Sym. and antisym Weak $SU(3)_{flavor}$ Couplings.

$$\Delta S = 0 \Rightarrow \Gamma_1^{P(n)} = +(-)\frac{1}{12}(F + D) + \frac{5}{36}(3F - D)$$

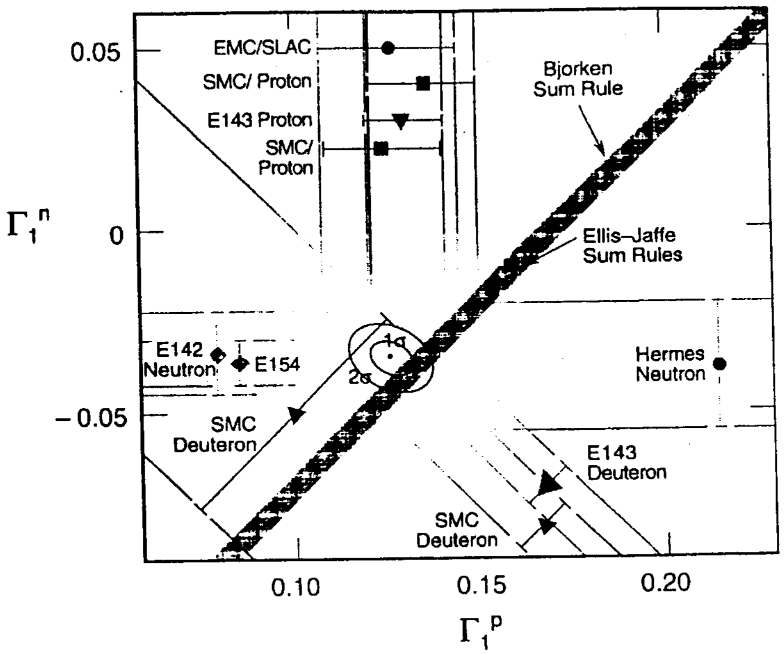


Figure 14 Measurements of the first moments Γ_1 of the spin-dependent structure function g_1 in the $\Gamma_1^p - \Gamma_1^n$ plane, from experiments at CERN, SLAC, and DESY. The results are compared with the Bjorken (line) and Ellis-Jaffe (point) sum rule predictions.

- Lessons from DIS:

  * Ellis-Jaffe Sum Rules unlikely
  * Bjorken Sum Rule ok ($\sim 1\sigma$)
  * $\Delta S \neq 0$ possible
  * Use the measured Γ_1^p and Γ_1^n, and F & D value determine Δu, Δd, Δs, at Leading order.

    $\Rightarrow a_0 = \Delta u + \Delta d + \Delta s \simeq 0.2 - 0.3 < 0.5$

    [First quoted EMC result give $\sum_q \Delta q$ Consistent with zero. This was "spin crisis". Now, zero is rather unlikely.]

  * Determination of $a_0 = \Delta u + \Delta d + \Delta s$ with NLO Contribution depends on renormalization scheme.

    [see Figure]

  * Issue: What carries the Spin of a nucleon? gluons? orbital?

    Part of Larger issue:

    Measurement of $\Delta g_N(x, Q^2)$

    $\Rightarrow$ teaches about nucleon structure.

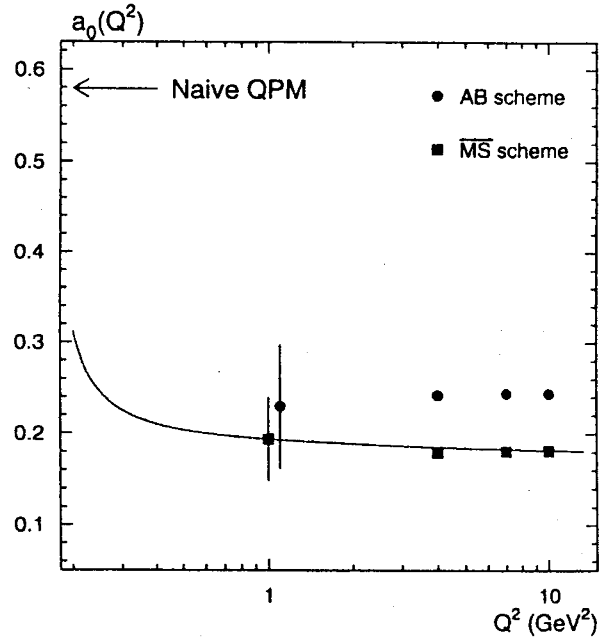


Figure 13 The total quark contribution to the proton spin obtained by SMC in the $\overline{\text{MS}}$ and AB renormalization schemes, as a function of Q^2. Statistical errors are shown only for the data points at $Q^2 = 1\,\text{GeV}^2$; the error bars for the other data points are similar. The solid line shows the predicted Q^2 evolution of a_0 in the $\overline{\text{MS}}$ scheme. Also shown is the naive quark-parton–model prediction for $\Delta s = 0$.

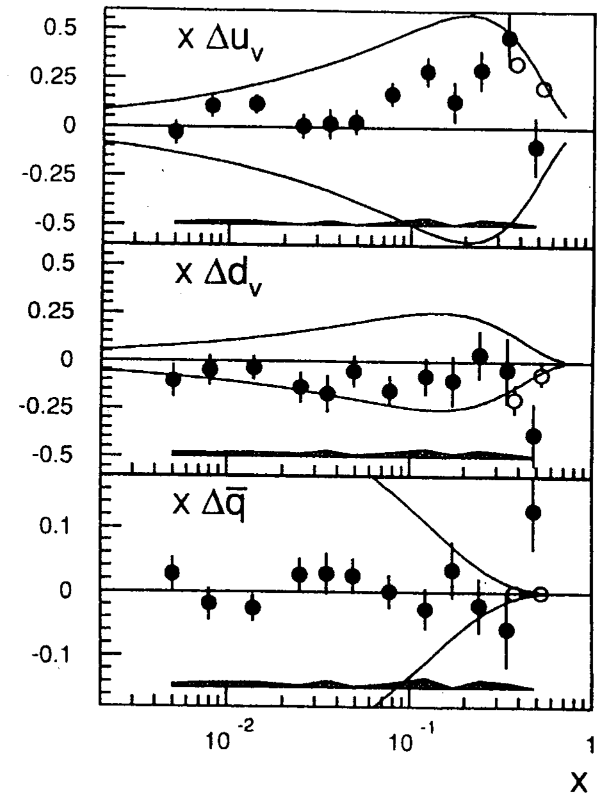


Figure 12 The polarized quark distributions $x\Delta u_v(x)$, $x\Delta d_v(x)$, and $x\Delta\bar{q}(x)$ measured by SMC, assuming $\Delta\bar{u}(x) = \Delta\bar{d}(x)$. The open circles are obtained when the sea polarization is set to zero; the solid circles are obtained without this assumption. The error bars are statistical and the shaded areas represent the systematic uncertainty. The solid lines show the limit $\pm xq(x)$ from unpolarized quark distributions at $Q^2 = 10\,\text{GeV}^2$. *Bottom*: Curves correspond to $\pm x(\bar{u}(x) + \bar{d}(x))/2$.

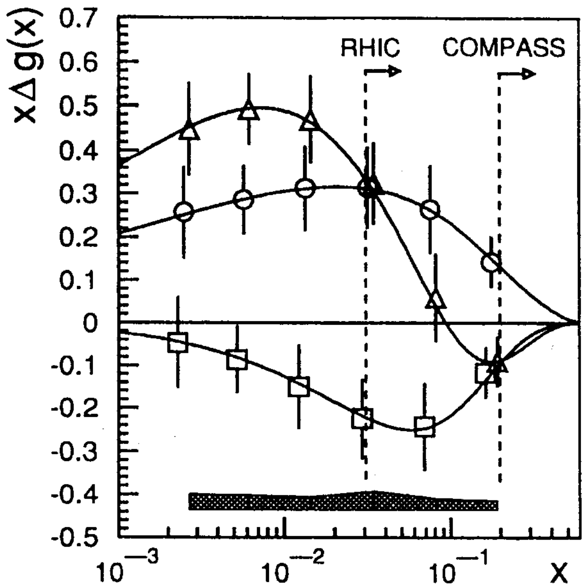


Figure 16 The polarized gluon distribution $x\Delta G$ in different models. The curve with circles superimposed shows $x\Delta G$ from a next-to-leading-order QCD fit to the SMC g_1 data. Triangles show gluon set C in the model of Gehrmann & Stirling (28). Squares show an instanton-induced gluon polarization proposed by Kochelev et al (80). Error bars indicate the statistical sensitivity of a measurement with dijet events with polarized beams of HERA for an integrated luminosity of 500 pb^{-1}; the corresponding systematic uncertainty is indicated by the band. Also shown are the x ranges accessible to experiments at RHIC and COMPASS (from Reference 81).

3. Skewed Parton Distributions

D. Müller, et al. Fortsch. Phys. 42 (9.

— Deep Virtual Compton Scattering (DVCS)

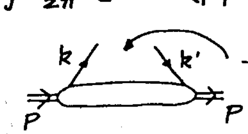
X. Ji PRD 55 (97

- Normal parton distributions (<u>Forward</u> "Scattering" Amplitude)

  = Matrix elements of light-cone <u>bilocal operators</u> between the <u>equal momentum</u> states

$$q(x,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P| \bar{\psi}_q(\tfrac{\lambda}{2}n) \frac{\gamma\cdot n}{2P\cdot n} \psi_q(-\tfrac{\lambda}{2}n) |P\rangle \Big|_{n\cdot A=0 \text{ gauge}}$$

$$= \quad \underbrace{\frac{\gamma\cdot n}{2P\cdot n}\, \delta(x-\frac{k\cdot n}{P\cdot n})\, d^4k'\, \delta^4(k'-k)}_{\text{Cut-vertex.}}$$



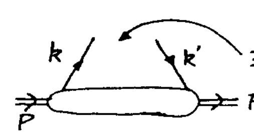
with a normalization: $\langle P'|P\rangle = 2E(2\pi)^3\delta^3(P'-P)$

- <u>Off-Forward</u> "Scattering" Amplitude:

  = Matrix elements of <u>the same</u> light-cone bilocal operat between <u>different</u> momentum states.

$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P'| \bar{\psi}_q(\tfrac{\lambda}{2}n) \frac{\gamma\cdot n}{2P\cdot n} \psi_q(-\tfrac{\lambda}{2}n) |P\rangle \Big|_{n\cdot A=0 \text{ ga}}$$

$$= \quad \frac{\gamma\cdot n}{2P\cdot n}\, \delta(x_1-\frac{k\cdot n}{P\cdot n})\, d^4k'\, \delta^4(k'-k-\Delta)$$



with $\Delta \equiv P'-P\ , \quad t \equiv \Delta^2 = (P'-P)^2$

$$\xi \equiv -n\cdot\Delta/2 = (P-P')\cdot n/2\ , \quad x_1 \equiv \frac{x+\xi}{1+\xi}\ .$$

- Skewed Parton distributions (off-forward parton distri.):

= <u>Form factors</u> of the off-forward "Scattering" amplitudes.

$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P' | \bar{\psi}_q(\tfrac{\lambda}{2}n) \frac{\gamma\cdot n}{2p\cdot n} \psi_q(-\tfrac{\lambda}{2}n) | P \rangle$$

$$\equiv H_q(x,\xi,t,\mu^2) \cdot \left[\bar{u}(P') \gamma^\mu u(p) \cdot \frac{n_\mu}{2p\cdot n} \right]$$

$$+ E_q(x,\xi,t,\mu^2) \cdot \left[\bar{u}(P') \frac{i\sigma^{\mu\nu}\Delta_\nu}{2M} u(P) \cdot \frac{n_\mu}{2p\cdot n} \right]$$

$H_q(x,\xi,t,\mu^2)$, $E_q(x,\xi,t,\mu^2)$ are skewed quark distri.

$\Rightarrow$ * two skewed parton distributions

Correspond to one normal parton distribution.

* As $\xi \to 0$ and $t \to 0$, skewed distributions are reduced to the normal distributions.

$$H_q(x,0,0,\mu^2) = q(x,\mu^2)$$

Similar equations hold for gluon, as well as polarized parton distributions.

* The 1st moments of these distributions are constrained by the form factors of Corresponding EM, a Axial Currents

$$\int_{-1}^{1} dx\, H_q(x,\xi,t,\mu^2) = F_1^q(t), \quad \int_{-1}^{1} dx\, E_q(x,\xi,t,\mu^2) = F_2^q(t), \ \ldots$$

- Relation between the Skewed parton distributions and the Spin Structure of a nucleon

* Recall: quark and gluon Contributions to the nucleon's spin

$$\hat{J}^i_{q,g} = \frac{1}{2}\epsilon^{ijk}\int d^3x \left[T^{ok}_{q,g} x^j - T^{oj}_{q,g} x^k \right] \equiv \int d^3x (\vec{x}\times \vec{T}_{q,g}$$

$\uparrow$ energy-momentum tensor

(1) $\Rightarrow$ $J_{q,g}(\mu^2) = \langle P\tfrac{1}{2} | \int d^3x (\vec{x}\times\vec{T}_{q,g})^z | P\tfrac{1}{2} \rangle$

Nucleon's spin: $\frac{1}{2} = J_q(\mu^2) + J_g(\mu^2)$

* $J_{q,g}$ can be extracted from the form factors of $T^{\mu\nu}_{q,g}$:

(2) $$\langle P' | T^{\mu\nu}_{q,g} | P \rangle = \bar{u}(P') \Big[A_{q,g}(t)\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}(t)\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M}$$

$$+ C_{q,g}(t)\Delta^{(\mu}\Delta^{\nu)}\frac{1}{M} \Big] u(P)$$

$\llcorner$ nucleon spin

$\Delta = P' - P$, $t = \Delta^2$, $\bar{P} = (P'+P)/2$

$(\ldots)$ Symmetrize and traceless: $\Delta^{(\mu}\Delta^{\nu)} \equiv \Delta^\mu\Delta^\nu - g^{\mu\nu}$

— Take $\mu = 0$. $\Delta = 0$ (forward limit), integrate 3-space

$\Rightarrow$ Momentum fractions carried by quarks and gluo

$$A_q(0) + A_g(0) = 1$$

— Substitute (2) into (1),

$$J_{q,g} = \frac{1}{2}\left[A_{q,g}(0) + B_{q,g}(0) \right]$$

to find $A(0)$ & $B($

* Relation between the Skewed parton distributions and the form factors of the energy-momentum tensor.

X. Ji, PRL (97)

$$\int_{-1}^{1} dx\, x\left[H_q(x,\xi,t) + E_q(x,\xi,t)\right] = A_q(t) + B_q(t)$$

- Measure the skewed quark distributions in <u>spin-averaged</u> experiments

$\Rightarrow$ Form factors of energy-momentum tensors

- Extrapolate the form factors to $t=0$

$\Rightarrow$ Obtain the total quark (helicity & orbital) contribution to the nucleon spin.

$$J_q = \frac{1}{2}\left[A_q(0) + B_q(0)\right]$$

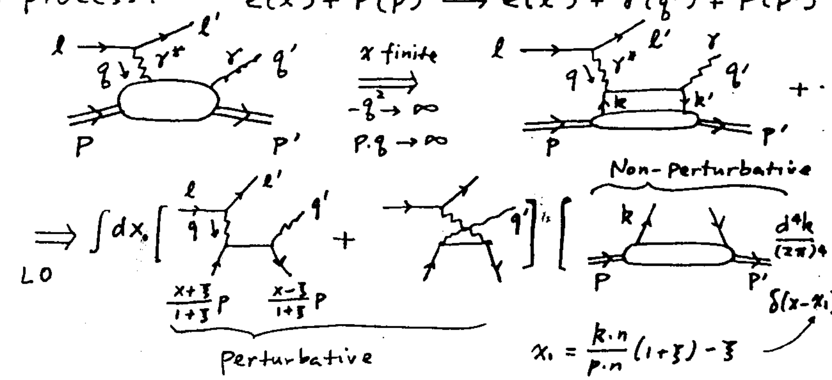
- Similar Sum rule for gluon.

Conclusion: Moments of the skewed parton distributions provide information on quark and gluon contributions to nucleon's spin.

- Deep Virtual Compton Scattering (DVCS):

— Measure the skewed parton distributions

* Process: $e(\ell) + P(p) \longrightarrow e(\ell') + \gamma(q') + P(p')$



* After Separating the spinor trace between the perturbative and the matrix element, DVCS amplitude depends on two off-forward matrix elements:

$F_q(x,\xi,t) \longleftrightarrow$ Same operator for $q(x,\mu^2)$

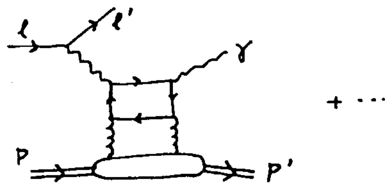
$\tilde{F}_q(x,\xi,t) \longleftrightarrow$ Same operator for $\Delta q(x,\mu^2)$.

* Measurement of DVCS $\Rightarrow$ Extraction of $F_q(x,\xi,t)$ & $\tilde{F}_q(x,\xi,$

Corresponding to $(H_q(x,\xi,t), E_q(x,\xi,t))$ and $(\tilde{H}_q(x,\xi,t)$ & $\tilde{E}_q(x,\xi,$

Their $t\to 0$ limit give J_q.

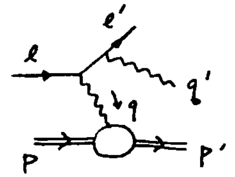
* Small x region for gluon Contributions:



$+ \cdots$

* Very difficult experimentally.

- key background : QED Bethe-Heitler process and its interference with DVCS.



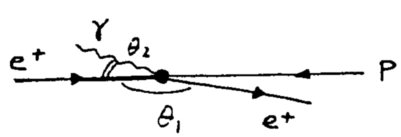
← depend on EM form factors.

- Higher Q^2, Smaller background,

  But, Smaller signal as well.

* First experimental measurement:

$$e^+p \to e^+\gamma p \quad \text{at} \quad ZEUS$$



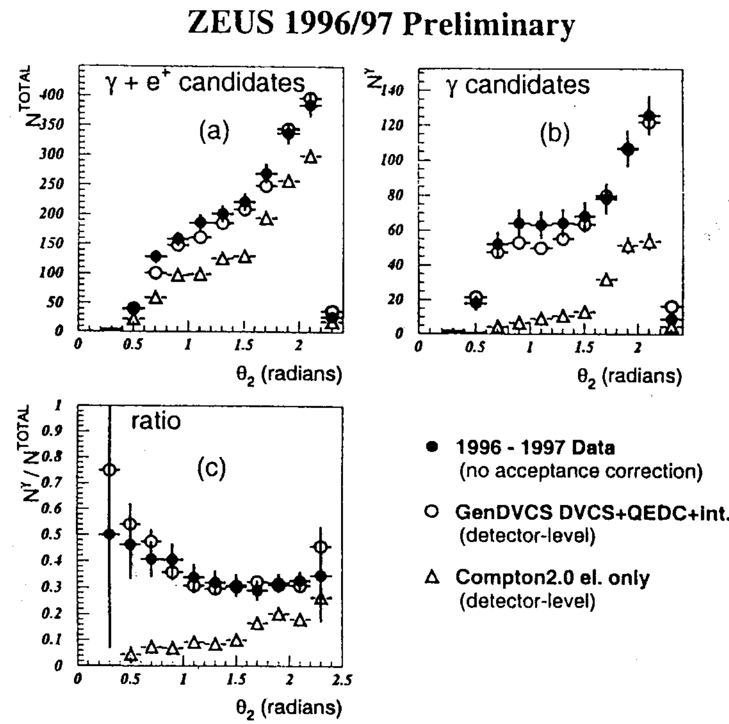


Figure 5: *(a) Distribution of the polar angle, θ_2, of the second EM candidate with energy $E > 2$ GeV; (b) the polar angle distribution for those EM candidates which do not have a track associated with the EM cluster; (c) the ratio of the distributions in (b) and (a). The data are shown as solid points; the (DVCS + QEDC + INT) Monte Carlo simulated events are shown as open circles; and the Compton2.0 Monte Carlo simulated events are shown as open triangles. The Monte Carlo predictions are normalized to the same luminosity as the data.*

ZEUS 1996/97 Preliminary

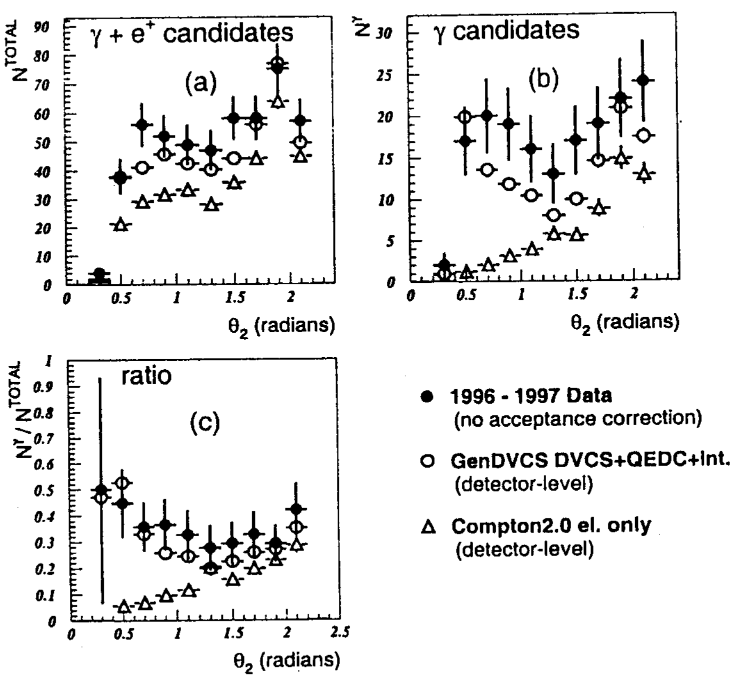


Figure 8: *(a) Distribution of the polar angle, θ_2, of the second EM candidate with energy $E > 5$ GeV; (b) the polar angle distribution for those EM candidates which do not have a track associated with the EM cluster; (c) the ratio of the distributions in (b) and (a). The data are shown as solid points; the (DVCS + QEDC + INT) Monte Carlo simulated events are shown as open circles; and the Compton2.0 Monte Carlo simulated events are shown as open triangles. The Monte Carlo predictions are normalized to the same luminosity as the data.*

4. Multiparton Correlation functions

- Definition:

  Matrix elements with more than Two-field ope

  e.g. $\underbrace{\langle P|\bar\Psi \hat{O} F^{+\alpha} F^{+}_{\alpha}\Psi|P\rangle}_{\text{Four-Field Correlation}}$, $\underbrace{\langle P,S|\bar\Psi \hat{Q} F^{+\alpha}\Psi|P}_{\text{Three-field Corre}}$

  γ matrices

  Provide much richer information than parton dist

- Difficulties:

  * Multiparton Correlation functions Correspond to power suppressed observables ⇒ Smaller ra

  * For a normal observable, multiparton correlatior correspond to power corrections

  ⇒ Hard to compete with the Leading power.

- Way out:

  * Find observables, which have No Leading power t multiparton correlation contribution is the Leadin

  * Identify the part of phase space, such observable are Not too Small.

- Single Spin Asymmetries without parity violation.

  Efremov, Teryaev; Qiu, Sterman; ....

* Processes: $A(P,S_T) + B(P') \longrightarrow C(\ell) + X$

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \llcorner \gamma, \pi, K, \ldots$

* Asymmetry: $A_N \equiv \dfrac{\sigma(S_T) - \sigma(-S_T)}{\sigma(S_T) + \sigma(S_T)}$

$\rightarrow m_q \rightarrow 0$ at scaling limit.

* Existing data from Fermilab:

A_N as large as 30% in forward region

* Beyond Leading power ($1/Q$ in QCD):

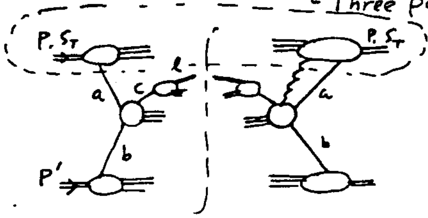
Non-vanishing asymmetry due to interference of a spin $\frac{1}{2}$ quark state and a quark-gluon state.

$\frac{1}{Q}$ Hunpol.

$$E_\ell \frac{d\Delta\sigma(S_\perp)}{d^3\ell} \propto \sum_{a,b,c} T_{a/A} \otimes \varphi_{b/B} \otimes H_{ab\to c} \otimes D_{c\to C} + \cdots$$

$\llcorner \gamma, \pi, K, \cdots$

Three parton correlation.



$\leftarrow T_{a/A}(S_T)$

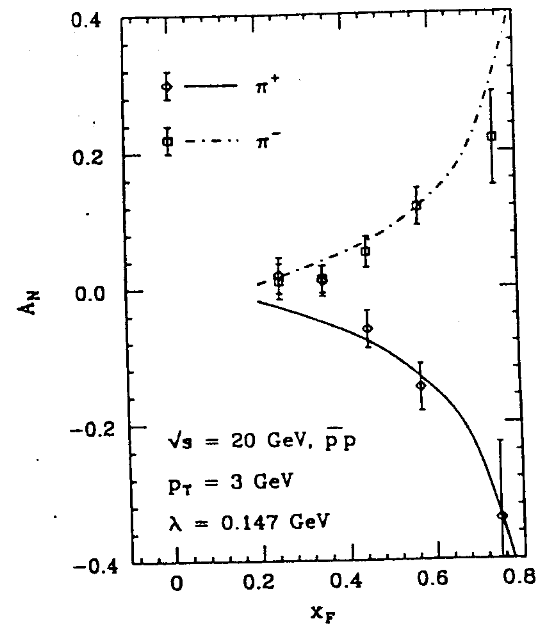
+ c.c.

Qiu & Sterman PRD (99).

* QCD asymmetry grows in forward direction (Large x_F).

$\bar{P}(S_\perp) + P \longrightarrow \pi^\pm + X \quad\quad P_{beam} = 200\,GeV$

Data: A. Bravar et al. PRL 77, 2626 (1996)

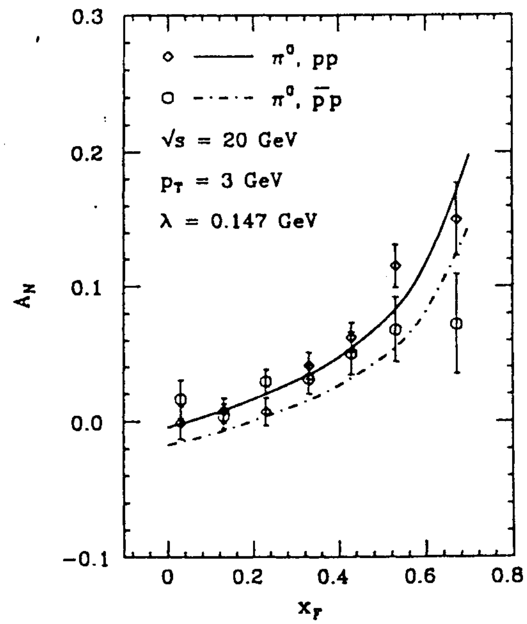


File: bp20_735.pt3

Theory: Qiu & Sterman

$\left.\begin{matrix} P(s_\perp) \\ \bar{P}(s_\perp) \end{matrix}\right\} + P \longrightarrow \pi^0 + X$ $\qquad P_{beam} = 200\,GeV$

Data: D.L. Adams et al. PL B261, 201 (1991)



File: pi20_735.pt3

Theory: Qiu & Sterman

5. Chiral Odd distributions:

- Quark transversity: $\delta q(x, Q^2)$

  quark distribution: $q(x,Q^2) \propto \langle p|\bar{\psi}(0)\gamma\cdot n\,\psi$

  polarized quark dis.: $\Delta q(x,Q^2) \propto \langle P,S|\bar{\psi}(0)\gamma\cdot n\gamma_5$

  transversity distri.: $\delta q(x,Q^2) \propto \langle P,S_\perp|\bar{\psi}(0)\underbrace{\gamma\cdot n\gamma_\perp}_{even}\psi$

- Chiral odd distributions have to appear as a pair.

  chiral odd ⊗ chiral odd.

  * Transversely polarized Drell-Yan at PP collid Ralston

  $A(P,S_T) + B(P,S_T') \longrightarrow \ell\ell'(Q^2) + X$

  $\Rightarrow A_{NN} \propto \delta q(x_1) \otimes \delta q(x_2)$

  * Inclusive pion production in Single transverse [Jaffe,

  $e(k) + P(P,S_T) \longrightarrow e(k') + \pi(\ell) + X$

  $\Rightarrow A_N \propto \delta q(x) \otimes e_\pi(z)$ chiral odd ⊗ c

  Nonvanish A_N observed at HERMES hep-ex/9910062 $\quad + g_T(x) \otimes D_\pi(z)$ chiral even ⊗ e

  $e_\pi(z)$: Chiral odd twist-3 quark to π fragme

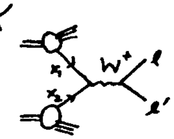
  $g_T(x)$: Chiral even twist-3 distribution.

  Difficulty: Separation between two Contribution

6. Spin at RHIC

- DIS alone does not provide enough information to separate the different flavor distributions.
- RHIC can have polarized proton-proton Collision, Which provides complementary information for extracting polarized distributions.
- Parity violating Single spin Asymmetries : A_L

  * $A(P, S_L) + B(p') \longrightarrow W^{\pm} (\text{or } Z^0) + X$

  * $A_L^{PV}(W^+) \propto \dfrac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$

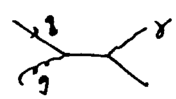
  * Forward Region : $x_1 \gg x_2 \Rightarrow A_L^{PV}(W^+) \sim \dfrac{\Delta u(x_1)}{u(x_1)}$

  $A_L^{PV}(W^-) \sim \dfrac{\Delta d(x_1)}{d(x_1)}$

  Backward Region: $x_1 \ll x_2 \Rightarrow A_L^{PV}(W^+) \sim -\dfrac{\Delta\bar{d}(x)}{\bar{d}(x_1)}$

- Direct Photon : A_{LL} $\quad A(P,S_L) + B(P',S_L') \longrightarrow \gamma(\ell) + X$

  Compton Dominated:

  $+ \cdots$

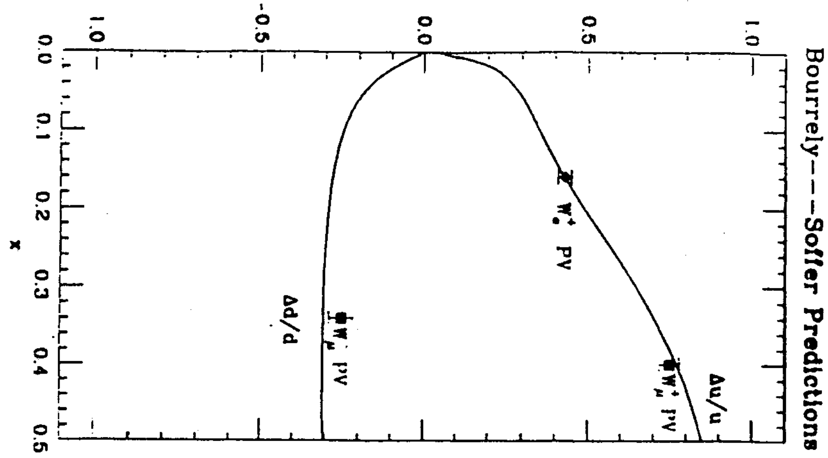
  $$A_{LL} \propto \frac{g_1(x_1)\,\Delta G(x_2)}{F_1(x_1)\,G(x_2)} + x_1 \leftrightarrow x_2$$

- Drell-Yan, jets, ...

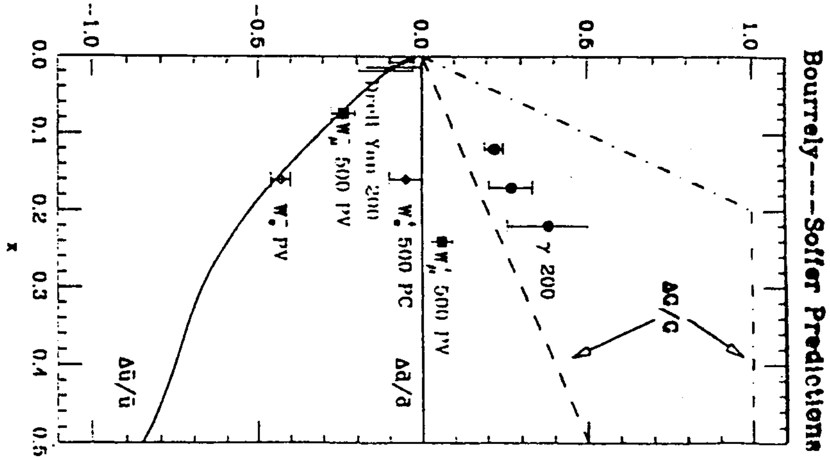
Channel	PHENIX	STAR	Typical B.G.
$ud \to W^+ \to e^+\nu$	15k	72k	5%(Z^0)
$ud \to W^+ \to \mu^+\nu$	6k x_{bj} sensitive		8%(Z^0)
$d\bar{u} \to W^- \to e^-\nu$	2.5k	21k	5%(Z^0)
$d\bar{u} \to W^- \to \mu^-\nu$	5k x_{bj} sensitive		10-20%
$q\bar{q} \to Z^0 \to l^+l^-$	e^+e^-: 120 $\mu^+\mu^-$: 700	4200	$\sim 0\%$ $\sim 0\%$
$q\bar{q} \to \gamma^* \to l^+l^-$	$\mu^+\mu^-$: 30k $9 < M < 12GeV$	e^+e^-: 37k $9 < M < 12GeV$	$\sim 0\%$
$q + g \to \gamma + q$	120k EMcal:$\Delta\eta = 0.01$ $p_t < 25GeV$ resolve π^0	300k Shower max $p_t < 20GeV$	10-20%
γ+jet	15% away jet efficiency	100k $G(x), x < 0.2$	$\sim 0\%$
$x + x \to jet + jet$	π^0 as leading particle	single:10^9 pair: 10^7 $p_t > 10GeV$	$\sim 0\%$ $\sim 0\%$
$g + g \to b\bar{b}/c\bar{c}$	200k $J/\psi \to e^+e^-$ 1M $J/\psi \to \mu^+\mu^-$ 25k $\Upsilon \to \mu^+\mu^-$ 6M $b \to \mu\nu$ @500GeV 6M $c \to \mu\nu$ @200GeV	e^+e^- sizable trigger high Pt	

Table 6: RHIC spin physics at a glance, RHIC-year-yield of the signals and typical backgrounds are shown for both detectors.

Δq/q---assume known from DIS



ΔG/G or $\Delta\bar{q}/\bar{q}$ to be measured



7. Conclusions.

- Spin dependence of parton distributions give fundamental information on nucleon structur
- It is Not impossible to answer the question What carries the spin of a nucleon.
- Spin program has potential to be an experimental benchmark for any theory of nucleon structure.
- Spin programs in DIS have provided a lot of valuable information on polarized parton distributions, and the test of QCC such as the Bjorken Sum Rule.
- RHIC Spin program will provide much mor useful information in next 10 years.