Applications of symmetry breaking in determining PDFs of the nucleon

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1. Symmetries in the PDFs
   - flavour symmetry, quark-antiquark symmetry
   - charge symmetry

2. Symmetry breaking in the meson cloud model

3. Strange distributions of the nucleon

4. Spin dependent structure functions

5. Summary
1. Introduction

Parton Distribution Functions (PDFs) of the Nucleon

\[ q(x, Q^2) = q^\uparrow(x, Q^2) + q^\downarrow(x, Q^2) \quad \text{unpolarized PDFs} \]
\[ \Delta q(x, Q^2) = q^\uparrow(x, Q^2) - q^\downarrow(x, Q^2) \quad \text{polarized PDFs} \]

\( q^\uparrow(x), q^\downarrow(x) \): number densities of quarks whose spin orientation is parallel (antiparallel) to the longitudinal spin direction of the proton

\( x \): the fractional parton momentum

- Non-perturbative inputs in higher-energy hadron processes
- The LHC will measure the PDFs in as yet unexplored kinematic regions of small \( x \) and high \( Q^2 \).
- Understanding the PDFs are important to the discovery of New Physics at the LHC.
Parton Distribution Functions of the Nucleon

• Determined via a global fit of experimental data
  – Certain function forms are assumed at an initial scale (but not in neutral network methods)
  – QCD evolution equations give PDFs at different scales
  – Comparing theoretical calculations with experimental measurements for various processes
• Can be calculated using various quark models
• Distributions for the sea quarks are not well determined

Sea quarks: $\bar{u}, \bar{d}, s, \bar{s}, c, \bar{c}, b, \bar{b}$
Generation of the nucleon sea

Perturbative mechanism for the nucleon sea

1. Introduction

Flavour symmetry

\[ u = d \]

Quark-antiquark symmetry

\[ q = \bar{q} \]

Charge symmetry

\[ d^p = u^n \]
\[ u^p = d^n \]

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1. Introduction

Non-perturbative mechanism for the nucleon sea

→ Meson cloud model \(|\pi^+ n\rangle > |\pi^- \Delta^{++}\rangle\)

→ Pauli blocking

→ Chiral perturbation theory

\[ u \to d \pi^+, \quad d \to u\pi^- \]

→ Chiral quark-soliton model

\[ \bar{d} - \bar{u} = N_c f(xN_c) \]

→ Instanton model

→ Isospin breaking
2. Symmetry breaking in the meson cloud model

Meson Cloud Model

\[
|p\rangle_{\text{phys}} = |p\rangle_{\text{bare}} + |n\pi^+\rangle + |\Delta^{++}\pi^-\rangle + |\Lambda K^+\rangle + \cdots
\]

-- Fock state expansion of proton’s wave function

- The photons may ‘see’ the anti-quarks in the mesons.
- Observed PDFs:

\[
q_{\text{phys}} = q_{\text{bare}} + \delta q \quad \text{with} \quad \delta q = \int_x^1 \frac{dy}{y} f_{BM}(y) q^{B(M)}(\frac{x}{y})
\]
• Each NBM vertex is described by an effective Lagrangian
e.g. \[ L = i g_{NN\pi} \overline{N} \gamma_5 \pi N \] for the \( NN\pi \) vertex

• \( f \) is calculated using time-order perturbative theory (TOPT) in the infinite momentum frame

\[ f_{BM}(y) = \sum_{\lambda\lambda'} \int_0^\infty dk_\perp^2 \left| \phi_{BM}(y, k_\perp^2) \right|^2, \quad \phi_{BM}(y, k_\perp^2) \propto V_{IMF}(y, k_\perp^2) G(y, k_\perp^2) \]

Phenomenological form factor

• Prescriptions for \( q_B(M) \)

→ Bag model calculations

→ Ansatz based on lattice calculations

\[ \int_0^1 \Delta V_\rho(x) dx = 0.6 \int_0^1 V_\rho(x) dx \]

→ \( \Delta V_\rho = 0.6 V_\rho = 0.6 V_\pi \)

→ SU(3) symmetry

\[ S^\Lambda = S^\Sigma = \frac{1}{2} u^N \]
Mechanism for symmetry breaking:

Probabilities are different;

PDFs of meson and baryon are different

\[ q_{phys} = q_{bare} + \delta q \quad \text{with} \quad \delta q = \int_x^1 \frac{dy}{y} f_{BM}(y) q_{BM}^{B(M)}(\frac{x}{y}) \]

Possible symmetry breaking:

1. Flavor symmetry breaking
2. Quark-antiquark symmetry breaking
3. Charge symmetry breaking
2. Symmetry breaking in the meson cloud model

Flavor symmetry breaking

• SU(2) flavour asymmetry in the unpolarized nucleon sea is well established

\[ \text{Prob}(p \rightarrow n \pi^+(u\bar{d})) > \text{Prob}(p \rightarrow \Delta \pi^0(\bar{u}d)) \Rightarrow \bar{d} > \bar{u} \]
Flavour asymmetry in the unpolarized nucleon sea


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Flavor symmetry breaking

Flavour asymmetry in the unpolarized nucleon sea

Data from Phys. Rev. D64 (2001) 052002

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Flavor symmetry breaking

• SU(2) flavour asymmetry in the unpolarized nucleon sea is well established

\[ \text{Prob}(p \rightarrow n \pi^+(ud)) > \text{Prob}(p \rightarrow \Delta \pi^0(\bar{u}d)) \Rightarrow \bar{d} > \bar{u} \]

• Possible SU(2) flavour asymmetry in the polarized nucleon sea?

• The extent of SU(3) flavour symmetry breaking

Common practice in most global QCD analyses of PDFs is

\[ s(x) + \bar{s}(x) = r\left[ \bar{u}(x) + \bar{d}(x) \right] \text{ with } r = 0.50 \ (\text{CTEQ6.5M}) \]

while \( r = 1.0 \) under SU(3) symmetry and \( q - \bar{q} \) symmetry.

Direct experimental evidence for the value of \( r \) is very weak.
SU(2) flavour asymmetry in the polarized nucleon sea
SU(3) flavour asymmetry in the unpolarized nucleon sea

\[ x \Delta(x) = x[\bar{d}(x) + \bar{u}(x) - s(x) - \bar{s}(x)] \]

CTEQ65S [JHEP 0704 : 089, 2007]:

\( s(x) + \bar{s}(x) \) has different shape from \( \bar{d}(x) + \bar{u}(x) \)

HERMES[PLB666(2008)446 also arXiv : 0803.2993]:

a measurement of \( s(x) + \bar{s}(x) \) and \( \Delta s(x) + \Delta \bar{s}(x) \)

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H. Chen, F.-G., A.I., Signal,
JPG37(2010) 105006

Early refs. e.g.,
S. Kumano,
PRD43(1991)59

Flavor symmetry breaking
SU(3) flavour asymmetry in the polarized nucleon sea
Quark-antiquark symmetry breaking

Strange-antistrange asymmetry and the measurement of $\sin^2 \theta_W$

NuTeV (2002): $0.2277 \pm 0.0013 \text{(stat)} \pm 0.0009 \text{(syst)}$

World Average: $0.2227 \pm 0.0004$

2% difference $\Rightarrow 3\sigma$ discrepancy $\Rightarrow$

The probability that it is consistent with the expected result is only about 1 in 400

NuTeV anomaly: Tony Thomas’ talk on Thursday
Quark-antiquark symmetry breaking

Strange-antistrange asymmetry and the measurement of $\sin^2 \theta_W$

NuTeV (2002): $0.2277 \pm 0.0013\,(\text{stat}) \pm 0.0009\,(\text{syst})$

World Average: $0.2227 \pm 0.0004$

2% difference $\Rightarrow 3\sigma$ discrepancy

\[ \sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} \]

\[ M_Z = 91.1882 \pm 0.0022 \]

$\leftarrow M_W = 80.451 \pm 0.033$

$\leftarrow M_W = 80.136 \pm 0.084$

* Preliminary

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• How to extract? Paschos-Wolfenstein ratio

\[ R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \frac{1}{2} - \sin^2 \theta_W \equiv \]

\[ \begin{array}{c}
\nu \\
\downarrow \\
Z \\
\uparrow \\
\nu \\
\hline
q \\
\quad \\
\quad
\end{array} 
\quad 
\begin{array}{c}
\bar{\nu} \\
\downarrow \\
Z \\
\uparrow \\
\bar{\nu} \\
\hline
q \\
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\end{array} 
\quad 
\begin{array}{c}
\nu \\
\downarrow \\
W^+ \\
\uparrow \\
\mu^- \\
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q \\
\quad \\
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\end{array} 
\quad 
\begin{array}{c}
\bar{\nu} \\
\downarrow \\
W^- \\
\uparrow \\
\mu^+ \\
\hline
q' \\
\quad \\
\quad
\end{array} 
\quad 
\begin{array}{c}
q \\
\quad \\
\quad
\end{array} \]
• QCD corrections to the Paschos-Wolfenstein ratio

\[ R^- = \frac{\sigma^\nu_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^\nu_{CC} - \sigma^{\bar{\nu}}_{CC}} = \frac{1}{2} - \sin^2 \theta_W + 1.3 \left[ \frac{1}{2} (\langle \delta u \rangle - \langle \delta d \rangle) - (\langle s \rangle - \langle \bar{s} \rangle) \right] \]

\[ \delta u = u^p - d^n; \quad \delta d = d^p - u^n \quad \text{Charge symmetry breaking} \]

\[ \langle s \rangle = \int_0^1 dx \ x \ s(x); \quad \langle \bar{s} \rangle = \int_0^1 dx \ x \ \bar{s}(x) \quad \text{s-sbar asymmetry} \]

[ … ]=−0.0038 is needed to explain the NuTeV anomaly

• No well established experimental evidence for these symmetry breakings

• Models to break these symmetries are known, e.g. the Meson Cloud Model

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Strange-antistrange asymmetry: unpolarized nucleon sea

- No net strangeness: \( \int_0^1 dx \, s(x) = \int_0^1 dx \, \bar{s}(x) \)


\[
x \, s = \kappa \frac{u + d}{2} (1 - x)^\alpha, \quad x \, \bar{s} = \kappa^* \frac{\bar{u} + \bar{d}}{2} (1 - x)^{\bar{\alpha}}
\]

\( \Rightarrow \) No evidence for \( s(x) \neq \bar{s}(x) \)

- NuTeV (PRD 64 (2001) 112006)

\[
\langle s \rangle - \langle \bar{s} \rangle = -0.0004
\]

\[
\langle s \rangle - \langle \bar{s} \rangle = -0.0008
\]

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Quark-antiquark symmetry breaking


\[ s_-(x, Q_0) = s_+(x, Q_0) \frac{2}{\pi} \tan^{-1} \left[ c x^a (1 - \frac{x}{b}) e^{dx + ex^2} \right] \]

\[-0.001 < \langle x \rangle_{s_-} < 0.005\]

Large experimental uncertainties
Strange-antistrange asymmetry: unpolarized nucleon sea

• MCM calculation: \( p \rightarrow \Lambda K; \Sigma K; \Lambda K^*; \Sigma K^* \)

Prescription for the PDFs: \( s^\Lambda, s^\Sigma, s^K \)

\[ \rightarrow \text{Bag model calculations suggest} \quad s^\Lambda \neq s^\Sigma \neq \frac{1}{2} u^N \]

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Strange-antistrange asymmetry: unpolarized nucleon sea

- Contributions from $p \to \Lambda K^*; \Sigma K^*$
  
  Expected to be suppressed due to higher mass of $K^*$

- Fluctuation functions

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Strange-antistrange asymmetry: unpolarized nucleon sea

\[ \langle s \rangle - \langle \bar{s} \rangle = 0.00014 \quad \text{including only K} \]

\[ \langle s \rangle - \langle \bar{s} \rangle = -0.00014 \quad \text{including K+K*} \]

- Contributions from fluctuations involving K* are important
Strange-antistrange asymmetry: polarized nucleon sea

- Fluctuation functions

\[
\Delta f_{K^* \Lambda/N} + \Delta f_{K^* \Sigma/N} + \Delta f_{\Lambda K/N} + \Delta f_{\Sigma K/N} \]

Quark-antiquark symmetry breaking
Strange-antistrange asymmetry: polarized nucleon sea

- Strange-antistrange symmetry is broken in the polarized nucleon sea.

\[ \frac{1}{2} (\Delta s + \Delta \bar{s}) \]

Hermes (preliminary)
Strange-antistrange asymmetry: polarized nucleon sea

- Strange-antistrange asymmetry is more significant in the polarized nucleon sea than that in the unpolarized nucleon sea.
Charge symmetry breaking in the PDFs

- Definitions

\[ \delta u_V = u_V^p - d_V^n ; \quad \delta d_V = d_V^p - u_V^n ; \]
\[ \bar{\delta} u = \bar{u}_V - \bar{d}_V ; \quad \delta \bar{d} = \bar{d}_V - \bar{u}_V ; \quad \delta s = s^p - s^n ; \quad \delta \bar{s} = \bar{s}^p - \bar{s}^n \]

Tim Londergan (next talk):
CSB in spin distributions
Charge symmetry breaking in the PDFs

- Definitions

\[
\delta u_V = u^p_V - d^n_V; \quad \delta d_V = d^p_V - u^n_V; \\
\delta \bar{u} = \bar{u}^p_V - \bar{d}^n_V; \quad \delta \bar{d} = \bar{d}^p_V - \bar{u}^n_V; \quad \delta s = s^p - s^n; \quad \delta \bar{s} = \bar{s}^p - \bar{s}^n
\]

- CS is universally assumed in the quark phenomenology

- Nuclear physics: 1%

- EW interaction: \( \frac{m_d - m_u}{M} = \frac{3 \sim 5 \text{MeV}}{0.5 \sim 1 \text{GeV}} < 1\% \)
Quark model calculations:

EW interaction; mass differences of the struck quark; mass differences of the di-quark; quark wavefunction

(Ref: Prog. Par. Nucl 41 (1998) 41; Londegran and Thomas)
• MCM calculation for the charge symmetry breaking

\[ d^p = d^p_{\text{bare}} + d^p_{\text{per.}} + d^p_{\text{non}}; \quad u^n = u^n_{\text{bare}} + u^n_{\text{per.}} + u^n_{\text{non}}; \]

\[ \bar{d}^p = \bar{d}^p_{\text{per.}} + \bar{d}^p_{\text{non}}; \quad \bar{u}^n = \bar{u}^n_{\text{per.}} + \bar{u}^n_{\text{non}}; \]

\[ \downarrow \quad d^p_{\text{per.}} = \bar{d}^p_{\text{per.}}; \]

\[ d^p_V = d^p_{\text{bare}} + d^p_{\text{non}} - \bar{d}^p_{\text{non}}; \quad u^n_V = u^n_{\text{bare}} + u^n_{\text{non}} - \bar{u}^n_{\text{non}}; \]

\[ \delta d^p_V = \left[ d^p_{\text{bare}} - u^n_{\text{bare}} \right] + \left[ \left( d^p_{\text{non}} - \bar{d}^p_{\text{non}} \right) - \left( u^n_{\text{non}} - \bar{u}^n_{\text{non}} \right) \right]; \]

\[ \uparrow \quad \text{Calculated with quark models} \]

\[ \uparrow \quad \text{Calculated with the Meson cloud model} \]
Charge symmetry breaking

- MCM calculation for the charge symmetry breaking

Fluctuations considered include:

\[ p \rightarrow n \pi^+; \quad n \rightarrow p \pi^-; \quad m_p - m_n = -1.3 \text{MeV}, \]

\[ p \rightarrow \Delta^0 \pi^+; \quad n \rightarrow \Delta^+ \pi^-; \quad m_{\pi^\pm} - m_{\pi^0} = 4.6 \text{MeV}, \text{etc} \]

\[ p \rightarrow \Lambda K^+; \quad n \rightarrow \Lambda K^0 \]

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Charge symmetry breaking in the valence quarks

\[ \delta u_V = u_V^p - d_V^n, \quad \delta d_V = d_V^p - u_V^n; \]

\[ R_{\text{min}} = \frac{\delta d_V}{d_V}, \quad R_{\text{maj}} = \frac{\delta u_V}{u_V}; \]

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Charge symmetry breaking in the sea quarks

\[
\delta u = u_V - d_V; \quad \delta d = d_V - u_V; \quad \delta s = s^p - s^n; \quad \delta \bar{s} = \bar{s}^p - \bar{s}^n
\]

Meson cloud contributions to the CSV are much smaller than that calculated with quark models.

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3. Strange sea distributions

Strange sea distributions are not well determined compared with the valence distributions and light quark sea.
Strange sea distributions

CTEQ6.5S [H. L. Lai et. al, JHEP 0704:089 (2007)]

\[ s_{\pm}(x, Q_0) = s(x, Q_0) \pm \bar{s}(x, Q_0) \]

\[ s_+(x, Q_0) = A_0 x^{A_1} (1 - x)^{A_2} \]

\[ A_1^{s_+} = A_1^{(\bar{u} + \bar{d})_+} \text{ is assumed} \]

\[ A_0 \text{ is related to suppression factor} \]

\[ r = \frac{\langle x \rangle_{s_+}}{\langle x \rangle_{\bar{u}(x) + \bar{d}(x)}} \]

Light sea is almost unchanged while \( s_+(x) \) becomes smaller and softer compared to CTEQ6.5M.

\[ r = 0.44 \text{ (CTEQ6.5S)} \text{ vs. } 0.50 \text{ (CTEQ6.5M)} \]

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• Allowed range for $s_+(x)$

Momentum fraction
$0.018 < \langle x \rangle < 0.040$;
Different parameterizations
Strange sea distributions

$$x s_+ (x) = \left[ \bar{d} (x) + \bar{u} (x) \right]_{\text{Fit}} - x \Delta (x)_{\text{MCM}}$$

NLO analysis of NuTeV data PRL99(2007)192001

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The suppression factor \( r(x) = \frac{s(x) + \overline{s}(x)}{\overline{d}(x) + \overline{u}(x)} \)

Strange sea distributions

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4. Spin Dependent Structure Functions

\[ g_1(x, Q^2) = \sum_q e_q^2 \left[ \Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2) \right] \]

- Dominated by valence distributions
  \[ N \rightarrow N\pi, N \rightarrow \Delta\pi \] most important fluctuations

\[ \mathcal{L}_{int} = ig_{NN\pi} \bar{\psi} \gamma_5\pi\psi, \ f_{N\Delta\pi} \bar{\psi}\pi \partial_\mu \chi^\mu + h.c. \]

- At finite \( Q^2 \) spin of cloud hadrons are not parallel with initial nucleon spin

- Both longitudinal and transverse spin components of cloud contribute to observed structure functions
Spin Dependent Structure Functions

\[
\delta g_1(x, Q^2) = \frac{1}{1 + \gamma^2} \int_x^1 \frac{dy}{y} \left( [\Delta f_{1L}(y) + \Delta f_{1T}(y)] g_1^B \left( \frac{x}{y}, Q^2 \right) + [\Delta f_{2L}(y) + \Delta f_{2T}(y)] g_2^B \left( \frac{x}{y}, Q^2 \right) \right)
\]

\[
\delta g_2(x, Q^2) = -\frac{1}{1 + \gamma^2} \int_x^1 \frac{dy}{y} \left( [\Delta f_{1L}(y) - \Delta f_{1T}(y)/\gamma^2] g_1^B \left( \frac{x}{y}, Q^2 \right) - [\Delta f_{2L}(y) - \Delta f_{2T}(y)/\gamma^2] g_2^B \left( \frac{x}{y}, Q^2 \right) \right)
\]

\[
\gamma^2 = \frac{4x^2 m_N^2}{Q^2}
\]
Spin Dependent Fluctuations

- Long. fluctuations require both $N$ and $\Delta$
- $s = 3/2$ state important

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Spin Dependent Fluctuations

N is more important for transverse fluct.

n.b $\gamma \approx 0.19$
‘Bare’ Hadron SFs

- Use bag model for N, Δ parton distributions
  - Add Δg(x) ‘by hand’
  - Hyperfine splitting between N and Δ
- Use NLO evolution
- Unpol. dists agree with DIS data
- $g_2(x)$ from Wandzura-Wilczek

\[ g_2^{WW}(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y) \]

- No higher twist component
‘Bare’ Nucleon $g_1(x)$

- Data from Hermes

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Spin Dependent Structure Functions

‘Bare’ Nucleon $g_2(x)$

$x^2g_2$ (proton), $Q=2$ GeV

$x^2g_2$ (neutron), $Q=2$ GeV

- Data from E155, Jlab E-99-117

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‘Bare’ Hadrons $\Delta$ and $\rho$, $g_1(x)$ and $g_2(x)$

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The results for the neutron are very similar

$\Delta f_{1T}, \Delta f_{2L}, \Delta f_{2T}$ are important to $g_2^p$ and $g_2^n$
MC Contributions to $g_1^p$ and $g_1^n$

- $\Delta \pi$ is important while $N\rho$ is not
- $\Delta \pi$ increases $g_1^p$ more than that for $g_1^n$

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MC Contributions to $g_2^p$ and $g_2^n$

- $\Delta\pi$ is important
- $\Delta\pi$ affects $g_2^p$ more than that for $g_2^n$

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Comparison with data: $g_2^p$ and $g_2^n$

- 20~30% corrections from MC
- Improve the agreement with the experiment

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Nucleon spin

- Sea quarks also contribute to the nucleon spin

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g
\]

\[
\Delta \Sigma = \Delta U + \Delta D + \Delta \bar{U} + \Delta \bar{D} + \Delta S + \Delta \bar{S}
\]

\[
\Delta \Sigma \approx 0.3 \text{ from DIS}
\]

Bjorken sum rule

\[
S_B = \int_0^1 dx \left[ g_1^p(x) - g_1^n(x) \right]
\]

\[
= \frac{1}{6} \int_0^1 dx [\Delta u(x) - \Delta d(x)] + \frac{1}{6} \int_0^1 dx [\Delta \bar{u}(x) - \Delta \bar{d}(x)]
\]

Ellis-Jaffe sum rule

\[
S_{EJ} = \int_0^1 dx g_1^p(x) = \frac{1}{2} \sum_q e_q^2 \int_0^1 dx [\Delta q + \Delta \bar{q}(x)]
\]

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Nucleon spin

- Nucleon spin decomposition

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g
\]

Certainly not trivial and/or purely academic

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L'_q + L'_g
\]

What processes can be used to measure the OAMs of the quark and gluon?

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L''_q + L''_g
\]

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5. Summary

1. Non-perturbative QCD models for the nucleon structure can make reliable predictions for the symmetry breaking effects.

2. Strange sea distributions are not well constrained.

3. Combining the MCM calculations for the SU(3)$_f$ breaking effect with global analysis results for the light quark sea, we estimated the total strange sea distributions. The calculations agree with HERMES results, but not with the NLO analysis of NuTeV dimuon data.

4. Possible strange-antistrange asymmetry is of great interest.

5. MC contributions to $g_1$ are small and to $g_2$ are 20%.