Neutrino Scattering Physics
at
Neutrino Factories
**Neutrino Scatterings Topics at NuFact03**

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<td>11:00 G. Zeller</td>
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<td>12:00 K. McFarland</td>
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| | **Deep Inelastic Scattering** |
|-----------------|
| 14:00 U. Yang | Unified approach for modelling neutrino deep inelastic cross section from very high Q^2 |
| 14:30 F. Sergiampietri | Near liquid argon detector for near future |
| 15:00 B. Bernstein | NuTeV Structure Functions: Preliminary Results and Future Work |
| 15:30 Coffee |

| | **sin^2\theta_W: Recent Results and Future Measurements** |
|-----------------|
| 16:00 I. Younus | First Results from SLAC E-158: Measuring Parity Violation in Moller Scattering: [PPT](#), [PDF](#) |
| 18:30 P. Reimer | DIS-Parity: Measuring sin^2\theta_W with Parity Violating Deep Inelastic Scattering: [PPT](#), [PDF](#) |
| 17:00 J. Yu | Precision Measurement of sin^2\theta_W in the NuTeV Far Detector: [PPT](#), [PDF](#) |

**sin^2\theta_W anomaly**

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**Strangeness**

**Deep Inelastic Scattering**

**Cross Section**

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**Form Factors**
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<td>Nuclear modification of valence quark distributions and its effects on</td>
<td>S.Kumano (Saga)</td>
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<td>Study of strange quark in the nucleon with neutrino scattering</td>
<td>J.Morfin (FNAL)</td>
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<td>APS Study on Physics with Beta Beams and neutrino factory</td>
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Contents of this presentation

• **Lepton Scattering and Nucleon Structure:**
  - Structure Function and Form Factor

• **What we know about Structure Functions:**
  - Unpolarized structure function and parton distributions
  - Polarized structure function and parton distributions

• **What we know about Form Factors:**
  - Electric, Magnetic and Axial Form Factors
  - Strange Form Factors

• **Generalized Parton Distribution Function:**
  - Deeply Virtual Neutrino Scattering
**Structure Function:**
Hard scattering with parton in nucleon
Deep Inelastic Scattering regime
$(Q^2 > 1\, \text{GeV}^2 \text{ and } W^2 > 10\, \text{GeV}^2)$
Probability distribution of parton
which carries momentum fraction $x$ of nucleon:
with transverse size of $1/Q^2$

**Form Factor:**
Elastic, inelastic scattering
With momentum transfer "t"
$F(t) \leftrightarrow \rho(r)$
Charged Lepton / Neutrino Scattering

- **Charged lepton scattering:**
  - Through electric charge squared
    - can not distinguish quark and anti-quark
  - Flavor study requires additional information
    - from the other experiments
    - Flavor tagging with hadron coincidence measurement

- **Neutrino Scattering:**
  - Interaction through weak charge
  - Left-right handedness
    - quark anti-quark, flavor, spin structure
Structure Function

$q(x)$

$Q^2$

$1/Q$
Structure Function

Quark Parton Model:

\[ F_2^\gamma(x) = x \sum_q e_q^2 (q(x) + \bar{q}(x)) \]
\[ F_2^Z(x) = x \sum_q \left( (g_V^q)^2 + (g_A^q)^2 \right) (q(x) + \bar{q}(x)) \]
\[ g_V^q = \pm \frac{1}{2} - e_q \sin^2 \theta_W, \quad g_A^q = \pm \frac{1}{2} \]

Valence Component

\[ F_3^Z(x) = \sum_q 2 g_V^q g_A^q (q(x) - \bar{q}(x)) \]
\[ F_3^{W^+}(x) = 2 (-\bar{u}(x) + d(x) + s(x) - \bar{c}(x)...) \]
\[ F_3^{W^-}(x) = 2 (u(x) - \bar{d}(x) - \bar{s}(x) + c(x)...) \]

Neglecting flavor mixing

\[ \sigma^{l+N \rightarrow l'+X} \]
\[ (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}) F_1(x, Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P \cdot q} F_2(x, Q^2) \]
\[ -i \epsilon_{\mu\nu\alpha\beta} \frac{q^\alpha P^\beta}{2 P \cdot q} F_3(x, Q^2) \]
Structure functions in PDG


Proton

$F_2(x,Q^2) + c(x)$

- **H1**
- **ZEUS**
- **BCDMS**
- **E665**
- **NMC**
- **SLAC**

$\nu(x) = 0.3(\nu - 0.4)$

Nucleon (H1)

$Q^2 = 1500$ GeV$^2$
$Q^2 = 5000$ GeV$^2$
$Q^2 = 12000$ GeV$^2$

Nucleon (BCDMS)

$Q^2 = 40-180$ GeV$^2$

Nucleon (CCFR)

$\nu(x) = 0.12(\nu - 1)$

$x = 0.180$
$x = 0.275$
$x = 0.350$
$x = 0.450$
$x = 0.550$
$x = 0.650$
$x = 0.750$
$x = 0.0075$
$x = 0.0125$
$x = 0.0250$
$x = 0.050$
$x = 0.070$
$x = 0.110$
$x = 0.140$
Preliminary NuTeV results:

**DIS2003, hep-ex/0307005**

- \( R(x) \) measurement
- \( \sin^2\theta_W \) anomaly

**Session 2. S. Kumano**
Global QCD fit to available $F_i(x)$

CTEQ, GRV, MRS, ALEKHIN, …
PDF parameterizations are available.

ex.) CTEQ6

Chiral Quark Soliton Model:
Flavor symmetry of light flavor quarks
key for understanding QCD
Parton Distribution Functions

$E_\nu \sim 50 \text{ GeV}$

$Q^2 = 10 \text{ GeV}^2$

$\nu$ factory

S. Kumano @ NuFact03

CTEQ6 PDF (2.5 GeV2)

JHEP 0207:012, 2002

Wakamatsu, hep-ph/0209011

(b) SU(3) CQSM with $\Delta m_s$ correction

MIYACHI Yoshiyuki, Tokyo Institute of Technology
Structure function of Nucleus: S. Kumano @ FuFact03 & NuInt04

can be modified due to nuclear medium effects

Hadron Production: Session 3 & 5@NuInt04

can be differ from in nucleon. (EMC, WA21/59, SLAC, HERMES)
Spin Dependent Structure Functions

\[ \Delta q(x) = q^+(x) - q^-(x) \]

\[ \gamma^*, Z^0, W^\pm \]

\[ \langle F_{1,2,3} \rangle \]

\[ + i \epsilon_{\mu\nu\alpha\beta} \frac{q^\alpha}{P\cdot q} [S^\beta g_1(x, Q^2) + (S^\beta - S\cdot q P^\beta) g_2(x, Q^2)] \]

\[ + \frac{1}{P\cdot q} \left[ \frac{1}{2} (\hat{P}_\mu \hat{S}_\nu + \hat{P}_\nu \hat{S}_\mu) - \frac{S\cdot q}{P\cdot q} \hat{P}_\mu \hat{P}_\nu \right] g_3(x, Q^2) \]

\[ + \frac{S\cdot q}{P\cdot q} \left[ \frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q} g_4(x, Q^2) + (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}) g_5(x, Q^2) \right] \]

Parton Model:

\[
\begin{align*}
g_1^\gamma(x) &= \frac{1}{2} \sum_q e_q^2 (\Delta q(x) + \Delta \bar{q}(x)) \\
g_1^Z(x) &= \frac{1}{2} \sum_q (g_V^q + g_A^q) (\Delta q(x) + \Delta \bar{q}(x)) \\
g_5^Z(x) &= \sum_q g_V^q g_A^q (\Delta q(x) - \Delta \bar{q}(x)) \\
g_1^W^+ &= \Delta \bar{u} + \Delta d + \Delta \bar{c} + \Delta s \\
g_1^W^- &= \Delta u + \Delta \bar{d} + \Delta c + \Delta \bar{s} \\
g_5^W^+ &= \Delta \bar{u} - \Delta d + \Delta \bar{c} - \Delta s \\
g_5^W^- &= -\Delta u + \Delta \bar{d} - \Delta c + \Delta \bar{s}
\end{align*}
\]

EMC "Spin Puzzle":


\[
\Delta \Sigma = \int dx |\Delta u + \Delta d + \Delta s| \sim 0.2
\]
Spin Dependent Structure Functions

\[ \Delta \Sigma = \int dx \left( \Delta u + \Delta d + \Delta s \right) \sim 0.2 \]
\[ \Delta G = \int dx \Delta g(x) \gg 0 \]
\[ \Delta s = \int dx \Delta s(x) \sim -0.1 \]
Semi-inclusive DIS measurement

\[ d \sigma_h \propto \sum_q e_q^2 q(x) D_q^h(z) \]

produced hadron carries flavor information of quark involved to scattering through the fragmentation process

Longitudinally Polarized beam and target:

- \( e \): 27.6 GeV

\( e + N \rightarrow e' + h + X \)
Helicity Distribution from SIDIS

HERMES, hep-ex/0407032

Results from 5 flavor extraction:

assuming $\frac{\Delta \bar{s}}{\bar{s}} = 0$

Δs = 0 within errors

Contribution from low-x can amount ~30% of total integral assuming shape of PDF as done in QCD fit

Δu = 0.601 ± 0.039 ± 0.049
Δ\bar{u} = -0.002 ± 0.036 ± 0.023
Δd = -0.226 ± 0.039 ± 0.050
Δ\bar{d} = -0.054 ± 0.033 ± 0.011
Δs = 0.028 ± 0.033 ± 0.009

$x\Delta s(x)$ and $x\Delta \bar{s}(x)$ at $Q^2 = 1$ GeV$^2$

M. Wakamatsu, hep-ph/0209011

LSS fit
E704 observed **single spin asymmetries** in Transversely polarized (anti-)proton scattering:

\[ \vec{p} + p \rightarrow \pi + X \quad \vec{p} + p \rightarrow \pi + X \]

\[ A_N = \frac{1}{P_B \langle \cos \theta \rangle} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \]

Final state interaction
Transverse spin dependent Fragmentation require transverse motion

**PDFs were extended to have transverse momentum freedom:**

- \( q \): momentum distribution
- \( \Delta q \): helicity distribution
- \( \delta q \): transversity
- \( f^\perp_{1T} \): Siverse

and more ...

**Transversity and Sivers Asymmetries from SIDIS measurement**

Electron scattering off Transversely Polarized Nucleon Target

transverse momentum creates single spin asymmetry in azimuthal angle distribution of hadron production cross section

\[ e + \vec{N} \rightarrow e' + \pi + X \]

\[ A_{UT}^{collins} \propto \delta q \cdot H_q^\pi \]

\[ A_{UT}^{Sivers} \propto f_{1T}^\perp \cdot D_q^\pi \]

**Tensor charge**

**Orbital Angular Momentum**
Form Factor
### Nucleon Form Factors

In DIS regime:

\[
G_M^q = \frac{1}{m} (l_q - l_{\bar{q}}) + \frac{1}{2m} (s_q - s_{\bar{q}}) = \frac{1}{m} l_q + \frac{1}{2m} \delta q
\]

\[
G_A^q = s_q + s_{\bar{q}} = \Delta q
\]

Breit frame

\[
G_E = \frac{1}{2Me} \langle N|J_0|N \rangle \quad \chi_f^\dagger \chi_i \left( F_1 - \frac{Q^2}{4M^2} F_2 \right)
\]

\[
G_M = -\frac{1}{2|\vec{q}|e} \langle N|J_+|N \rangle \quad \chi_f^\dagger \vec{\sigma} \chi_i \times \vec{q} \frac{F_1 + F_2}{2M}
\]

\[
G_A = \langle N|\vec{A}|N \rangle \quad \chi_f^\dagger \vec{\sigma} \chi_i G_A
\]

\text{low momentum transfer limit}

\text{Helicity distribution}

\text{Transversity distribution}

\text{Sivers distribution}

\text{In DIS regime:}

\text{Helicity distribution}
Electromagnetic Form Factor

Cross section measurement:

\[
\frac{d\sigma}{d\Omega} \propto \epsilon G^2_{Ep}(Q^2) + \tau G^2_{Mp}(Q^2)
\]

\[
\epsilon = \left[ 1 + 2(1 + \tau) \tan^2(\theta/2) \right]^{-1}
\]

\[
\tau = \frac{Q^2}{4 M_p^2}
\]

Polarization transfer measurement:

\[
\tilde{e} + p \rightarrow e + \tilde{p}
\]

\[
\frac{\mu_p G_{Ep}}{G_{Mp}} \propto \frac{P_t}{P_l}
\]

Difference can be regarded as contribution from 2 photon exchange
more experimental information are needed
Neutrino scattering data

Next Generation Neutrino beam: R. Gran, J. Monroe, S. Boyd … @ NuInt04

1 Track CC-QE
K2K Preliminary:
\[ M_A = 1.06 \pm 0.03 \pm 0.14 \]

MiniBooNE CC-QE Preliminary

will be discussed in WG1 and WG2
Strange Form Factors
from parity violating electron scattering

Parity Violating Electron Scattering:
SAMPLE, HAPPEX, A4, G0, E91004

\[ A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = \frac{-G_F Q^2 \varepsilon G_E G_E^Z + \tau G_M G_M^Z - (1 - 4 \sin^2 \theta_W) \varepsilon' G_M G_A^e}{4\sqrt{2} \pi \alpha} \]

\[ \varepsilon (G_E^2 + \tau (G_M)^2) \]

\[ \tau = \frac{Q^2}{4 M^2}, \quad \varepsilon = \left( 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right)^{-1} \]

\[ \frac{dG_E^s (Q^2=0)}{dQ^2} = -\frac{1}{6} \rho_s^2, \quad G_M^s (Q^2=0) = \mu_s \]
Strange Axial Form Factor: W.M. Alberico, R. Tayloe@NuFact03, B. Fleming@NuInt04

\[ G_A^s(Q^2=0) = \Delta s \]

NC over CC ratio:

\[ R_{NC/CC}(Q^2) = \frac{(d\sigma/dQ^2)^{NC}_{\nu}}{(d\sigma/dQ^2)^{CC}_{\nu}} \]

Asymmetry:

\[ A(Q^2) = \frac{(d\sigma/dQ^2)^{NC}_{\nu}}{(d\sigma/dQ^2)^{CC}_{\nu}} - \frac{(d\sigma/dQ^2)^{NC}_{\bar{\nu}}}{(d\sigma/dQ^2)^{CC}_{\bar{\nu}}} \]

\[ A_{p(n)} = \frac{1}{4} \left( \frac{G_A^s}{G_A^s} \right) \times \left[ \pm 1 - 2\sin^2 \theta_W \frac{G_M^{p(n)}}{G_M^3} - \frac{1}{2} \frac{G_M^3}{G_M^3} \right] \]

Ratio p/n

\[ R_{p/n}^{NC}(Q^2) = \frac{(d\sigma/dQ^2)^{NC}_{(\nu,p)}}{(d\sigma/dQ^2)^{NC}_{(\nu,n)}} \]

\[ -0.25 \leq G_A^s \leq 0 \]


Session 3. T.-A. Shibata

MIYACHI Yoshiyuki, Tokyo Institute of Technology
Strange Form Factor Extraction

Global analysis using HAPPEX and E734 results:


TABLE II. Two solutions for the strange form factors at $Q^2 = 0.5 \text{ GeV}^2$ produced from the E734 and HAPPEX data.

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<th>Solution 1</th>
<th>Solution 2</th>
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<td>$G^s_E$</td>
<td>0.02 ± 0.09</td>
<td>0.37 ± 0.04</td>
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<tr>
<td>$G^s_M$</td>
<td>0.00 ± 0.21</td>
<td>-0.87 ± 0.11</td>
</tr>
<tr>
<td>$G^s_A$</td>
<td>-0.09 ± 0.05</td>
<td>0.28 ± 0.10</td>
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Generalized Parton Distribution

GPD
**Generalized Parton Distribution Function**

**Hard Exclusive Production:** \( Q^2 > 1 \text{GeV}^2 \)

\[
 l + N \rightarrow l + (\gamma, \pi, \rho, \ldots) + N'
\]

**Form Factors:**

- Dirac: \( \int_{-1}^{1} dx \, H^q(x, \xi, t) = F_1^q(t) \)
- Pauli: \( \int_{-1}^{1} dx \, E^q(x, \xi, t) = F_2^q(t) \)
- Axial vector: \( \int_{-1}^{1} dx \, \tilde{H}^q(x, \xi, t) = G_A^q(t) \)
- Pseudoscalar: \( \int_{-1}^{1} dx \, \tilde{E}^q(x, \xi, t) = h_A^q(t) \)

**Parton Angular Momentum:**

\[
 \int_{-1}^{1} dx \, x \left( H^q + E^q \right) = J^q
\]

\[
 G_M = F_1 + F_2
\]

\[
 H(x, \xi, t) \tilde{N}(P') n \gamma N(P) \quad E(x, \xi, t) \tilde{N}(P') \frac{i \sigma^{\alpha \beta} n_\alpha \Delta_\beta}{2M} N(P) \quad \text{(vector coupling)}
\]

\[
 \tilde{H}(x, \xi, t) \tilde{N}(P') n \gamma_5 N(P) \quad \tilde{E}(x, \xi, t) \tilde{N}(P') \frac{\Delta \cdot n}{2M} \tilde{N}(P') \gamma_5 N(P) \quad \text{(axial vector coupling)}
\]
Deeply Virtual Compton Scattering

\[ e + N \rightarrow e' + \gamma + N' \]

\[ \sigma_{BH} \gg \sigma_{DVCS} \]

DVCS amplitude can be measured through the interference term

\[ A_{LU}(\phi) \propto F \cdot H \sin \phi \]

Beam Spin Azimuthal Asymmetry:

DVCS on Nuclear targets (Ne, N, Kr) have been also measured by HERMES and also studied by A. Kirchner and D. Muller, Eur. Phys. J. C 32 (2004) 347

MIYACHI Yoshiyuki, Tokyo Institute of Technology
Deeply Virtual Neutrino Scattering

\[ \nu + N \rightarrow \nu' + \gamma + N' \]
\[ \nu + A \rightarrow \nu' + \gamma + A' \]

P. Amore et. al, hep-ph/0404121

\[ \alpha(x=0.3) \text{[nb/GeV}^4\text{]} \]

\[ Q^2 \]

comparable to other reactions in QE
\[ \sim 10^{-5} \text{ nb} \]

See also R. Ransome's talk at NuInt04

MIYACHI Yoshiyuki, Tokyo Institute of Technology
Summary (1)

- **Structure function:**
  - have been studied over 3 decades, using both charged lepton and neutrino scattering
  - Valence type structure can be precisely studied at Neutrino Factory together nuclear modification on PDF
  - From pol. semi-inclusive measurement $\Delta s = 0$ within error was obtained
    - Low and high $x$ structure have to be studied experimentally
    - Light flavor quark structure is key

- **Form Factor:**
  - $Q^2$ dependence of Electromagnetic Form Factors
  - Next Generation of neutrino experiments will determine the axial form factor precisely
Summary (2)

• **Strange Form Factors:**
  – Parity violating electron scattering experiments: $G_{E,M}^s$
  – Neutrino scattering data is essential to determine strange axial form factor
  – Global analysis using both information

• **Generalized Parton Distribution Function:**
  – GPD connects structure function and form factor
  – Beam spin azimuthal asymmetry of DVCS has been measured at HERMES and CLAS
  – Deeply Virtual Neutrino Scattering
    • It can be one of applications to be attacked in the future neutrino factories.