High-Energy Hadron Physics at J-PARC

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Riken, Wako, Japan

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(Talk on April 7)
Contents

1. General comments on hadron projects at J-PARC
   Hadron physics with 30 – 50 GeV proton beam

2. Structure functions
   Possible roles of J-PARC projects in
   • Unpolarized and Polarized parton distribution functions (PDFs), Nuclear PDFs
   • Fragmentation functions
   • Tensor structure functions
General comments on J-PARC projects with 30 – 50 GeV proton beam

J-PARC workshops on hadron physics


• J-PARC-NP08, http://j-parc.jp/NP08/

Refs. My talks on “Possible Hadron Physics at J-PARC”

in Trieste (2006)  http://www.pg.infn.it/hadronic06/


Haron Physics at J-PARC

- Strangeness nuclear physics (1st experiment)
- Exotic hadrons
- Hadrons in nuclear medium
- Hard processes (50 GeV recovery)
- Nucleon spin (proton polarization)
- Quark-hadron matter (heavy ion)
Purposes of J-PARC hadron physics

Understanding of strongly interacting matter & Search for new state of matter

Quantum Chromodynamics (QCD)

- Asymptotic freedom, …
  Perturbative QCD, Parton distribution functions, Nucleon spin, …
- Color confinement
  Hadron spectroscopy, Quark-hadron matter
- Chiral symmetry
  Hadrons in nuclear medium
Hadron physics with 30 – 50 GeV proton beam

30 GeV
- J/ψ production
- Transition: Hadron → Quark degrees of freedom
- Hadron interactions in nuclear medium
- Short-range $NN$ interactions
- GPDs
- ...

50 GeV
- Drell-Yan (unpolarized PDFs)
- Single spin asymmetries
- Tensor structure at 50 GeV (Spin-1 hadrons)
- Fragmentation functions (Hadron productions)
- ...

Proton-beam polarization
- Drell-Yan: Double asymmetries (Polarized PDFs)
- Complimentary to RHIC-Spin (large $x$ physics)
- ...

S. Sawada
M. Stratmann, A. Taketani, J.-C. Peng
S. Yokkaichi
M. Ohtani, S. Ohta
P. Reimer, T. Iwata
D. Sivers
I. Nakagawa
R. Seidl, Y. Goto, M. Bai
Neutrino: Y. Miyachi
**Hadron facilities**

e.g. Drell-Yan: $x_1 x_2 = \frac{m_{\mu\mu}^2}{s} \frac{s}{x} \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}}$

\[ p + p(A) \rightarrow \mu^+ \mu^- + X \quad (q \bar{q} \rightarrow \mu^+ \mu^-) \]

- $s = (p_1 + p_2)^2$

- $m_{\mu\mu} \geq 3 \text{ GeV}$

\[ x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}} \geq \frac{3}{10} = 0.3 \quad \text{J-PARC} \]

\[ \geq \frac{3}{200} = 0.02 \quad \text{RHIC} \]

\[ \geq \frac{3}{14000} = 0.0002 \quad \text{LHC} \]

**Large-\(x\) facility** (Medium-\(x\))

**Small-\(x\) facility**
Flavor asymmetric antiquark distributions: $\bar{u} / \bar{d}$

Related talks: P. Reimer, S. Sawada, J.-C. Peng, S. Choi, Y. Goto@J-PARC-NP08

This project is suitable for probing “peripheral structure” of the nucleon.

J-PARC proposal, M. Bai et al. (2007)

E866

J-PARC

E906

http://www.acuonline.edu/academics/cas/physics/research/e906.html

**Applicability of perturbative QCD**

Yokoya, Stratmann@J-PARC-HS05

(1) Higher-order $\alpha_s$ corrections
(2) Soft-gluon resummation

Cross section = $p\text{QCD} \times \text{“hadron structure” (PDFs)}$

In order to extract the hadron-structure part, $p\text{QCD}$ should be understood.

Large contributions come from the partonic threshold region

$z = \frac{M_{\mu\mu}^2}{\hat{s}} \sim 1.$

**Figure:**

- Fixed order: $\text{LO, NLO, N}^k\text{LO}$
- Resummation: $\alpha_s L^2, \alpha_s L, \alpha_s^k L^{2k-1}$

Higher-order corrections are large at J-PARC (50 GeV); however, the $p\text{QCD}$ terms could be under control.

Mellin moments: $\int_0^1 dx x^{N-1} f(x)$
Elastic Scattering: $A+B \rightarrow C+D$ at large $p_T$

Brodsky@J-PARC-HS05

Transition from hadron degrees of freedom to quark-gluon d.o.f.

Constituent counting rule

$$\frac{d\sigma}{dt}(AB \rightarrow CD) \sim s^{2-n} f(\theta_{c.m.})$$

$$n = n_A + n_B + n_C + n_D$$

(total number of interacting elementary particles)

J-PARC: $p + p \rightarrow p + p$

L.Y. Zhu et al.,
PRL 91 (2003) 022003
Color Transparency

“Probe of dynamics of elementary reactions”

At large momentum transfer, a small-size component of the hadron wave function should dominate. This small-size hadron could freely pass through nuclear medium. (Transparent)

Brodsky, Strikman@J-PARC-HS05

Investigate $pA \rightarrow p\,p\,(A-1)$

Nuclear transparency: $T = \frac{\sigma_A}{A\sigma_N}$

Hadron size $\sim 1 / \text{hard scale}$

Color transparency:
$T \rightarrow \text{larger, as the hard scale } \rightarrow \text{larger}$

(BNL-EVA) J. Aclander et al., PRC 70 (2004) 015208

Possibility at J-PARC

Incident energy (GeV)

$^{12}\text{C}$

$(p,2p)$ at J-PARC
Generalized Parton Distributions (GPDs)

GPDs are defined as correlation of off-forward matrix.

Bjorken variable \( x = \frac{Q^2}{2p \cdot q} \)

Momentum transfer squared \( t = \Delta^2 \)

Skewness parameter \( \xi = \frac{p^- - p'^+}{p^+ + p'^+} = -\frac{\Delta^+}{2P^+} \)

Forward limit: PDFs

First moments: Form factors

Dirac and Pauli form factors \( F_1, F_2 \)

Axial and Pseudoscalar form factors \( G_A, G_P \)

Second moments: Angular momenta

Sum rule: \( J_q = \frac{1}{2} \int dx [H_q(x, \xi, t = 0) + E_q(x, \xi, t = 0)] \)

Special cases:

- PDFs: \( F_1 = \frac{1}{2} \int dx f(x) \)
- Form factors: \( F_1 \), \( F_2 \)
- GPDs: \( H(x, \xi, t) \), \( \tilde{H}(x, \xi, t) \)

Notice that there is no analog in \( E \) and \( \tilde{E} \).
GPDs in different $x$ regions and GPDs at J-PARC

Quark distribution
- Emission of quark with momentum fraction $x+\xi$
- Absorption of quark with momentum fraction $x-\xi$

Meson distribution amplitude
- Emission of quark with momentum fraction $x+\xi$
- Emission of antiquark with momentum fraction $\xi-x$

Antiquark distribution
- Emission of antiquark with momentum fraction $\xi-x$
- Absorption of antiquark with momentum fraction $-x-\xi$

GPDs at J-PARC:
SK, M. Strikman, K. Sudoh, in progress.
Short-range NN interaction

Ciofi degli Atti@J-PARC-NP07
Strikman@INPC07
E. Piasetzky et al.,
PRL97 (2006) 162504

Nuclei do not collapse → Short-range repulsive core

Nucleon size $r \approx 0.8$ fm

Average nucleon separation in a nucleus: $R \approx 2$ fm $\sim 2r$

→ The short-range part is important as the density becomes larger (neutron star).

A(p, 2pN)X experiment for short range correlation
Parton Distribution Functions
and
Fragmentation Functions
Motivations for studying PDFs

(1) To establish QCD

Perturbative QCD

• In principle, theoretically established in many processes. (There are still issues on resummations and small-x physics.)
• Experimentally confirmed (unpolarized, polarized ?)

Non-perturbative QCD (PDFs)

• Theoretical models: Bag, Soliton, … (It is important that we have intuitive pictures of the nucleon.)
• Lattice: Reliable $x$-distributions have not been obtained.

→ Determination of the PDFs from experimental data.
For discussing any high-energy reactions, accurate PDFs are needed.

- origin of nucleon spin: quark- and gluon-spin contributions
- exotic events at large $Q^2$: physics of beyond current framework
- heavy-ion reactions: quark-hadron matter
- neutrino oscillations: nuclear effects in $\nu + ^{16}\text{O}$
- cosmology: ultra-high-energy cosmic rays
Unpolarized Parton Distribution Functions (PDFs) in the nucleon

The PDFs could be obtained from
http://durpdg.dur.ac.uk/hepdata/pdf.html

![Graph showing parton distribution functions](image)

- Gluon distribution / $5$
- Valence-quark distributions
PDF uncertainty

Other PDF

CTEQ6 (J. Pumplin et al.), JHEP 0207 (2002) 012

CTEQ5M1

MRS2001

CTEQ5HJ

Important $x$ region for finding an “exotic event” in a high-$p_T$ region at LHC

J-PARC $x$ region

If processes are well understood theoretically including pQCD terms, J-PARC measurements are important for finding new physics at LHC or possibly in cosmic rays.
Nuclear Parton Distribution Functions

http://research.kek.jp/people/kumanos/nuclp.html
Why nuclear PDFs?

(1) Basic interest to understand nuclear structure in the high-energy region (description of nuclei in terms quark and gluon degrees of freedom), Determination of $\sin^2 \theta_W$

- perturbative & non-perturbative QCD
- $\sin^2 \theta_W$ in neutrino scattering (NuTeV)

(2) Practical purpose to describe hadron cross sections precisely

- heavy-ion reactions: properties of quark-gluon matters
- long-baseline neutrino experiments: nuclear effects in $\nu + ^{16}\text{O}$
- nuclear corrections for extracting $u_\nu$ and $d_\nu$ *in the nucleon* from NuTeV / CCFR
- high-energy cosmic ray interactions
Experimental data: total number = 1241

(1) $F_2^A / F_2^D$ 896 data

- NMC: p, He, Li, C, Ca
- SLAC: He, Be, C, Al, Ca, Fe, Ag, Au
- EMC: C, Ca, Cu, Sn
- E665: C, Ca, Xe, Pb
- BCDMS: N, Fe
- HERMES: N, Kr

(2) $F_2^A / F_2^{A'}$ 293 data

- NMC: Be / C, Al / C, Ca / C, Fe / C, Sn / C, Pb / C, C / Li, Ca / Li

(3) $\sigma_{DY}^A / \sigma_{DY}^{A'}$ 52 data

- E772: C / D, Ca / D, Fe / D, W / D
- E866: Fe / Be, W / Be
**Functional form**  
Nuclear PDFs “per nucleon”

If there were no nuclear modification

\[ Au^A(x) = Zu^p(x) + Nu^n(x), \quad Ad^A(x) = Zd^p(x) + Nd^n(x) \quad p = \text{proton}, \quad n = \text{neutron} \]

**Isospin symmetry**:  
\[ u^n = d^p \equiv d, \quad d^n = u^p \equiv u \]

\[ \rightarrow u^A(x) = \frac{Zu(x) + Nd(x)}{A}, \quad d^A(x) = \frac{Zd(x) + Nu(x)}{A} \]

Take account of nuclear effects by \( w_i(x, A) \)

\[ u_v^A(x) = w_{u_v}(x, A) \frac{Zu_v(x) + Nd_v(x)}{A}, \quad d_v^A(x) = w_{d_v}(x, A) \frac{Zd_v(x) + Nu_v(x)}{A} \]

\[ \bar{u}^A(x) = w_{\bar{q}}(x, A) \frac{Z\bar{u}(x) + N\bar{d}(x)}{A}, \quad \bar{d}^A(x) = w_{\bar{q}}(x, A) \frac{Z\bar{d}(x) + N\bar{u}(x)}{A} \]

\[ \bar{s}^A(x) = w_{\bar{q}}(x, A)\bar{s}(x) \]

\[ g^A(x) = w_g(x, A)g(x) \quad \text{at } Q^2=1 \text{ GeV}^2 (\equiv Q_0^2) \]
Results & Future experiments

JLab
ν Factory
MINAR
ν A

Fermilab
J-PARC
RHIC
LHC
eLIC
eRHIC

J-PARC proposal
J. Chiba et al. (2006)

E866
E906

u_ν

vFactory
MINARvA

LO
NLO
Q^2 = 1 GeV^2

(JKN07)
Polarized Parton Distribution Functions

http://spin.riken.bnl.gov/aac/
Nucleon Spin

Naïve Quark Model

\[ \Delta \Sigma = \Delta u_v + \Delta d_v = 1 \]

Electron / muon scattering

\[ \Delta \Sigma \approx 0.1 \sim 0.3 \]

Almost none of nucleon spin is carried by quarks!

QCD

Sea-quarks and gluons?

Gluon: \( \Delta G \)

Sea-quarks: \( \Delta q_{sea} \)

Recent data indicate \( \Delta G \) is small at \( x \sim 0.1 \).

Orbital angular momenta?

Future experiments

\[ L_q, L_g \]

Nucleon Spin:

\[
\frac{1}{2} = \frac{1}{2} \left( \Delta u_v + \Delta d_v + \Delta q_{sea} \right) + \Delta G + L_q + L_g
\]
Current polarized data are kinematically limited.

\[ x = \frac{Q^2}{2p \cdot q} \approx \frac{Q^2}{ys} \]

Fixed target: \( \min(x) = \frac{Q^2}{2M_N E_{\text{lepton}}} \leq \frac{1}{2E_{\text{lepton}} (\text{GeV})} \)

If \( Q^2 \geq 1 \text{ GeV}^2 \)

For \( E_{\text{lepton}} (\text{SMC}) = 190 \text{ GeV} \), \( \min(x) = \frac{1}{400} = 0.003 \)

(from H1 and ZEUS, hep-ex/0502008)
General strategies for determining polarized PDFs

Spin asymmetry  \( A_1 \approx g_1 \frac{2x(1 + R)}{F_2} \)

\[ R = \frac{F_L}{2xF_1} = \frac{F_2 - 2xF_1}{2xF_1} \]

\[ g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \int_x^1 \frac{dy}{y} \left[ \Delta q(x/y, Q^2) + \Delta \bar{q}(x/y, Q^2) \right] \left[ \delta(1 - y) + \frac{\alpha_s(Q^2)}{2\pi} \Delta C_q(y) + \cdots \right] \]

\[ + \frac{1}{2} \left( \langle e_q^2 \rangle \int_x^1 \frac{dy}{y} \Delta g(x/y, Q^2) \right) \left[ n_f \frac{\alpha_s(Q^2)}{2\pi} \Delta C_g(y) + \cdots \right] \]

\[ \langle e_q^2 \rangle = \frac{1}{n_f} \sum_q e_q^2 \]

Leading Order (LO)  Next to Leading Order (NLO)

\( \Delta C_q \)  \( \Delta C_g \) = quark (gluon) coefficient function

\[ F_2(x, Q^2) = x \sum_q e_q^2 \int_x^1 \frac{dy}{y} \left[ q(x/y, Q^2) + \bar{q}(x/y, Q^2) \right] \left[ \delta(1 - y) + \frac{\alpha_s(Q^2)}{2\pi} C_q^{(2)}(y) + \cdots \right] \]

\[ + x \langle e_q^2 \rangle \int_x^1 \frac{dy}{y} g(x/y, Q^2) \left[ n_f \frac{\alpha_s(Q^2)}{2\pi} C_g^{(2)}(y) + \cdots \right] \]

Unpolarized PDFs
Description of $\pi^0$ production

Parton interactions

Fragmentation functions

Parton distribution functions

$$\Delta \sigma \sim \sum_{a,b,c} \Delta f_a(x_a,Q^2) \otimes \Delta f_b(x_b,Q^2) \otimes \Delta \hat{\sigma}(ab \rightarrow cX) \otimes D_c^\pi(z,Q^2)$$

$g + g \rightarrow q(g) + X$ processes are dominant at small $p_T$

$q + g \rightarrow q(g) + X$ at large $p_T$

The $\pi^0$ production process is suitable for finding the gluon polarization $\Delta g$. 
Situation of polarized PDFs

Gluon and antiquark distributions have large uncertainties at large $x$.

$Q^2 = 1 \text{ GeV}^2$

$x\Delta u_v(x)$

$x\Delta d_v(x)$

$x\Delta \bar{q}(x)$

$Q^2 = 1 \text{ GeV}^2$
Fragmentation Functions

http://research.kek.jp/people/kumanos/ffs.html
Purposes of investigating fragmentation functions

Semi-inclusive reactions have been used for investigating

- **origin of proton spin**
  \[ \bar{e} + \bar{p} \rightarrow e' + h + X \text{ (e.g. HERMES), } \bar{p} + \bar{p} \rightarrow h + X \text{ (RHIC-Spin)} \]

Quark, antiquark, and gluon contributions to proton spin
(flavor separation, gluon polarization)

- **properties of quark-hadron matters**  \[ A + A' \rightarrow h + X \text{ (RHIC, LHC)} \]

Nuclear modification
(recombination, energy loss, …)

\[ \sigma = \sum_{a,b,c} f_a(x_a, Q^2) \otimes f_b(x_b, Q^2) \otimes \hat{\sigma}(ab \rightarrow cX) \otimes D^\pi_c(z, Q^2) \]
Fragmentation Function

Fragmentation function is defined by

\[ F^h(z,Q^2) = \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma(e^+ e^- \rightarrow hX)}{dz} \]

where \( \sigma_{\text{tot}} \) is the total hadronic cross section.

\[ z \equiv \frac{E_h}{\sqrt{s}/2} = \frac{2E_h}{Q} = \frac{E_h}{E_q}, \quad s = Q^2 \]

Variable \( z \)
- Hadron energy / Beam energy
- Hadron energy / Primary quark energy

A fragmentation process occurs from quarks, antiquarks, and gluons, so that \( F^h \) is expressed by their individual contributions:

\[ F^h(z,Q^2) = \sum_i \int_z^1 \frac{dy}{y} C_i \left( \frac{z}{y},Q^2 \right) D_i^h(y,Q^2) \]

Calculated in perturbative QCD

Non-perturbative (determined from experiments)

\( C_i(z,Q^2) \) = coefficient function

\( D_i^h(z,Q^2) \) = fragmentation function of hadron \( h \) from a parton \( i \)
Fragmentation functions at J-PARC

Gluon and light-quark fragmentation functions have large uncertainties.

Large differences between the functions of various analysis groups.

\[ \hat{s} = x_a x_b s \sim (0.4)^2 (10 \text{ GeV})^2 \]

\[ \sqrt{\hat{s}} = 0.4 \cdot 10 = 4 \text{ GeV} \]

\[ z \sim \frac{p_T}{\sqrt{\hat{s}} / 2} = \frac{p_T}{2} \sim 1 \] (large \( z \))
Exotic hadron search
by fragmentation functions

$f_0(980)$ as an example
Criteria for determining $f_0$ structure
by its fragmentation functions

Possible configurations of $f_0(980)$

(1) ordinary $u,d$ - meson
\[ \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d}) \]

(2) strange meson, $s\bar{s}$

(3) tetraquark ($K\bar{K}$), $\frac{1}{\sqrt{2}} (u\bar{u}s\bar{s} + d\bar{d}s\bar{s})$

(4) glueball $gg$

Contradicts with experimental widths
\[
\Gamma_{\text{theo}}(f_0 \rightarrow \pi\pi) = 500 - 1000 \text{ MeV} \\
\Gamma_{\text{exp}} = 40 - 100 \text{ MeV}
\]

\[
\Gamma_{\text{theo}}(f_0 \rightarrow \gamma\gamma) = 1.3 - 1.8 \text{ keV} \\
\Gamma_{\text{exp}} = 0.205 \text{ keV}
\]

Contradicts with lattice-QCD estimate
\[
m_{\text{lattice}}(f_0) = 1600 \text{ MeV} \\
m_{\text{exp}} = 980 \text{ MeV}
\]

Discuss 2nd moments and functional forms (peak positions) of the fragmentation functions for $f_0$ by assuming the above configurations, (1), (2), (3), and (4).
Experimental data for $f_0$

Total number of data: **only 23**

<table>
<thead>
<tr>
<th>Exp. collaboration</th>
<th>$\sqrt{s}$ (GeV)</th>
<th># of data</th>
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<td>8</td>
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<tr>
<td>DELPHI</td>
<td>91.2</td>
<td>11</td>
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</tbody>
</table>

**pion**

Total number of data: **264**

<table>
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<tr>
<td>SLD [light quark]</td>
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</tr>
<tr>
<td>SLD [c quark]</td>
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</tr>
<tr>
<td>SLD [b quark]</td>
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<tr>
<td>DELPHI [light quark]</td>
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<td>17</td>
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<tr>
<td>DELPHI [b quark]</td>
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<td>17</td>
</tr>
</tbody>
</table>

One could foresee the difficulty in getting reliable FFs for $f_0$ at this stage.
Large uncertainties

2nd moments

\[ M_u = 0.0012 \pm 0.0107 \]
\[ M_s = 0.0027 \pm 0.0183 \]
\[ M_g = 0.0090 \pm 0.0046 \]

\[ \rightarrow M_u / M_s = 0.43 \pm 6.73 \]

The uncertainties are order-of-magnitude larger than the distributions and their moments themselves.

At this stage, the determined FFs are not accurate enough to discuss internal structure of \( f_0(980) \).

\[ \rightarrow \] Accurate data are awaited not only for \( f_0(980) \) but also for other exotic and “ordinary” hadrons.
Tensor Structure at High-Energies
For Spin-1 Hadrons

Note: Proton-beam polarization is not needed.
Polarized deuteron target is enough at J-PARC!

http://www-conf.kek.jp/J-PARC-HS05/program.html
**Tensor Structure in High-energy Reactions**

(Note: No polarized proton beam is needed!)

P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571.

**Structure Functions (in e scattering)**

\[ F_1 \propto \langle d\sigma \rangle \]

\[ g_1 \propto d\sigma(\uparrow,+1) - d\sigma(\uparrow,-1) \]

\[ b_1 \propto d\sigma(0) - \frac{d\sigma(+1) + d\sigma(-1)}{2} \]

**Parton Model**

\[ F_i = \frac{1}{2} \sum_i e_i^2 (q_i + q_i) \]

\[ q_i = \frac{1}{3} (q_i^{+1} + q_i^0 + q_i^{-1}) \]

\[ g_1 = \frac{1}{2} \sum_i e_i^2 (\Delta q_i + \Delta q_i) \]

\[ \Delta q_i = q_i^{+1} - q_i^{-1} \]

\[ b_1 = \frac{1}{2} \sum_i e_i^2 (\delta q_i + \delta q_i) \]

\[ \delta q_i = q_i^0 - \frac{q_i^{+1} + q_i^{-1}}{2} \]

\[ \left[ q^H_{\uparrow}(x,Q^2) \right] \]
Tensor Structure in Proton-Deuteron Drell-Yan

**b₁ for spin-1 particles**

(Note: No polarized proton beam is needed!)

Spin asymmetries

\[ A_{LL} = \sum_a e_a^2 \left[ \Delta q_a(x_A) \Delta q_a(x_B) + \Delta q_a(x_A) \Delta q_a(x_B) \right] \]

\[ A_{TT} = \frac{\sin^2 \theta \cos(2\phi)}{1 + \cos^2 \theta} \sum_a e_a^2 \left[ \Delta_T q_a(x_A) \Delta_T q_a(x_B) + \Delta_T q_a(x_A) \Delta_T q_a(x_B) \right] \]

\[ A_{UQ₀} = \sum_a e_a^2 \left[ q_a(x_A) \delta \bar{q}_a(x_B) + \bar{q}_a(x_A) \delta q_a(x_B) \right] \]

1st measurement of \( b₁ \):

(HERMES) A. Airapetian et al., PRL 95 (2005) 242001.

**Only in S-wave** \( b₁ = 0 \)

Polarized proton-deuteron Drell-Yan

(Theory) S. Hino and SK,

PR D 59 (1999) 094026,

D 60 (1999) 054018.

(Experiment) None → J-PARC

\[ \delta q_i = q_i^0 - q_i^{+1} + q_i^{-1} \]

Note: \( \delta \neq \) transversity in my notation

Unpolarized proton + Tensor polarized deuteron

Unique advantage of J-PARC (\( \delta \bar{q} \) measurement)

\[ \int dx b₁^D(x) = 0 + \frac{1}{9} \left( \delta Q + \delta \bar{Q} \right) \text{sea} \]

F. E. Close and SK, PRD42, 2377 (1990)

Gottfried: \[ \int dx \left[ F_2^n(x) - F_2^u(x) \right] = \frac{1}{3} + \frac{2}{3} \int dx \left[ u - d \right] \]
Our works related to this talk

(1) Overview on “Possible Hadron Physics at J-PARC”

(2) $u\bar{u}/d\bar{d}$

(3) Nuclear PDFs
   M. Hirai, SK, and M. Miyama, Phys. Rev. D 64 (2001) 034003;

(4) Polarized PDFs, Asymmetry Analysis Collaboration (AAC)

(5) Global analyses for FFs of $\pi, K,$ and $p$ + their uncertainties
   Exotic hadron search by using FFs e.g. for $f_0(980)$

(6) Sum rule for $b_1(x)$
   General formalism for polarized proton+deuteron Drell-Yan
Summary

J-PARC will be an important facility in hadron and nuclear physics communities.

In high-energy hadron physics
- Structure functions of hadrons
- Fragmentation
- Hadron interactions in nuclear medium
- Short-range NN interactions
- Hadron $\rightarrow$ Quark degrees of freedom
- Hadron spin
- ...

I introduced some topics. More contributions are needed for the hadron project at J-PARC!

Need to discuss possible topics with 30 GeV, 50 GeV, and 50 GeV polarized proton beams.