Plan for a proposal in high-energy hadron physics at J-PARC

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Outline

• Uniqueness of hadron physics studied at HiPBL of J-PARC

• Physics Processes under consideration:
  • Drell-Yan process
  • Hard exclusive process
  • Charm production process

• Feasibility study of exclusive Drell-Yan process in E50 spectrometer

• Summary & Questions
J-PARC High-momentum Beam Line (Hi-P BL)

- High-intensity secondary Pion beam
- High-resolution beam: $\Delta p/p \sim 0.1\%$

![Diagram of J-PARC Hi-P BL](image)
J-PARC High-momentum Beam Line
(Hi-P BL)

- High-intensity secondary Pion beam
- High-resolution beam: $\Delta p/p \sim 0.1\%$

* Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m
KEK theory center workshop on
Hadron physics with high-momentum hadron beams at J-PARC in 2013
Kobayashi Hall, 1st Floor, Kenkyu-Honkan (15th, 18th)
Seminar Hall, 1st Floor, 3rd building (16th, 17th)
January 15 – 18, 2013, KEK, Tsukuba, Japan
## Workshops

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<th>Workshop</th>
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<tr>
<td>Mini workshop on “Structure and productions of charmed baryons II”</td>
<td>Aug.7–9, 2014</td>
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<td>Workshop on High-energy QCD and nucleon structure</td>
<td>March 7–8, 2014</td>
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<td>KEK theory center workshop on J-PARC hadron physics in 2014</td>
<td>Feb. 10–12, 2014</td>
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<td>Hadron-structure physics at J-PARC and related topics</td>
<td>March 18, 2013</td>
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<td>Heavy Quark Hadrons at J–PARC 2012 (partly in English)</td>
<td>June.25–29, 2012</td>
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<td>Future Prospects of Hadron Physics at J–PARC and Large Scale Computational Physics (program, slides, photo, participant list)</td>
<td>Feb. 9–11, 2012</td>
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Uniqueness of hadron physics studied at HiPBL of J-PARC

- The beam energy of hadrons at J-PARC at 5-15 GeV ($\sqrt{s} = 3 - 5.5$ GeV) might be most ideal for studying the **hard exclusive processes** and discerning the quark-hadron transition in the strong interaction.
  - Valance-like partonic degrees of freedom of hadrons could be discerned, compared to the collisions at low-energy regime.
  - Reasonably large cross sections, compared to those at higher energies.
Constituent-Counting Rule in Hard Exclusive Process

Kawamura et al., PRD 88, 034010 (2013)

\[ \frac{d\sigma}{dt}(a + b \rightarrow c + d) = \frac{1}{s^{n-2}} f(\theta_{CM}) \quad n = n_a + n_b + n_c + n_d \]

\[ n = 1 + 3 + 2 + 3 = 7 \]
\[ \gamma + p \rightarrow \pi^+ + n \]

\[ n = 2 + 3 + 2 + 3 = 8 \]
\[ \pi^- + p \rightarrow K^0 + \Lambda \]
Physics Processes

- **Drell-Yan process**
  - Inclusive pion-induced Drell-Yan:
    - $u/d(x)$ at large $x$
    - Violation of Lam-Tung relation, BM functions
    - Pion PDF and DA
  - Exclusive pion-induced Drell-Yan
    - GPD and TDA of proton
    - Pion DA

- **Hard exclusive production process**
  - Exclusive pion-N Lambda(1405) production
    - Valence quark structure of Lambda(1405)

- **Charm production process**
  - Inclusive pion-N J/psi production: J/psi production mechanism
  - Exclusive pion-N J/psi production: Intrinsic charm?
  - Exotic charmed baryons
Quark and Gluon Wigner Phase-Space Distributions in Protons

Wigner Distribution
\[ W(\vec{r}, x, \vec{k}_T) \]

\[ \int d\vec{r} \]
\[ \int e^{i\vec{q} \cdot \vec{r}} d\vec{r} d\vec{k}_T \]
\[ \xi = q^z / 2E_q, \quad t = -\vec{q}^2 \]

Transverse Momentum Dependent PDF
\[ f(x, \vec{k}_T) \]

Generalized Parton Distr.
\[ F(x, \xi, t) \]

PDF
\[ f(x) \]

Form Factors
\[ F_1(t), F_2(t) \]

Ji, PRL91, 062001 (2003)
Light Antiquark Flavor Asymmetry: Drell-Yan Experiments with Proton Beam

- Naïve Assumption: \( \bar{d}(x) = \bar{u}(x) \)
- NMC (Gottfried Sum Rule):
  \[ \int_0^1 [\bar{d}(x) - \bar{u}(x)] \, dx \neq 0 \]
- NA51 (Drell-Yan, 1994):
  \( \bar{d} > \bar{u} \) at \( x = 0.18 \)
- E866/NuSea (Drell-Yan, 1998):
  \( \frac{\bar{d}(x)}{\bar{u}(x)} \) for \( 0.015 \leq x \leq 0.35 \)

\[ h_A \rightarrow q \rightarrow T \]
\[ h_B \rightarrow q^* \rightarrow l \]
\( \bar{d}(x)/\bar{u}(x) \) Measured by FNAL E906/SeaQuest Experiment

\[ x_B x_T = \frac{M}{s}; \text{ smaller } s, \text{ larger } x_T \]

- Unpolarized Drell-Yan using 120 GeV proton beam from Main Injector
- \(^1\)H, \(^2\)H, and nuclear targets

\[ (\bar{d}(x) / \bar{u}(x)) \text{ up to } x_T \sim 0.45 \]
$\bar{d} / \bar{u}$ at large $x$

Advange of relatively low beam energy

J-PARC Proposal P-04 (Peng and Sawada)
50-GeV proton beam

$10^{12}$ protons per spill (3 s)
50-cm long $LH_2 / LD_2$ targets
60-day runs for each targets
assuming 50% efficiency
Ratios of $d(x)/u(x)$ at large $x$?

\[ |p\rangle \uparrow = \frac{1}{\sqrt{2}} u \uparrow (ud)_{s=0,s_z=0} + \frac{1}{\sqrt{18}} u \uparrow (ud)_{s=1,s_z=0} - \frac{1}{3} u \downarrow (ud)_{s=1,s_z=1} \]

\[ -\frac{1}{3} d \uparrow (uu)_{s=1,s_z=0} + \frac{\sqrt{2}}{3} d \downarrow (uu)_{s=1,s_z=1} \]

1) SU(6) symmetry

\[ \frac{d}{u} = \frac{1}{2} \quad \frac{F_2^n}{F_2^p} = \frac{2}{3} \]

2) Dominance of $S = 0$ diquark configurations (Close, Carlitz)

Ignoring terms with $S = 1$ diquarks, then

\[ \frac{d}{u} = 0 \quad \frac{F_2^n}{F_2^p} = \frac{1}{4} \]

2) Dominance of $S_Z = 0$ diquark configurations (Farrar, Jackson)

Ignoring terms with $S_Z = 1$ diquarks, then

\[ \frac{d}{u} = \frac{1}{5} \quad \frac{F_2^n}{F_2^p} = \frac{3}{7} \]
How to make a precise measurement of $d(x) / u(x)$?

1) “spectator tagging” (BONUS experiment)

2) “Super ratio $^3\text{He}/^3\text{H}” (Marathon experiment)

- Extract $F_2^n/F_2^p$ from ratio of measured $^3\text{He}/^3\text{H}$ structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2R - \frac{F_2^3\text{He}}{F_2^3\text{H}}}{2\frac{F_2^3\text{He}}{F_2^3\text{H}} - R}$$
Ratios of $d/u(x)$ at large $x$ by pion-induced Drell-Yan processes

• At large $x_1$ and $x_2$:
  $\sigma_{DY}(\pi^- p) \sim 4\bar{u}^\pi (x_1)u^p(x_2)$
  $\sigma_{DY}(\pi^- n) \sim 4\bar{u}^\pi (x_1)d^p(x_2)$  \textbf{Deuterium target}
  $\sigma_{DY}(\pi^+ p) \sim \bar{d}^{\pi^+} (x_1)d^p(x_2)$

• With deuterium target and spectator tagging:
  $\frac{\sigma_{DY}(\pi^- n)}{\sigma_{DY}(\pi^- p)} \sim \frac{4\bar{u}^\pi (x_1)d^p(x_2)}{4\bar{u}^\pi (x_1)u^p(x_2)} \sim \frac{d^p(x_2)}{u^p(x_2)}$

• With both $\pi^+$ and $\pi^-$ beams:
  $\frac{\sigma_{DY}(\pi^+ p)}{\sigma_{DY}(\pi^- p)} \sim \frac{\bar{d}^{\pi^+} (x_1)d^p(x_2)}{4\bar{u}^\pi (x_1)u^p(x_2)} \sim \frac{d^p(x_2)}{4u^p(x_2)}$

  \textbf{No nuclear correction for deuteron is needed}
Drell-Yan decay angular distributions

θ and φ are the decay polar and azimuthal angles of the μ⁺ in the dilepton rest-frame

Collins-Soper frame

\[
\frac{d\sigma}{d\Omega} \propto (1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{v}{2} \sin^2 \theta \cos 2\phi)
\]

\[
\propto (W_T (1 + \cos^2 \theta) + W_L (1 - \cos^2 \theta) + W_\Delta \sin 2\theta \cos \phi + W_{\Delta\Delta} \sin^2 \theta \cos 2\phi)
\]

q\bar{q} annihilation parton model:

\( O(\alpha_s^0) \) \( \lambda=1, \mu=v=0; W_T = 1, W_L = 0 \)

Lam-Tung relation (1978)

Collinear pQCD: \( O(\alpha_s^1) \), \( W_L = 2W_{\Delta\Delta} ; 1 - \lambda - 2v=0 \)
E615 (PRD 39, 92 (1989)):
Higher Twist Effect at large $x_\pi$

$\cos \theta$

$0.52 < x_\pi < 0.60$

$0.60 < x_\pi < 0.68$

$0.68 < x_\pi < 0.76$

$0.76 < x_\pi < 0.84$

$0.84 < x_\pi < 0.92$

$0.92 < x_\pi < 1.00$

$\lambda$

GJ frame
$4.05 < m_{\mu \nu} < 4.95$ GeV/$c^2$

- modified Berger–Brodsky
- pure Berger–Brodsky
E615 @ FNAL: Violation of LT Relation

PRD 39, 92 (1989)

252-GeV $\pi^- + W$

$1 - \lambda - 2\nu = 0$

$\cos 2\phi$ modulation at large $p_T$
Berger and Brodsky (PRL 42, 940, (1979)):
Higher Twist Effect at large $x_\pi$

\[
d\sigma \propto (1 + \alpha \cos^2 \theta)
\]

\[
d\sigma \propto (1 - x_\pi)^2 (1 + \cos^2 \theta) + \frac{4x_\pi^2 \langle k_T^2 \rangle}{9m_{\mu\mu}^2} \sin^2 \theta
\]
Brandenburg et al. (PRL 73, 939 (1994)): Pion Distribution Amplitude

\[
\frac{Q^2 \, d\sigma(\pi^- N \rightarrow \mu^+ \mu^- X)}{dQ^2 \, dQ_T^2 \, dx_L \, d\Omega} = \frac{1}{(2\pi)^4} \frac{1}{64} \int_0^1 dx_u \, G_{u/N}(x_u) \int_0^1 dx_{\bar{u}} \, \frac{x_{\bar{u}}}{1 - x_{\bar{u}} + Q_T^2/Q^2} |M|^2 \\
\times \delta(x_L - x_{\bar{u}} + x_{\bar{u}} - Q_T^2 s^{-1}(1 - x_{\bar{u}})^{-1})
\]

\[
M = \int_0^1 dz \, \phi(z, \tilde{Q}^2) T, \quad \times \delta(Q^2 - s x_u x_{\bar{u}} + Q_T^2 (1 - x_{\bar{u}})^{-1}) + \{u \rightarrow \bar{d}, \bar{u} \rightarrow d\}.
\]

**Pion distribution amplitude**: distribution of LC momentum fractions in the lowest-particle number valence Fock state.

**Pion Distribution Amplitude**

QCD evolution

\[ \varphi_\pi(y, \mu_0^2) \]

\[ \varphi_\pi(y, \mu^2) \]

asymptotic-like form = \(6y(1-y)\)

Chernyak-Zhitnitsky (CZ)-like form

Nonlocal QCD sum rules
Sensitivity of Pion DA to $\lambda, \mu, \nu$

$$\rho = \frac{P_T^*}{\gamma^*} \frac{\rho}{M^*}$$

$\rho = 0.06$

$\rho = 0.3$

$\rho = 0.5$

Dimuon pairs of Large $P_T$ or small $M$
### Theoretical Interpretations of Lam-Tung Violation in pion-induced DY

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<th>Boer-Mulders Function</th>
<th>QCD chromo-magnetic effect</th>
<th>Glauber gluon</th>
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<tr>
<td>Origin of effect</td>
<td>Hadron</td>
<td>QCD vacuum</td>
<td>Pion specifically</td>
</tr>
<tr>
<td>Quark-flavor dependence</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Hadron dependence</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Large $P_T$ limit</td>
<td>0</td>
<td>Nonzero</td>
<td>0</td>
</tr>
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Measurements with different beams $\pi^\pm, p, K^\pm, \bar{p}$ and at wide kinematical ranges would help differentiating the origin.

Competing with CERN COMPASS DY Program
Pasquini and Schweitzer (PRD 90, 014050 (2014))
Boer-Mulders Functions of Pion and Proton in Light-Front Constituent Model

(a) \(\nu(q_T)\) vs. \(q_T\) (GeV)

(b) \(\nu(q_T)\) vs. \(q_T\) (GeV)

(c) \(\nu(q_T)\) vs. \(q_T\) (GeV)

(d) \(\nu(x_1)\) vs. \(x_1\)

(e) \(\nu(x_1)\) vs. \(x_1\)

(f) \(\nu(x_1)\) vs. \(x_1\)
Consistency of LT relation for DY events in pd, pp
Boer-Mulders functions from unpolarized pD and pp Drell-Yan

Z. Lu and I. Schmidt,
PRD 81, 034023 (2010)

V. Barone et al.,
PRD 82, 114025 (2010)

\[ h_1^{+q}(x, p_T^2) = h_1^{+q}(x) \frac{1}{\pi p_{bm}^2} \exp\left(-\frac{p_T^2}{p_{bm}^2}\right). \]

Sign of BM functions and their flavor dependence?
Flavor separation of the Boer–Mulders functions
Z. Lu et al. (PLB 639 (2006) 494)

\[
\langle W \rangle = \left\langle \frac{q_T^2 \cos 2\phi}{4M_A M_B} \right\rangle = \int d\phi d^2q_T \frac{d\sigma(h_A h_B \rightarrow l\bar{l}X)}{d\Omega dx_A dx_B d^2q_T} \frac{q_T^2 \cos 2\phi}{4M_A M_B}
\]

Deuterium target
Quark and Gluon Wigner Phase-Space Distributions in Protons

\[ W(\vec{r}, x, \vec{k}_T) \]

\[ \int d\vec{r} \]

\[ e^{i\vec{q} \cdot \vec{r}} \int d\vec{r} d\vec{k}_T \]

\[ \xi = q^z / 2E_q, \quad t = -q^2 \]

Transverse Momentum Dependent PDF \( f(x, \vec{k}_T) \)

Generalized Parton Distr. \( F(x, \xi, t) \)

\( x = 0 & \xi = 0 \)

PDF \( f(x) \)

Form Factors \( F_1(t), F_2(t) \)

Ji, PRL91,062001(2003)
Generalized Parton Distribution (GPD)

\[ H_f(x,0,0) = q_f(x) = -\bar{q}_f(-x) \]
\[ \tilde{H}_f(x,0,0) = \Delta q_f(x) = -\Delta \bar{q}_f(-x) \]

\[
\begin{align*}
\int dx \sum_{f} H_f(x,\xi,t) &= F_1(-t) \\
\int dx \sum_{f} E_f(x,\xi,t) &= F_2(-t) \\
\int dx \sum_{f} \tilde{H}_f(x,\xi,t) &= g_A(-t) \\
\int dx \sum_{f} \tilde{E}_f(x,\xi,t) &= g_p(-t)
\end{align*}
\]

\[ J_f = \frac{1}{2} \Delta \Sigma^f + L_f = \frac{1}{2} \int_{-1}^{1} x dx [H_f(x,\xi,0) + E_f(x,\xi,0)] \]

Ji’s sum rule
Spacelike vs. Timelike Processes
Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering

\( q^2 < 0 \)

\begin{align*}
F(\xi = \eta, t, Q^2) \xrightarrow{\text{SL} \rightarrow \text{TL}} F(\xi = -\eta, t, -Q^2), \\
F(\xi, t, Q^2) &= \int_{-1}^{1} dx \sum_{i=u,d,\ldots,g} sT^i(x, \xi)F^i(x, \xi, t, \mu^2),
\end{align*}

Timelike Compton Scattering

\( q^2 > 0 \)

\( t < 0, \text{ space-like GPD} \)
Spacelike vs. Timelike Processes
Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Meson Production

Exclusive Meson-induced DY

\[ q^2 < 0 \]

\[ t < 0, \text{ space-like GPD} \]
\[ \pi N \rightarrow \mu^+ \mu^- N \]

(PLB 523 (2001) 265)

\[
\begin{align*}
\pi \rightarrow \mu^+ \mu^- N & \quad \text{Diagram} \\
\pi(q) & \rightarrow \gamma(q') \rightarrow N(p') \quad \text{Decay} \\
\phi_\pi & \rightarrow H, E \quad \text{Decay} \\
\end{align*}
\]

\[
\begin{align*}
\frac{d\sigma}{dQ'^2 dt d(\cos \theta) d\varphi} &= \frac{\alpha_{em}}{256\pi^3} \frac{\tau^2}{Q'^6} \sum_{\lambda', \lambda} |M^{0\lambda', \lambda}(\pi^- p \rightarrow \gamma^* n)|^2 \sin^2 \theta, \\
Q'^2 &= q'^2 > 0, \\
t &= (p - p')^2, \\
\tau &= \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s - M_N^2}, \\
\eta &= \frac{(p - p')^+}{(p + p')^+}
\end{align*}
\]

\[
\begin{align*}
M^{0\lambda', \lambda}(\pi^- p \rightarrow \gamma^* n) &= -ie \frac{4\pi f_\pi}{3} \frac{1}{Q'} (p + p')^+ \bar{u}(p', \lambda') \\
&\times \left[ \gamma^+ \gamma_5 \tilde{H}^{du}(-\eta, \eta, t) + \gamma_5 (p' - p)^+ \tilde{\xi}^{du}(-\eta, \eta, t) \right] u(p, \lambda). \\
\tilde{H}^{du}(\xi, \eta, t) &= \frac{8}{3} \alpha_s \int \frac{dz}{1 - z^2} \\
&\times \int dx \left[ \frac{e_d}{\xi - x - i\epsilon} - \frac{e_u}{\xi + x - i\epsilon} \right] \\
&\times \left[ \tilde{H}^d(x, \eta, t) - \tilde{H}^u(x, \eta, t) \right],
\end{align*}
\]
\[ \pi N \rightarrow \mu^+ \mu^- N \]

(PLB 523 (2001) 265)

\[
M^{0\lambda', \lambda}(\pi^- p \rightarrow \gamma^* n) = -i e \frac{4\pi f_\pi}{3} \frac{1}{Q' (p + p')^+} \bar{u}(p', \lambda') \times \left[ \gamma^+ \gamma_5 \tilde{H}^{du}(-\eta, \eta, t) \right. \\
\left. + \gamma_5 (p' - p)^+ \frac{\tilde{d}u(-\eta, \eta, t)}{2M} \right] u(p, \lambda).
\]

\[
\tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s - M_N^2} = x_B
\]

\[
t = (p - p')^2
\]

\[
Q'^2 = q'^2 > 0
\]

\[
\eta = \frac{(p - p')^+}{(p + p')^+} = \frac{\tau}{2 - \tau}
\]

\[
\frac{d\sigma}{dQ'^2 dt d(\cos \theta) d\phi} = \frac{\alpha_{em}}{256\pi^3} \frac{\tau^2}{Q'^6} \sum_{\lambda', \lambda} |M^{0\lambda', \lambda}|^2 \sin^2 \theta,
\]
Differential Cross Sections \((Q^2, t, \tau)\)


\[
\frac{d\sigma}{d Q'^2 dt} (\pi^- p \rightarrow \gamma^n n)
\]

\[
= \frac{4\pi \alpha_{em}^2}{27} \frac{\tau^2}{Q'^8} f^2 \times \left[ (1 - \eta^2) |\mathcal{H}_d u|^2 - 2\eta^2 \text{Re}(\mathcal{H}_d u^* \mathcal{E}_d u) 
- \eta^2 \frac{t}{4M^2} |\mathcal{E}_d u|^2 \right],
\]

\( t = (p - p')^2 \)

\( \tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s - M^2_N} = x_B \)

\( Q'^2 = q'^2 > 0 \)

\( \eta = \frac{(p - p')^+}{(p + p')^+} = \frac{\tau}{2 - \tau} \)
Evaluation of Cross Sections

• Input:
  – GPD $\tilde{H}(x, \eta, t; Q^2)$, $\tilde{E}(x, \eta, t; Q^2)$
  – Pion distribution amplitude (DA) $\varphi(z; Q^2)$

• QCD evolutions:
  – GPD: Vinnikov framework for LO evolution
  – Pion DA: construction by Gegenbauer polynomials of order 3/2.

• Matrix elements of Exclusive DY.
• Differential cross sections ($Q^2, t, \tau$)
GPD $\tilde{H}(x, \eta, t)$ Double Integration

$$\tilde{H}^u(x, \eta, t) - \tilde{H}^d(x, \eta, t)$$
$$= \left[ \tilde{h}^u(x, \eta) - \tilde{h}^d(x, \eta) \right] g_A(t)/g_A(0).$$  \hspace{1cm} (6)

We take the parameterization $g_A(t)/g_A(0) = (1 - t/M_A^2)^{-2}$ with $M_A = 1.06$ GeV from [17]. The functions

$$\tilde{h}^q(x, \eta) = \int_0^1 dx' \int_{-1+x'}^{1-x'} dy'$$
$$\times \delta(x - x' - \eta y') \Delta q_V(x') \pi(x', y'),$$  \hspace{1cm} (38)

$$\pi(x', y') = \frac{3 (1 - x')^2 - y'^2}{4 (1 - x')^3}.$$  \hspace{1cm} (39)

$\tilde{H}(x, \eta = 0, t = 0)$=polarized valance distribution.
GPD $\tilde{E}(x, \eta, t)$ Pion-pole Dominance


\[
\tilde{E}^u(x, \eta, t) - \tilde{E}^d(x, \eta, t) = \Theta(\eta - |x|) \frac{1}{\eta} \phi_{\pi}\left(\frac{x}{\eta}\right) F(t)
\]

\[
F(t) = \frac{4.4 \text{ GeV}^2}{m_{\pi}^2 - t} \left[1 - \frac{B(m_{\pi}^2 - t)}{(1 - Ct)^2}\right]
\]

with $B = 1.7 \text{ GeV}^{-2}$ and $C = 0.5 \text{ GeV}^{-2}$. Note

\[
\tilde{E}^u - \tilde{E}^d(x, \xi, t) \xrightarrow{t \to m_{\pi}^2} \theta(|x| < |\xi|) \frac{1}{2|\xi|} \phi_{\pi}\left(\frac{x + \xi}{2\xi}\right) \frac{4m^2 g_A(0)}{m_{\pi}^2 - t}
\]
\[ \pi N \rightarrow \mu^+ \mu^- N \]


\[ Q'^2 = q'^2 = 5 \text{ GeV}^2 \]

\[ \tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s-M_N^2} = 0.2 \]

Cross sections increase toward small \( s \)!

\[ t = (p - p')^2 = -0.2 \text{ GeV}^2 \]

\[ (1 - \eta^2) |\tilde{H}^{du}|^2 - 2\eta^2 \text{Re}(\tilde{H}^{du*}\tilde{E}^{du}) - \eta^2 \frac{t}{4M^2} |\tilde{E}^{du}|^2 \]

blue \hspace{1cm} red \hspace{1cm} green
GPD $\tilde{H}(x, \eta, t)$ Double Integration

$$F^i(x, \xi, t) = \int_{-1}^{1} d\rho \int_{-1+|\rho|}^{1-|\rho|} d\eta \delta(\rho + \xi \eta - x) f_i(\rho, \eta, t)$$

$$+ D_i(x, t) \Theta(\xi^2 - x^2),$$

(4)

$$f_i(\rho, \eta, t) = F^i(\rho, \xi = 0, t) w_i(\rho, \eta).$$

$$F^i(\rho, \xi = 0, t) = F^i(\rho, \xi = 0, t = 0) \exp(tp_{f_i}(\rho)).$$

$$p_{f_i}(\rho) = -\alpha'_{f_i} \ln \rho + b_{f_i},$$

$$w_i(\rho, \eta) = \frac{\Gamma(2n_i + 2)}{2^{2n_i+1} \Gamma^2(n_i + 1)} \frac{[(1 - |\rho|)^2 - \eta^2]^n_i}{(1 - |\rho|)^{2n_i+1}}$$
GPD $\tilde{H}(x, \eta, t)$ Double Integration


\[ \tilde{H}^q_{\text{val}}(\rho, \xi = t = 0) = \eta_q A_q \rho^{-\alpha h_q(0)} (1 - \rho)^3 \sum_{j=0}^{2} \tilde{c}_{qj} \rho^j, \]

**Table 2** Parameters used for the GPD $\tilde{H}$. Evolution is parametrized through the variable $L = \ln(Q^2/Q_0^2)$ with $Q_0^2 = 4 \text{ GeV}^2$

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<tr>
<th></th>
<th>$u_{\text{val}}$</th>
<th>$d_{\text{val}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha(0)$</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>$\alpha'$</td>
<td>0.45 GeV$^{-2}$</td>
<td>0.45 GeV$^{-2}$</td>
</tr>
<tr>
<td>$b_h$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\tilde{c}_0$</td>
<td>$0.170 + 0.03L$</td>
<td>$-0.320 - 0.040L$</td>
</tr>
<tr>
<td>$\tilde{c}_1$</td>
<td>$1.340 - 0.02L$</td>
<td>$-1.427 - 0.176L$</td>
</tr>
<tr>
<td>$\tilde{c}_2$</td>
<td>$0.120 - 0.40L$</td>
<td>$0.692 - 0.068L$</td>
</tr>
</tbody>
</table>

42
GPD $\tilde{E}(x, \eta, t)$ Pion-pole Dominance

$\tilde{E}^u_{\text{pole}} = -\tilde{E}^d_{\text{pole}} = \Theta(|x| \leq \xi) \frac{F_P(t)}{4\xi} \Phi_\pi \left(\frac{x + \xi}{2\xi}\right),$

$F_P(t) = -m_N f_\pi \frac{2\sqrt{2} g_{\pi NN} F_{\pi NN}(t)}{t - m_\pi^2}.$

$F_{\pi NN} = \frac{\Lambda_N^2 - m_\pi^2}{\Lambda_N^2 - t'}$

with $\Lambda_N = 0.44$ GeV.

$\Phi_\pi(\tau) = 6\tau (1 - \tau) \left[ 1 + a_2 C_2^{3/2} (2\tau - 1) \right].$
Cross Sections of Exclusive DY

Cross sections increase toward small $s$!

A.V. Vinnikov, hep-ph/0604248

$\tau = \frac{Q^{'2}}{2pq} \approx \frac{Q^{'2}}{s - M_N^2} = 0.2$
Pion Distribution Amplitude
($Q^2 = 1 \text{ GeV}^2$)

\[ \phi_\pi(z) \]

- Asym
- CZ
- Kroll
- DSE

DSE (PRL 111, 092001 (2013))
Pion Distribution Amplitude

\[ \varphi_{\pi}(z, Q^2) = \varphi_{\pi}^{asym}(z)[1 + \sum_{j=2,4,6,\ldots}^{\infty} a_j^{3/2}(Q^2) C_j^{(3/2)}(z)] \]

\[ \varphi_{\pi}(z, Q^2 \to \infty) = \varphi_{\pi}^{asym}(z) = \frac{3}{4} (1 - z^2) \]

\[ C_j^{(3/2)} : \text{Gegenbauer } \alpha=3/2 \text{ polynomials} \]

<table>
<thead>
<tr>
<th>$\pi$ DA</th>
<th>Asymptotic</th>
<th>Chernyak-Zhitnitsky (CZ)</th>
<th>Kroll</th>
<th>Dyson-Schwinger equation (DSE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2 \ (\text{GeV}^2)$</td>
<td>infty</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$a_2$</td>
<td>0</td>
<td>0.56</td>
<td>0.22</td>
<td>0.20</td>
</tr>
<tr>
<td>$a_4$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.093</td>
</tr>
<tr>
<td>$a_6$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.055</td>
</tr>
</tbody>
</table>

\[ a_n^{\text{LO}}(\mu_F^2) = a_n(\mu_0^2) \left[ \frac{\alpha_s(\mu_F^2)}{\alpha_s(\mu_0^2)} \right] \gamma_n^{(0)}/(2b_0) \]  

QCD evolution
Pion Distribution Amplitude

$Q^2 = 4 \text{ GeV}^2$

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

$Q^2 = 100 \text{ GeV}^2$

$Q^2 = 10000 \text{ GeV}^2$
Pion DA Dependence: Pire GPD

The differential cross sections of exclusive DY process shows good sensitivity to pion DA $\varphi_\pi(z)$. 
The differential cross sections of exclusive DY process shows good sensitivity to pion DA $\varphi_\pi(z)$.
The discrimination of pion DA and GPD could be done in multi-dimensional distributions.
Hard exclusive production process
Constituent-Counting Rule in Hard Exclusive Process
Kawamura et al., PRD 88, 034010 (2013)

\[ \frac{d\sigma}{dt} (a + b \rightarrow c + d) = \frac{1}{s^{n-2}} f(\theta_{CM}) \]

\[ n = n_a + n_b + n_c + n_d \]

\[ n = 1 + 3 + 2 + 3 = 7 \]
\[ \gamma + p \rightarrow \pi^+ + n \]

\[ \pi^- + p \rightarrow K^0 + \Lambda \]
Quark Degrees of $\Lambda(1405)$

Kawamura et al., PRD 88, 034010 (2013)

$\pi^- + p \rightarrow K^0 + \Lambda(1405)$

$J_{PC}^i = 1^{--}(1405)$

$\frac{d^2\sigma}{dtds} = \frac{\mathcal{B}}{(s/\Lambda^2)^2}\left(\frac{\Lambda^2}{s}\right)^{3/2} = \frac{3\mathcal{B}}{(s/\Lambda^2)^2}\left(\frac{\Lambda^2}{s}\right)^{3/2}$

$\frac{d\sigma}{dQ} = \frac{\mathcal{B}}{s^{3/2}}$

A $\Xi(1530)/\bar{\Xi}(1530)$ resonance

$5q$ for $\Lambda(1405)$

$3q$ for $\Lambda(1405)$

1-100 pb

Thomas (’73)

Model I

Model II

5q scaling

J-PARC
Charm production process
WA98: π(252GeV) N→J/ψ +X
PRL 58, 2523 (1987)

qqbar annihilation dominating and exclusive production?

\[ d^2\sigma/d\cos\theta d\phi = 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{1}{2} \nu \sin^2 \theta \cos 2\phi. \]

FIG. 4. The J/ψ decay angular distribution vs cosθ for the five regions of φ, and summed over all φ in the highest x_F bin, 0.95 < x_F < 1.0. The histograms are the result of the fit described in the text. (a) -π < φ < -0.6π, (b) -0.6π < φ < -0.2π, (c) -0.2π < φ < 0.2π, (d) 0.2π < φ < 0.6π, (e) 0.6π < φ < π, (f) -π < φ < π.
Cornell and SLAC:

SLAC:
Double Arm: published
Single arm: unpublished
large errors <12 GeV

\[ \sigma : \text{SLAC} \approx \text{Cornell} \]

\[ \frac{d\sigma}{dt} = A \cdot \exp Bt \]

E_\gamma GeV \quad 11. \quad 19
B (GeV)^{-2} \quad 1.13 \pm 0.18 \quad 2.9 \pm 0.3

Indication: a slow decrease of cross section towards the threshold
Production near threshold

Should probe the particle distributions at high \( x \).
Several constituents from the target should take part.
No detailed calculation exists so far.
Qualitative arguments on \( \sigma(E_\gamma) \)

\[
\frac{d\sigma}{dt} = N_2 g v \frac{(1-x)^2}{R^2 M^2} F_1 \left( \frac{t}{4} \right) (s - m_p^2)^2 \quad \frac{d\sigma}{dt} = N_3 g v \frac{(1-x)^0}{R^4 M^4} F_1 \left( \frac{t}{9} \right) (s - m_p^2)^2
\]

where:
\( x = \frac{S_{\text{thresh}} - m_p^2}{S - m_p^2} \), \( M = 2 m_c \), \( R \approx 1/m_c \)

- Applicable at \( x \approx 1 \Rightarrow E_\gamma < 12 - 15 GeV \)
- The factors \( N \) - fit to the data
Leading Hadron Production from Intrinsic Charm

Coalescence of Comoving Charm and Valence Quarks Produce \( J/\psi, \Lambda_c \) and other Charm Hadrons at High \( x_F \)
J-PARC: An Exotic Charm Factory!

- Charm quarks at high $x$ -- allows charm states to be produced with minimal energy
- Charm produced at low velocities in the target -- the target rapidity domain $x_F \sim -1$
- Charm at threshold -- maximal domain for producing exotic states containing charm quarks
- Attractive QCD Van der Waals interaction -- “nuclear-bound quarkonium”
  Miller, sjb; de Teramond,sjb
- Dramatic Spin Correlations in the threshold Domain $\sigma_L$ vs. $\sigma_T, A_{NN}$
- Strong SSS Threshold Enhancement
A neutron target would be useful for the search of some exotic charmed baryons like $d du u \bar{c}$ in I=0 channel.
Missing mass Spectroscopy

- Large Acceptance, Multi-Particle
  - K, π from D⁰ decays
  - Soft π from D*⁻ decays
  - (Decay products from Υ_c*)
- High Resolution
- High Rate
  - SFT/SSD op. >10M/spill at K1.8

Use forward D mesons production
No Bias measurements up to 3GeV/c² of Charmed Baryon mass

Stage-1 approved by J-PARC PAC-18, August 12, 2014.
J-PARC E50 Spectrometer + MuID

Acceptance: ~ 60% for $D^*$, ~80% for decay $\pi^+$
Resolution: $\Delta p/p \sim 0.2\%$ at ~5 GeV/c (Rigidity: ~2.1 Tm)
## Yield Estimation

<table>
<thead>
<tr>
<th>Beam Energy</th>
<th>10 GeV/c</th>
<th>15 GeV/c</th>
<th>20 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Intensity</td>
<td>High</td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Total Cross Section</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of Exclusive DY</td>
<td>High</td>
<td></td>
<td>Low</td>
</tr>
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<td>Low</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Acceptance</td>
<td>Low</td>
<td></td>
<td>High</td>
</tr>
</tbody>
</table>

**π^- beam** (prod. angle 0 deg)  
**π^+ beam** (prod. angle 3.1 deg)
Yield Estimation

Assumptions:

- J-PARC High-\(p\) Beam Line
- Beam Time
  - \(\pi^-\) beam : 50 days (prod. angle 0 deg)
  - \(\pi^+\) beam : 150 days (prod. angle 3.1 deg)

- \(I_{\text{beam}} = 10^7 \pi/s\), Target; 57cm LH\(_2\), \(\varepsilon(\text{DAQ, Tracking, PID}) = 0.9*0.7*0.9\), \(\rightarrow 1\) events/day/pb
- Beam momentum resolution: \(\Delta p/p = 0.1\%\)
- Detector resolution: \(\Delta M/M = 1\%\)
Yield Estimation

Event Generator

- Inclusive Drell-Yan
  * Pythia 6.4.26

- Exclusive Drell-Yan

- Background
  * JAM 1.132

Particle Transportation + Detector

* Geant 4.9.3
  (E-50 spectrometer + Muon ID)

Total Cross Section

Inclusive Drell-Yan ($M_{\mu\mu}>1.5$ GeV)

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>$\pi^-$</th>
<th>$\pi^+$</th>
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<tbody>
<tr>
<td>10</td>
<td>2.11 nb</td>
<td>0.323 nb</td>
</tr>
<tr>
<td>15</td>
<td>2.71 nb</td>
<td>0.493 nb</td>
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<td>20</td>
<td>3.08 nb</td>
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Exclusive Drell-Yan ($M_{\mu\mu}>1.5$ GeV)

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<tr>
<td>10</td>
<td>9.98 pb</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>7.53 pb</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>5.83 pb</td>
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<tr>
<td>10</td>
<td>26.9 mb</td>
<td>24.8 mb</td>
</tr>
<tr>
<td>15</td>
<td>25.8 mb</td>
<td>24.1 mb</td>
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<td></td>
</tr>
<tr>
<td>20 GeV</td>
<td>5.83 pb</td>
<td></td>
</tr>
</tbody>
</table>

Background might be several times larger

<table>
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</tr>
</thead>
<tbody>
<tr>
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<td>25.1 mb</td>
<td>23.5 mb</td>
</tr>
</tbody>
</table>
\[ \pi^- p \rightarrow \mu^+ \mu^- n \]

\[ M_X \text{ In E-50 Spectrometer + MuID} \]

\[ \pi^- \text{ beam 50 days} \]

\[ 1.5 < M_{\mu^+\mu^-} < 2.9 \text{ GeV/c}^2 \]

Beam Momentum

- **10 GeV**

- **15 GeV**

- **20 GeV**

\[ \text{Nevent (0.01 GeV/c}^2) \]

\[ \text{Missing Mass } M_X \text{ (GeV/c}^2) \]

\[ \text{Exclusive DY} \]

\[ \text{Inclusive DY} \]

\[ \text{BG} \]

The signal of exclusive Drell-Yan processes can be clearly identified in the missing mass spectrum of dimuon pairs.

Because of the low event rate, this study could be accommodated into the E50 experiment.
GPD($x_B, Q^2$) in both space-like and time-like regime

J-PARC’s results in the time-like and large-$Q^2$ region will be complementary to what to be obtained in space-like processes from the deeply virtual Compton scattering (DVCS) deeply virtual meson scattering (DVMS) process to be measured in JLab.
Inclusive DY

$$\left(\pi^+/\pi^-\right) p \rightarrow \mu^+ \mu^- X$$

$d/u$ measurement with E-50 Spectrometer + MuID

$$\pi^+ \text{ beam } 150 \text{ days}$$
$$\pi^- \text{ beam } 50 \text{ days}$$

$$1.5 < M_{\mu^+\mu^-} < 2.9 \text{ GeV/c}^2$$

Beam Momentum

10 GeV

15 GeV

20 GeV

$$\frac{d}{u}$$

Statistics strongly depends on the prod. angle for secondary beam

Red lines : CTEQ6.6M
Experimental Difficulties of Detecting $\pi^- p \rightarrow K^0 \Lambda(1405)$

• Multi-particle Acceptance:
  $\pi^- + p \rightarrow K^0 + \Lambda(1405)$
  $K^0 \rightarrow \pi^+ + \pi^-$
  $\Lambda(1405) \rightarrow \pi + \Sigma$

• Background?
Pion-Induced Exclusive Drell-Yan Process

Bernard Pire, IWHS2011

Small cross sections

Large \( t = (q - q')^2 \)

\[ \phi_\pi : \text{pion distribution amplitude (DA) } \]

- DA characterizes the minimal valence Fock state of hadrons.
- DA of pion are also explored by pion-photon transition form factor in Belle and Barbar Exps.

\[ \text{TDA : } \pi \text{-} \text{N transition distribution amplitude} \]

- TDA characterizes the next-to-minimal valence Fock state of hadrons.
- TDA of pion-nucleon is related to the pion cloud of nucleons.

Exclusive Vector Boson Production

- $\pi^- p \rightarrow \gamma^* n$
- $\pi^- p \rightarrow \gamma^* \Delta^0$
- $\pi^- n \rightarrow \gamma^* \Delta^-$
- $\pi^+ n \rightarrow \gamma^* p$
- $\pi^+ p \rightarrow \gamma^* \Delta^{++}$
- $\pi^+ n \rightarrow \gamma^* \Delta^+$
- $\pi^- p \rightarrow J/\psi n$
- $\pi^- p \rightarrow J/\psi \Delta^0$
- $\pi^- n \rightarrow J/\psi \Delta^-$
- $\pi^+ n \rightarrow J/\psi p$
- $\pi^+ p \rightarrow J/\psi \Delta^{++}$
- $\pi^+ n \rightarrow J/\psi \Delta^+$
New Physics Search in Drell-Yan like Processes
Dark Photon A’

Acceptance: ~ 60% for $D^*$, ~80% for decay $\pi^+$
Resolution: $\Delta p/p \sim 0.2\%$ at ~5 GeV/c (Rigidity: ~2.1 Tm)
Summary (I)

• High-energy hadron beam at J-PARC is ideal for studying hard exclusive processes.
• The study of $\pi$-induced DY/charm production and hard exclusive processes will offer important understanding on
  • **Nucleon structure**: valence quarks PDF; TMD (BM), GPD (TDA)
  • $\pi$ **structure**: DA and PDF
  • **Structure of exotic hadrons**
  • **$J/\psi$ production mechanism, exotic charmed baryons**
Summary (II)

- Spectrometer with large acceptance and good mass resolution is required for the measurement and such measurement in E-50 conceptual detectors seems promising.
- Availability of deuterium target together with the detection of recoiled protons will enable the measurement of flavor separation of BM functions, valance-quark distributions at large-x and search for some exotic charmed baryons.
- More collaborators are critically necessary!
Questions

• Will the factorization of exclusive DY process based on a crossing symmetry of DVMP process be a major concern?

• What is the relationship between the inclusive DY process at xF→ 1 limit and the exclusive one? If these two processes are different, how to differentiate them experimentally, e.g. the missing mass or angular distribution of dimuon pairs?

• What is the relationship between the inclusive J/psi production process at xF→ 1 limit and the exclusive one?