Exclusive Hard Processes for Studying Hadron Structures at J-PARC

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September 23-26, 2019, Tsukuba, Japan
Outline

• Secondary Beams in High-momentum beamline at Hadron Hall, J-PARC
• Physics programs: [K. Shirotori, Thursday afternoon]
  – Charm and strangeness production
  – Hard exclusive hadronic process
  – Exclusive Drell-Yan process
• Summary
J-PARC Facility (KEK/JAEA)

South to North

Experimental Areas

Neutrino Beams (to Kamioka)

Materials and Life Experimental Facility

Linac

3 GeV Synchrotron

50 GeV Synchrotron

JFY2007 Beams

JFY2008 Beams

JFY2009 Beams

Bird's eye photo in January of 2008
J-PARC High-momentum Beam Line (Hi-P BL)  
New Primary Beam Line (high-p) in Hadron Hall

30 GeV proton ($\sim 10^{10} - 10^{12}$ pps)  
Beam line will be available around the end of JFY2019.
J-PARC High-momentum Beam Line (Hi-P BL)

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

15kW Loss Production Target

30 GeV proton
Unseparated Secondary Beam In High-momentum Beam Line

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

* Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m
Hard exclusive hadronic process
Quark Structure of Exotic Hadrons

Various excitations of baryons

- **Conventional**
- **Exotic**

Physical state: superposition of $3q$, $5q$, MB, ...

\[
|\Lambda(1405)\rangle = N_{3q}\left|uds\right\rangle + N_{5q}\left|uds\, q\bar{q}\right\rangle + N_{KN}\left|\bar{K}N\right\rangle + \cdots
\]

T. Hyodo, NSTAR 2015
Λ(1405)

- S.-i. Nam and A. Hosaka [PRC 100, 015205 (2019); 1902.09106]: chiral unitary model, $\bar{K}N$ molecule.
- Y. Kamiya and T. Hyodo [PRC 93, 035203 (2016); 1509.00146]: compositeness property, $\bar{K}N$ molecule.
- K. Miyahara and T. Hyodo [PRC 93, 015201 (2016); 1506.05724]: KN local potential based on chiral SU(3) dynamics
- J. Hall et al. [PRL 114, 132002 (2015); 1411.3402]: Lattice QCD, $\bar{K}N$ molecule.
- T. Sekihara and S. Kumano [PRC 89, 025202 (2014); 1311.4637]: radiative decay for determining the compositeness.
- L. Roca and E. Oset [PRC 87, 055201 (2013); 1301.5741]: Two-pole structures, $\bar{K}N$ and $\pi\Sigma$.
- …

Production channels, photon asymmetry, decay, size and medium effect …
J-PARC E31 Experiment

measuring an $\bar{K}N \rightarrow \pi \Sigma$ scattering below the $\bar{K}N$ threshold in the $d(K^-,n)\pi \Sigma$ reactions

1 GeV/c

- 2 step process
- Producing $\Lambda(1405)$ by virtual $\bar{K}$

ChiralUnitary Model:
D. Jido et al., NPA750(03)181

The 52nd Reimei Workshop, Jan 2019
Large-angle (Hard) Exclusive Process
\( a + b \rightarrow c + d \)


\[
\frac{d\sigma_{ab\rightarrow cd}}{dt} \approx \frac{1}{16\pi s^2} \sum_{\text{pol}} |M_{ab\rightarrow cd}|^2,
\]

\( s, |t| \gg m_i^2 (i = a, b, c, d) \)

\[
M_{ab\rightarrow cd} = \int [dx_a][dx_b][dx_c][dx_d] \phi_c([x_c])\phi_d([x_d])
\times H_{ab\rightarrow cd}([x_a], [x_b], [x_c], [x_d], Q^2) \phi_a([x_a])\phi_b([x_b]),
\]

[\hat{M}_{ab\rightarrow cd}] = \begin{bmatrix}
\frac{1}{(P^2)^{n/2-1}} & \frac{1}{P^{n/2-2}} \\
\frac{1}{P^{n/2-2}} & \frac{1}{s^{n/2-2}}
\end{bmatrix}

Leading and connected Feynman diagrams

Gluon propagator

External quarks

Quark propagator
Large-angle (Hard) Exclusive Process

\[ a + b \rightarrow c + d \]


\[
\frac{d\sigma_{ab\rightarrow cd}}{dt} \approx \frac{1}{16\pi s^2} \sum_{\text{pol}} |M_{ab\rightarrow cd}|^2,
\]

\[ s, |t| \gg m_i^2 \quad (i = a, b, c, d) \]

\[ M_{ab\rightarrow cd} = \int [dx_a][dx_b][dx_c][dx_d]\phi_c(x_c)\phi_d(x_d) \times H_{ab\rightarrow cd}(x_a, x_b, x_c, x_d, Q^2)\phi_a(x_a)\phi_b(x_b), \]

\[
\left[ \hat{M}_{ab\rightarrow cd} \right] = \begin{bmatrix}
\frac{1}{(P^2)^{n/2-1}} & 1 \\
\frac{1}{P^{n/2-2}} & P^{n/2}
\end{bmatrix} = \begin{bmatrix}
\frac{1}{s^{n/2-2}}
\end{bmatrix}.
\]

Gluon propagator

External quarks

Quark propagator
Constituent-Counting Rule in Hard Exclusive Process


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


\[ \gamma + p \rightarrow \pi^+ + n \]

\[ \pi^- + p \rightarrow K^0 + \Lambda \]
Constituent-Counting Rule in Photoproduction of Hyperons
Chang, Kumano, Sekihara, PRD 93, 034006 (2016)

\[ \Lambda; \ n=10.0 \]

\[ \Sigma; \ n=11.4 \]

\[ \Lambda(1405); \ n=10.6 \]

\[ \Lambda(1520); \ n=9.8 \]
Valence-Quark Degrees of $\Lambda(1405)$


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

$J^-_{PARC}$

T. Sekihara
KEK workshop 2015
Drell-Yan process
Multi-dimensional Partonic Structures

\[ f(x, k_\perp) \]

Wigner Distributions

\[ W(x, k_\perp, r_\perp) \]

Generalized Parton Distributions (GPDs)

\[ f(x, \xi, t) \]

Transverse Momentum Dependent Distributions (TMDs)

\[ d^2 r_\perp \]

\[ d^2 k_\perp \]

\[ \delta z_\perp \sim 1/Q \]

Parton Distribution Functions

\[ f(x) \]

\[ Q^2 \]

Form Factors

\[ F_{1,2}(t) \]

Electromagnetic Form Factors

- Proton
  - Space-like ($q^2 < 0$): Elastic scattering
  - Time-like ($q^2 > 0$): $e^+e^-$ or hadron pair annihilation

- Pion
  - Space-like ($q^2 < 0$)
  - Time-like ($q^2 > 0$): GE=GM(TL)

https://goo.gl/SZuBwe
Multi-dimensional Partonic Structures

\[ f(x, k_\perp) \]

Transverse Momentum Dependent Distributions (TMDs)

\[ W(x, k_\perp, r_\perp) \]

Wigner Distributions

\[ f(x, \xi, t) \]

Generalized Parton Distributions (GPDs)

\[ F_{1,2}(t) \]

Form Factors

Deep Inelastic Scattering (DIS) and Drell-Yan Processes

\[ \sigma_{\text{proton}}(x, Q^2) \sim f_{\text{nucleon}}(x, Q^2) \otimes \hat{\sigma}_{\text{hard}}(Q^2) \]
Parton distributions of Protons
From Global Analysis

MMHT14 NNLO, $Q^2 = 10 \text{ GeV}^2$

$x f(x, Q^2)$

$Q = 2 \text{ GeV}$

$\bar{u} - \bar{d}$

arXiv:1412.3989

arXiv:1208.1178
\[ \tilde{d}(x) - \tilde{u}(x) \text{ from Lattice QCD} \]

\[ \tilde{q}(x) = -q(-x) \]


-C. Alexandrou et al., PRD 96, 014513 (2017)
Multi-dimensional Partonic Structures

\[ f(x, k_{\perp}) \]

\[ W(x, k_{\perp}, r_{\perp}) \]

\[ f(x, \xi, t) \]

\[ F_{1,2}(t) \]

Wigner Distributions

Generalized Parton Distributions (GPDs)

Transverse Momentum Dependent Distributions (TMDs)

Parton Distribution Functions

Form Factors

Generalized Parton Distributions

Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering

\[ q^2 < 0 \]

\[ t < 0 \]

\[ -1 < x < \xi, \xi < x < 1 \]

Deeply Virtual Meson Production

\[ q^2 < 0 \]

\[ t < 0 \]

\[ |x| < \xi \]

Collins, Frankfurt and Strikman, PRD 56, 2982 (1997)
Tomographic image of the proton

JLAB CLAS DVCS data

PRD 95, 011501(R) (2017)
Generalized Parton Distributions

Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering

\[ q^2 < 0 \]
\[ x + \xi, \xi < x < 1 \]
\[ s \leftrightarrow u \text{ channel crossing} \]

Deeply Virtual Meson Production

\[ q^2 < 0 \]
\[ |x| < \xi \]
\[ s \leftrightarrow u \text{ channel crossing} \]

Time-like Compton Scattering

\[ q^2 > 0 \]
\[ t < 0 \]
\[ -1 < x < \xi, \xi < x < 1 \]

Exclusive meson-induced DY

\[ q^2 > 0 \]
\[ t < 0 \]
\[ |x| < \xi \]

Collins, Frankfurt and Strikman, PRD 56, 2982 (1997)
\[ \pi N \rightarrow l^+ l^- N \] (handbag diagram)


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

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

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

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

\[ \tilde{x} = -\frac{(q + q')^2}{2(p + p') \cdot (q + q')} \approx -\frac{Q'^2}{2s - Q'^2} = -\xi \]

\[ \frac{d\sigma}{dQ'^2 \, dt \, d(\cos\theta) \, d\varphi} = \frac{\alpha_{em}}{256\pi^3} \frac{\tau^2}{Q'^6} \sum_{\lambda', \lambda} |M^{0\lambda', \lambda}|^2 \sin^2 \theta, \]

\[ \left. \frac{d\sigma_L}{dt \, dQ'^2} \right|_{\tau} = \frac{4\pi\alpha_{em}^2}{27} \frac{\tau^2}{Q'^8} f_\pi^2 \left[ (1 - \xi^2) |\tilde{H}^{du}(\tilde{x}, \xi, t)|^2 \right. \]

\[ - 2\xi^2 \text{Re} \left( \tilde{H}^{du}(\tilde{x}, \xi, t)^* \tilde{E}^{du}(\tilde{x}, \xi, t) \right) - \xi^2 \frac{t}{4m_N^2} |\tilde{E}^{du}(\tilde{x}, \xi, t)|^2 \bigg], \]
Beyond the Leading Twist

\[
\frac{d\sigma}{dt dQ'^2 d\cos \theta d\phi} = \frac{3}{8\pi} \left( \sin^2 \theta \frac{d\sigma_L}{dt dQ'^2} + \frac{1 + \cos^2 \theta}{2} \frac{d\sigma_T}{dt dQ'^2} \right)
\]

\[
+ \sin 2\theta \cos \varphi \frac{d\sigma_{LT}}{\sqrt{2} dt dQ'^2} + \sin^2 \theta \cos 2\varphi \frac{d\sigma_{TT}}{dt dQ'^2} \right)
\]

Transversity GPDs: \(H_T, \bar{E}_T\)

S.V. Goloskokov, P. Kroll, PLB 748 (2015) 323
HADES: $\pi^- p \rightarrow ne^+ e^-$ with $P_{\pi^-} < 1$ GeV

Electromagnetic TFF for baryons ($N^*$) Joachim Stroth | QNP2018

$\pi^- p \rightarrow N^* \rightarrow n(\gamma^*, \rho, \eta...) \rightarrow ne^+ e^-$

$\pi^- + p \rightarrow \pi^- + \pi^+ + n$

$\rho_{\pi} = [556, 690, 748, 800]$ MeV

$Q' < 0.5$ GeV

No sensitivity to the partonic structures!
Exclusive DY cross sections

J-PARC \((P_{\pi}=10-20 \text{ GeV})\) \(\sigma = 5 \sim 15 \text{ pb}\)

CERN COMPASS \((P_{\pi}=190 \text{ GeV})\) \(\sigma = 0.65 \text{ pb}\)

Dropping with the increase of \(\sqrt{s}\)
Optimization of Exclusive Drell-Yan Measurement

- **Factorization**: $Q^2 \gg 1 \text{ GeV}^2$
- **Cross sections**:
  - Cross sections decrease rapidly with an increase of $Q^2$. $Q^2 < 9 \text{ GeV}^2$
  - $\sqrt{s}$ should be small enough to keep $\sqrt{\tau} = \frac{Q}{\sqrt{s}} = \sqrt{x_\pi x_N}$ large enough. Take $Q = 2 \text{ GeV}$, $\sqrt{\tau} = \sqrt{0.5 \times 0.3} = 0.39$, $\sqrt{s} = 5 \text{ GeV}$, pion beam momentum should be less than 15 GeV.
- **Exclusivity**: missing-mass technique
  - Good resolution for missing mass
  - Open aperture without the hadron absorber before measuring the momentum of lepton tracks
  - Reasonably low track multiplicity

The high-momentum beam line at J-PARC with 10-20 GeV $\pi^-$ beam ($\sqrt{s} = 4 - 6 \text{ GeV}$) is most appropriate for the measurement!
J-PARC E50 Experiment (Charmed Baryon Spectroscopy)

Stage-1 approved by J-PARC PAC-18, August 12, 2014.

Acceptance:
~ 60% for $D^*$,
~ 80% for decay $\pi^+$

Resolution:
$\Delta p/p \sim 0.2\%$ at $\sim 5$ GeV/c
(Rigidity: $\sim 2.1$ Tm)

Cross Section:
$\sigma(\Lambda_c) \sim 1$ nb (no meas.)

H. Noumi, KEK workshop 2015
Exclusive Drell-Yan measurement in J-PARC E50 Spectrometer

Top View

Original Configuration for Charmed Baryon Spectroscopy

Stage-1 approved by J-PARC PAC-18, August 12, 2014.

Proposal is currently being prepared.
Simulation

Assumptions:

- Target: 57cm LH$_2$ ($n_{TGT} = 4$ g/cm$^2$)
- Beam momentum resolution ($\Delta p/p$) = 0.1%
- $1.83/1.58/1.00 \times 10^7 \pi^-$/spill for 10/15/20 GeV beam
- Data Taking: 50 days (*Proposal of E50: 100 days)
- E50 spectrometers + $\mu$ ID system

Expected cross sections for the exclusive/inclusive Drell-Yan processes

<table>
<thead>
<tr>
<th></th>
<th>Exclusive Drell-Yan</th>
<th>Inclusive Drell-Yan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_{\mu^+\mu^-} &gt; 1.5$ GeV, $</td>
<td>t - t_0</td>
</tr>
<tr>
<td></td>
<td>“BMP2001”</td>
<td>“GK2013”</td>
</tr>
<tr>
<td>$P_\pi = 10$ GeV</td>
<td>6.29 pb</td>
<td>17.53 pb</td>
</tr>
<tr>
<td>$P_\pi = 15$ GeV</td>
<td>4.67 pb</td>
<td>10.65 pb</td>
</tr>
<tr>
<td>$P_\pi = 20$ GeV</td>
<td>3.70 pb</td>
<td>7.25 pb</td>
</tr>
</tbody>
</table>

- Total hadronic interaction cross sections of $\pi^- p$ is about 20-30 mb while the production of $J/\psi$ is about 1-3 nb

The exclusive Drell-Yan events could be identified by the signature peak at the nucleon mass in the missing-mass spectrum for all three pion beam momenta.

- Data Taking: 50 days
- $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV
- $|t - t_0| < 0.5$ GeV$^2$
- “GK2013” GPDs
The statistics sensitivity is good enough for discriminating the predictions from two current GPD models.
Kinematic regions of GPDs explored by space-like and time-like processes

- JLAB, HERMES, COMPASS → Space-like approach
- J-PARC → Time-like approach
“GPD” and “Transition GPD”

“Transition GPD”: L. L. Frankfurt et al., PRD 60, 014010 (1999)

- $\pi^- p \rightarrow \gamma^* n$
- $\pi^- p \rightarrow \gamma^* \Delta^0$
- $\pi^- n \rightarrow \gamma^* \Delta^-$
- $\pi^+ n \rightarrow \gamma^* p$
- $\pi^+ p \rightarrow \gamma^* \Delta^{++}$
- $\pi^+ n \rightarrow \gamma^* \Delta^+$
- $K^- p \rightarrow \gamma^* \Lambda$
- $K^- p \rightarrow \gamma^* \Lambda(1405)$
- $K^- p \rightarrow \gamma^* \Lambda(1520)$
- $K^- n \rightarrow \gamma^* \Sigma^-$
- $K^+ n \rightarrow \gamma^* \Theta^+$
\[ \pi N \rightarrow l^+ l^- N \quad \text{vs.} \quad KN \rightarrow l^+ l^- \Lambda \]

\[ s = 30 \text{ GeV}^2; Q'^2 = 4 \text{ GeV}^2 \]

Separated high-momentum kaon beamline is required!
LETTER OF INTENT

Studying Generalized Parton Distributions with Exclusive Drell-Yan process at J-PARC

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A total of 23 collaborators from Japan, Korea, U.S. and Taiwan

Submitted to the 27th J-PARC PAC, Jan. 16th - 18th 2019
Summary

• It is unique to investigate the constituent-quark and partonic structures of (exotic) hadrons via the hard exclusive processes.

• Preliminary study shows that the measurement of exclusive Drell-Yan process is feasible within the E-50 spectrometer in the coming high-momentum beamline at J-PARC.