Exclusive Hard Processes for Studying Hadron Structures at J-PARC

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With an appropriate hard scale, exclusive hadronic processes could provide novel information of the internal quark-gluon configurations of hadrons. The availability of 10-20 GeV secondary meson beam in the coming high-momentum beam line of Hadron Hall at J-PARC offers an unique opportunity to carry out the measurements of the exclusive hard processes. We address this interesting approach by two possibilities: (a) $\pi^-$ $p \rightarrow K^0\Lambda(1405)$ for the constituent quark structure of $\Lambda(1405)$, and (b) exclusive pion-induced Drell-Yan process $\pi^- p \rightarrow \gamma^* n \rightarrow l^+ l^- n$ for the generalized parton distributions (GPDs) of nucleons. Realization of such measurements at J-PARC will open up a new way of accessing the internal quark structure of exotic hadrons and also the nucleon GPDs based on a solid theoretical foundation of perturbative QCD.

KEYWORDS: Exclusive hard process, Hadron Structure, $\Lambda(1405)$, Drell-Yan process

1. Introduction

Exclusive hadronic processes with a full identification of the initial and final states are mostly studied at low energies considering large enough cross sections. Nevertheless, the sensitivity of the reactions to the partonic structures of hadrons involved is constrained by the soft energy scale. With the modern high-luminosity accelerators and large-acceptance detector systems, exclusive processes probed with hard scales become an effective tools to explore the partonic structure of hadrons. We consider such possible physics programs in coming high-momentum beam line of Hadron Hall at J-PARC.

An important feature of the J-PARC accelerator is the high intensity of the primary 30-GeV proton beam [1]. A high-momentum beam line is under construction at the Hadron Hall now. In addition, by installing a thin production target at the branching point, one can obtain unseparated secondary beams such as pions, kaons and anti-protons. Constrained by the radiation safety of beam loss from a 20-mm long gold target, the maximum intensities of primary proton beam are $9 \times 10^{13}$ protons per pulse (ppp) at a 5.2 sec repetition cycle time (83.8 kW). The momentum profile of secondary beams for $\pi^-$ would be 10-20 GeV with the typical intensity of $10^7$-$10^8$/sec. A beam momentum resolution of better than 0.1% can be obtained by using the dispersive method. The high momentum beamline of delivering the primary 30-GeV proton beam is scheduled to complete in early 2020. Afterward it might take 5 years or more to make the secondary beam available.

In this proceedings, we consider two kinds of hard exclusive reactions: exclusive $\Lambda(1405)$ production at large momentum transfer, and exclusive $\pi$-induced Drell-Yan process. Both of them are novel approaches to access important partonic structure of hadrons and are planned to be measured in J-PARC E50 experiment. We introduce the physic importance of measuring these two processes.

Speaker

1
The feasibility of carrying out the exclusive Drell-Yan process will be discussed in details.

2. Constituent quark configuration of \( \Lambda(1405) \)

The exact constituent quark configuration of \( \Lambda(1405) \) has been a long-standing and controversial question. This exotic hadron has been considered as a conventional 3-\( q \) baryon, \( \bar{K}N \) molecule or exotic 5-\( q \) pentaquark. There have been tremendous theoretical and experimental efforts in revealing its true properties [2, 3]. Recently an important result is the evidence of \( \Lambda(1405) \) as \( \bar{K}N \) molecule from the lattice QCD calculation [4]. Nevertheless the requirement of experimental confirmation remains. Despite many measurements of production and decay channels as well as the medium effect of \( \Lambda(1405) \), there is a lack of conclusive results of its true hadronic configuration.

The constituent-counting rule based on the perturbative QCD [5] has been known for a long time. From the perspective of pQCD, hard gluon exchange should occur to maintain the exclusive nature of an exclusive hard process [6]. In a hard exclusive process of strong interaction, the degree of power suppression depends on the sum of constituent-quark degrees of freedom for all participating particles. The differential cross sections of a hadronic interaction \( a + b \to c + d \) at a large scattering angle \( \theta \) in the CM system should scale like \( d\sigma/dt \sim \sqrt{s}^{-n} f(\theta_{CM}) \), where \( s \) and \( t \) are Mandelstam variables, \( \theta_{CM} \) is the scattering angle in the CM system and \( n \) is the sum of numbers of elementary constituents in hadron \( a, b, c \) and \( d \). The measurement of scaling factor \( n \) of the exclusive production reaction of the exotic hadron would provide the information of its quark configuration.

The data of photoproduction of hyperon resonances are used for a preliminary check of constituent-counting rule in Ref. [7]. As shown in Fig. 1, the best-fit scaling factor \( n \) in the region of \( \sqrt{s} \geq 2.5 \) GeV are 10 and 9.2 for the \( \gamma p \to K^+\Lambda \) and \( K^+\Sigma^0 \) reactions, respectively. This indicate that the number of the elementary constituents is consistent with \( n_p = 1, n_p = 3, n_{K^+} = 2, \) and \( n_{\Lambda} = n_{\Sigma^0} = 3 \).

Then, the analysis is made for the photoproduction of the hyperon resonances \( \Lambda(1520) \) and \( \Lambda(1405) \). The obtained values of \( n \) are 9.8 and 10.6 for these two cases. The accuracy of current data is not good enough to conclude the numbers of their quark configuration.

Similar ideas have been suggested for checking the constituent quark content of \( \Lambda(1405) \) with pion beam at J-PARC. In Ref. [6] Kawamura et al. obtained the cross section of of \( \pi^- p \to K^0\Lambda(1405) \) \( d\sigma/d\Omega = 1.09 \pm 0.21 \mu b/sr \) at \( \sqrt{s} = 2.02 \) GeV, assuming the scaling behavior of \( \Lambda(1405) \) as a 5-\( q \) hadron. Then they predicted the cross section of \( \pi^- p \to K^0\Lambda(1405) \) at CM production angle of 90 degree to be in the order of either 100 pb or a few pb at J-PARC energy of \( \sqrt{s} = 4.5 \) GeV, depending on the scaling relation of 3-\( q \) or 5-\( q \) nature of \( \Lambda(1405) \). Because of the relatively large \( \sqrt{s} \) compared to that of photoproduction data, the dependence of production cross sections on the nature of constituent quark shall be good enough to be discriminated by measurements done at J-PARC. Achieving the determination of energy scaling behavior of \( \Lambda(1405) \) shall hopefully provide a robust experimental test of the constituent quark properties of this exotic hadron.

3. Exclusive Drell-Yan process

In recent decades, tremendous efforts have been spent in extending the measurements to the multi-dimensional partonic structure of nucleons: generalized parton distributions (GPDs) [8] and transverse-momentum-dependent parton distribution functions (TMDs) [9]. The multidimensional information becomes essential for a deeper understanding of the partonic structures of the nucleon, including the origin of the nucleon spin and its flavor structure. With a factorization of perturbatively calculable short-distance hard part and universal long-distance soft hadronic matrix elements, the nucleon parton distributions, which are the common non-perturbative objects, could be obtained from various spacelike and timelike reactions. Taking into account the QCD evolution effect, the experimental verification of the universality of the nucleon parton distributions in both spacelike and
Fig. 1. Check of scaling behavior of constituent-counting rule in the data of photoproduction of hyperons.

(a) Data of $\gamma p \rightarrow K^+\Lambda$ fit by the scaling factor $n = 10.0$.

(b) Data of $\gamma p \rightarrow K^+\Sigma^0$ fit by $n = 9.2$.

(c) Data of $\gamma p \rightarrow K^+\Lambda(1520)$ fit by $n = 9.8$.

(d) Data of $\gamma p \rightarrow K^+\Lambda(1405)$ fit by $n = 10.2$.

As illustrated in Fig. 2, GPDs were introduced in connection with two hard exclusive processes of lepton production of photons and mesons off protons: deeply virtual Compton scattering (DVCS) and deeply virtual meson production (DVMP). There have been many experimental activities of measuring DVCS and DVMP processes with lepton beams. Data have been taken by HERMES, H1 and ZEUS at DESY and HALL-A and CLAS at JLab. Recently the status of nucleon GPDs in the valence region with the global analysis of existing DVCS and DVMP data is reviewed in Ref. [10, 11]. Further measurements were performed at COMPASS experiment at CERN and planned for JLab after 12-GeV upgrade.

Other than lepton beams, it was suggested that GPDs could be accessed using real photon and hadron beams as well, such as timelike Compton scattering (TCS) [12], lepton-pair production with meson beam [13, 14] and pure hadronic reaction [15, 16]. For example, invoking the properties under time-reversal transformation and analyticity under the change from spacelike to timelike virtuality [17], the exclusive pion-induced Drell-Yan process $\pi N \rightarrow \gamma^* N \rightarrow l^+l^- N$ [13, 14], as illustrated in Fig. 2 is assumed to factorize in a way analogous to the DVMP processes, and can serve as an
independent probe to access nucleon GPDs.

In Ref. [13,14], it has been shown that at large dilepton mass ($Q'$) scaling limit, the corresponding leading-twist cross section of $\pi^- (q) + p(p) \to \gamma^* (q') + n(p')$ as a function of $t$ and $Q'^2$ is expressed in terms of convolution integrals $\tilde{H}du$ and $\tilde{E}du$, as follows [13]

\[
\frac{d\sigma_L}{dtdQ'^2} \bigg|_{\tau} = \frac{4\pi\alpha_s^2}{27} \frac{R_F^2}{Q'^8f_\pi^2} \left[ (1 - \xi^2)|\tilde{H}du(\tilde{x}, \xi, t)|^2 - 2\xi^2 \text{Re} (\tilde{H}du(\tilde{x}, \xi, t)^* \tilde{E}du(\tilde{x}, \xi, t)) - \xi^2 \frac{t}{4m_N^2} |\tilde{E}du(\tilde{x}, \xi, t)|^2 \right],
\]  

(1)

where the scaling variable $\tilde{x}$ is given by $\tilde{x} = -(q + q')^2 / (2(p + p') \cdot (q + q')) \approx -Q'^2 / (2s - Q'^2) = -\xi$, and the pion decay constant $f_\pi$. The subscript “L” of the cross section indicates the contribution of the longitudinally polarized virtual photon.

The convolution integral $\tilde{H}^{du}$ involves two soft objects: the GPD for $p \to n$ transition and the twist-two pion distribution amplitude (DA) $\phi_\pi$. The expression of $\tilde{H}^{du}$ is given, at the leading order in $\alpha_s$, by [13]

\[
\tilde{H}^{du}(\tilde{x}, \xi, t) = \frac{8}{3} \alpha_s \int_{-1}^{1} dz \frac{\phi_\pi(z)}{1 - z^2} \left( e_d \frac{e_u}{\tilde{x} - x - i\epsilon} - e_u \frac{e_d}{\tilde{x} + x - i\epsilon} \right) (\tilde{H}^d(x, \xi, t) - \tilde{H}^u(x, \xi, t)),
\]  

(2)

where $e_{u,d}$ are the electric charges of $u,d$ quarks in units of the positron charge. The corresponding expression of $\tilde{E}^{du}$ is given by (2) with $\tilde{H}^q$ replaced by the proton GPDs $\tilde{E}^q$. Due to the pseudoscalar nature of the pion, the cross section (2) receives the contributions of $\tilde{H}$ and $\tilde{E}$ only, among the GPDs.
The leading-twist cross section (1) enters the four-fold higher-twist differential cross sections for
\[ \pi^- p \rightarrow \gamma^* n \] as [14],

\[
\frac{d\sigma}{dQ^2 d\cos \theta d\phi} = \frac{3}{8\pi} (\sin^2 \theta \frac{d\sigma_L}{dQ^2} + \frac{1 + \cos^2 \theta}{2} \frac{d\sigma_T}{dQ^2}) \cos 2\phi + \frac{\sin 2\theta \cos \phi}{\sqrt{2}} \frac{d\sigma_{LT}}{dQ^2} + \sin^2 \theta \cos 2\phi \frac{d\sigma_{TT}}{dQ^2},
\] (3)

with the angles (\(\theta, \phi\)) specifying the directions of the decay leptons from \(\gamma^*\). In Eq. (3), \(d\sigma_T/(dQ^2)\) denotes the cross section contributed by the transversely-polarized virtual photon. The \(d\sigma_{LT}/(dQ^2)\) and \(d\sigma_{TT}/(dQ^2)\) are the longitudinal-transverse interference and transverse-transverse (between helicity +1 and −1) interference contributions, respectively. The \(d\sigma_{LT}/(dQ^2)\) is of twist-three and is suppressed asymptotically by \(1/Q^2\) compared to the twist-two cross section \(d\sigma_L/(dQ^2)\), while \(d\sigma_T/(dQ^2)\) and \(d\sigma_{TT}/(dQ^2)\) are suppressed by one more power of \(1/Q^2\) as twist-four effects. The angular structures of these four terms, characteristic of the associated virtual-photon polarizations, allow us to separate the contribution of the leading-twist cross section \(d\sigma_L/(dQ^2)\) from the measured angular distributions of dilepton pairs.

4. Feasibility study of measuring exclusive Drell-Yan process at E50 experiment

Realization of the exclusive Drell-Yan measurement is interesting as well as important to verify the universality of GPDs in both spacelike and timelike processes. Below we present the results of feasibility study [18] based on the known experimental beam conditions and the setup of target and detectors of J-PARC E50 experiment with addition of a muon identification system.

The E50 experiment [19] plans to investigate charmed-baryon spectroscopy via the measurement of \(\pi^- p \rightarrow Y_c^* + D^{*-}\) reaction at the high-momentum beam line at J-PARC. The mass spectrum of \(Y_c^*\) will be constructed by the missing-mass technique following the detection of \(D^{*-}\) via its charged decay mode. Spectroscopy of \(Y_c^*\) could reveal the essential role of diquark correlation in describing the internal structure of hadrons. The E50 experiment has received the stage-1 approval in 2014.

Figure 3 shows the conceptual design of the E50 spectrometer. The spectrometer is composed of a dipole magnet and various particle detectors [19]. Since the secondary beams are unseparated, beam pions are tagged by gas Cherenkov counters (Beam RICH) placed upstream of the target. High-granularity drift chambers placed downstream of the magnet are for detection of charged tracks, e.g., kaons and pions from \(D^{*-}\) decay. TOF counters and ring-imaging Cherenkov counters are placed downstream of the drift chambers for high-momentum kaon/pion separation. In the current spectrometer configuration, a missing-mass resolution of \(D^{*-}\) is expected to be as good as 5 MeV [19].

Conventionally the measurement of Drell-Yan process in the fixed-target experiments requires a hadron absorber immediately after the targets to avoid large track densities in the spectrometer. Thanks to the relatively low track density at the energy regime of J-PARC and high-granularity tracking chambers, the measurement of Drell-Yan process could be operated without the installation of hadron absorber in front of the spectrometer. Excluding the multiple-scattering effect in the hadron absorber is essential in achieving a good momentum determination of muon tracks so that the exclusive Drell-Yan process can be characterized via the missing-mass technique. A dedicated \(\mu\) identification system, composed of tracking devices and stopping materials, is planned to be placed in the most downstream position.

We perform the feasibility study of measuring the exclusive pion-induced Drell-Yan process \(\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n\) using E50 detector configuration together with \(\mu\)ID system [18]. The assumed integrated luminosity is 2-4 fb\(^{-1}\) for 50-day worth beam time. Both inclusive and exclusive Drell-Yan events are generated together with the other dimuon sources like \(J/\psi\) and the random combinatorial from minimum-bias hadronic events in the event simulation. The estimated total cross sections for the
exclusive and inclusive Drell-Yan events for the dimuon mass $M_{\mu^+\mu^-} > 1.5$ GeV and the $|t - t_0| < 0.5$ GeV$^2$ are about 10-20 pb and 2-3 nb, respectively. In the range of beam momentum 10-20 GeV, the total hadronic interaction cross sections of $\pi^- p$ is about 20-30 mb while the production of $J/\psi$ is about 1-3 nb. More details are referred to Ref. [18].

Using GK2013 GPDs [20] for the exclusive Drell-Yan process, the Monte-Carlo simulated missing-mass $M_X$ spectra of the $\mu^+\mu^-$ events with $M_{\mu^+\mu^-} > 1.5$ GeV and $|t - t_0| < 0.5$ GeV$^2$ for $P_\pi=10, 15,$ and 20 GeV is shown in Fig. 4, where $t_0$ is the limiting value of 4-momentum transfer square $t$. Lines with different colors denote the contributions from various sources: exclusive Drell-Yan (red, dashed), inclusive Drell-Yan (blue, dotted), $J/\psi$ (cyan, dash-dotted) and random background (purple, solid), respectively. Signals of $J/\psi$ are only visible in the invariant mass distributions for $P_\pi=15$ and 20 GeV. It is clear that the exclusive Drell-Yan events could be identified by the signature peak at the neutron mass ($M_n \sim 0.940$ GeV) in the missing-mass spectrum for all three pion beam momenta. With the leading-twist expression as Eq. (1), the measured differential cross sections $d\sigma/dt$ can be included in the global analysis for the extraction of $\tilde{H}$ and $\tilde{E}$ GPDs. To extend the GPDs determination to the higher-twist ones by the dimuon angular dependence in Eq. (3), a new spectrometer with an enlarged acceptance other than the currently designed one is preferred.

5. Summary and Outlook

Exclusive hard hadronic process is an effective way to access the constituent quark structures. In terms of reasonable cross sections and good enough hard scale, the meson beam of 10-20 GeV momentum to be available at high-momentum beam line of J-PARC is most optimized for the measurement. The energy scaling relation of $\pi^- p \rightarrow K^0\Lambda(1405)$ can be used for exploring the constituent quark structure of $\Lambda(1405)$, while exclusive Drell-Yan process $\pi^- p \rightarrow \gamma' n \rightarrow \mu^+\mu^- n$ will yield the important information of GPDS of nucleons.

In the framework of the J-PARC E50 experiment, we addressed the feasibility of measuring the exclusive pion-induced Drell-Yan process. A clean signal of exclusive pion-induced Drell-Yan process can be identified in the missing-mass spectrum of dimuon events with 2–4 fb$^{-1}$ integrated
Fig. 4. The Monte-Carlo simulated missing-mass $M_X$ spectra of the $\mu^+\mu^-$ events with $M_{\mu^+\mu^-} > 1.5$ GeV and $|t-t_0| < 0.5$ GeV$^2$ for $P_\pi=$10, 15, and 20 GeV. Lines with different colors denote the contributions from various sources. The GK2013 GPDs is used for the evaluation of exclusive Drell-Yan process. Figures from [18].

luminosity. Fig. 5 illustrates the kinematic regions of GPDs in terms of $Q^2$ versus $x_B$ for spacelike processes and $Q'^2$ versus $\tau$ for timelike ones to be explored by the existing and coming experiments. Testing the universality of nucleon GPDs through both the measurements of spacelike and timelike processes on the same kinematic region shall be of fundamental importance.

Fig. 5. The kinematic regions of GPDs explored by the experiments at JLab, HERMES and COMPASS (DVCS or DVMP) and J-PARC (exclusive Drell-Yan). The region is either [$Q^2$, $x_B$] for spacelike processes or [$Q'^2$, $\tau$] for timelike ones. Figures from [18]

A letter of intent for studying the nucleon GPDs via exclusive Drell-Yan process at J-PARC has been submitted to the PAC of J-PARC in 2019 [21]. With an appropriate trigger setting, the measurement of exclusive hard process could be carried out simultaneously with the approved program of charm-baryon spectroscopy in J-PARC E50 experiment. A full proposal to request a stage-1 approval of exclusive Drell-Yan program is being prepared. The E50 experiment is aimed for commissioning
in 2025 as long as the secondary beam is ready.

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