LETTER OF INTENT

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

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Executive Summary

We propose to measure the exclusive pion-induced Drell-Yan process $\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$ using E50 high-resolution spectrometer in the coming high-momentum beam line of Hadron Hall at J-PARC. The cross sections of this reaction will provide information of the proton generalized parton distributions (GPDs) and the pion distribution amplitudes (DAs) through a timelike approach. A feasibility study has been carried out [PRD 93, 114034]. A clean signal of exclusive Drell-Yan process can be identified in the missing-mass spectrum of dimuon events with 2-4 fb^{-1} integrated luminosity. The statistics accuracy is adequate for discriminating two current GPD modelings. Realization of such measurement at J-PARC will provide a fundamental test of perturbative QCD descriptions of a novel class of hard exclusive reactions. It will also open up a new way of accessing nucleon GPDs in the timelike regions, complementary to the conventional GPD measurement using lepton beam.

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I. INTRODUCTION

In recent decades, tremendous efforts have been spent in extending the measurements of the partonic structure of nucleons to multi-dimensional structures: generalized parton distributions (GPDs) [1–6] and transverse-momentum-dependent parton distribution functions (TMDs) [7–10] as shown in Fig. 1. 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 timelike processes is essential.

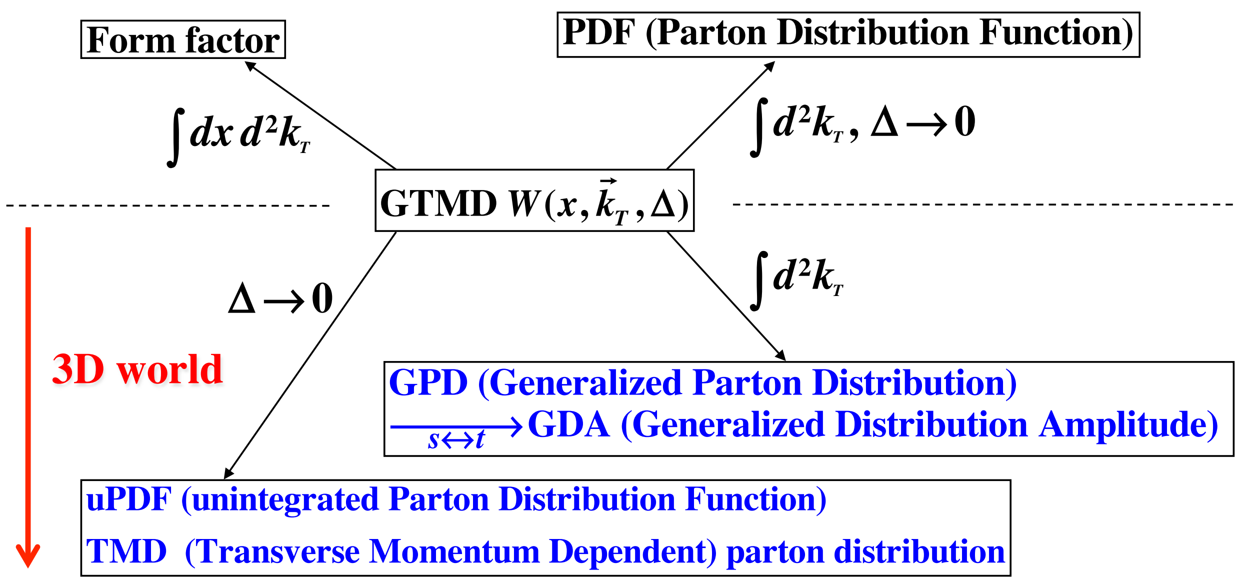


FIG. 1. Three-dimensional structure functions from the generalized transverse-momentum-dependent parton distribution (GTMD).

GPDs [11] were introduced in connection with two hard exclusive processes of leptoproduction of photons and mesons off protons: deeply virtual Compton scattering (DVCS) [12–14] and deeply virtual meson production (DVMP) [15, 16]. There have been tremendous experimental efforts on 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 "global analysis" of nucleon GPDs in the valence region with existing DVCS and DVMP data is reviewed in Refs. [17] and [18] respectively. Further measurements have been performed at COMPASS experiment at CERN [19, 20] and planned for JLab after 12-GeV upgrade [21].

As well as lepton beams, it was suggested that GPDs could also be accessed using real photon and hadron beams, such as timelike Compton scattering (TCS) [22], lepton-pair production with meson beam [23, 24] and pure hadronic reaction [25, 26]. For example, invoking the properties under time-reversal transformation and analyticity under the change from spacelike to timelike virtuality, the exclusive pion-induced Drell-Yan process $\pi N \to \gamma^* N \to \mu^+\mu^- N$ [23, 24] is assumed to factorize in a way analogous to the DVMP processes, and can serve as a complementary probe to access nucleon GPDs [27]. Such a measurement is interesting as well as important to verify the universality of GPDs in both spacelike and timelike processes. Upon the completion of high-momentum beam line (HiPBL), a high-flux primary proton beam and secondary particles of π, K or $\bar{p}$ with momentum 5-15 GeV will be available. This is an unique opportunity to carry out a measurement of the exclusive Drell-Yan process at J-PARC.

The proposed measurement is briefly described in Sec. II and the essential experimental apparatus is introduced in Sec. III. Based on a recent work [28] done by some of the authors, the results from the feasibility of expected signals in missing-mass spectrum and statistic uncertainties are shown in Sec. IV. We conclude in Sec. V.

II. EXCLUSIVE DRELL-YAN PROCESS

We first consider a massive dimuon production with pion beam, namely the inclusive pion-induced Drell-Yan process $\pi N \to \gamma^* X \to \mu^+\mu^- X$. The leading contribution comes from the transversely-polarized virtual photon γ^*, as a consequence of the helicity conservation in the annihilation of the on-shell quark and antiquark pair. On the other hand, the dimuon angular distribution in the forward region has been experimentally observed to reveal that the polarization direction of virtual photon γ^* varies from transverse to longitudinal [29, 30] which could be understood as the dominance of higher-twist contribution in the forward production [31]. In the limit of large x_π, the annihilating $\bar{u}$ antiquark from the pion is highly off-shell, while the u quark from the nucleon is nearly on-shell. The antiquark of the pion is subject to the bound-state effects characterized by the distribution amplitude and it could be resolved via a large-virtuality gluon exchange with the spectator quark as illustrated in Fig. 2(a). When the highly virtual gluon has timelike momentum instead of spacelike momentum, the leading-twist contribution may be obtained by neglecting the transverse momentum of the gluon, such that the spectator quark becomes collinear to the pion and may be absorbed by the remnant of the target. When this "complete annihilation" of the pion constituents is accompanied by the final hadronic state $X = N$, this process turns into the "exclusive" Drell-Yan production $\pi N \to \gamma^* N \to \mu^+\mu^- N$ in the forward direction, as illustrated in Fig. 2(b).

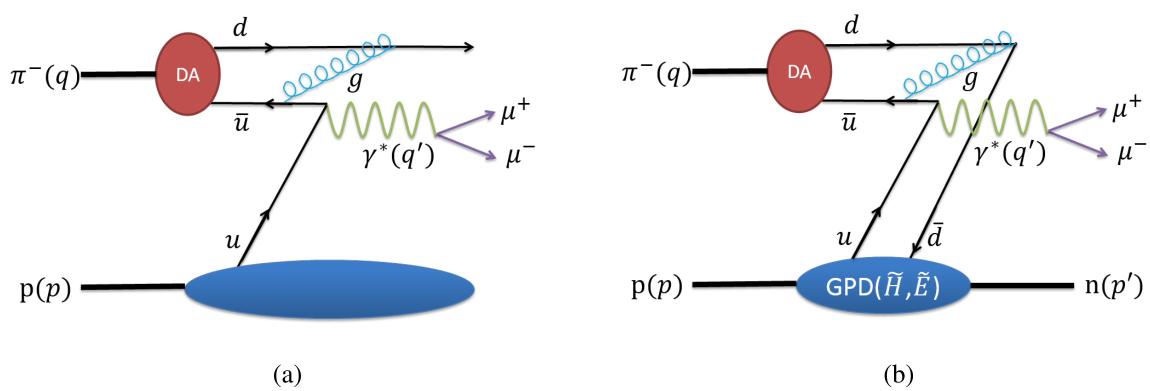


FIG. 2. (a) Semi-exclusive pion-induced Drell-Yan process at large x_π (b) Exclusive pion-induced Drell-Yan process.

In the exclusive Drell-Yan process, the relevant amplitude is expressed as the convolution of the short-distance partonic annihilation processes with the two parts of long-distance nature, associated with the nucleon and the pion: the generalized parton distribution functions (GPDs) as an off-forward nucleon matrix element, and the pion distribution amplitudes (DAs) as a pion-to-vacuum matrix element of a bilocal quark operator whose information can be constraint by other measurements such as $\gamma\gamma^* \to \pi^0$ at *BABAR* [32] and Belle [33] although there are still some ambiguities.

Here, the GPDs for the nucleon are the functions of the relevant invariants, namely the light-cone momentum fractions x of the average momentum, the skewness $\xi \equiv (p - p')^+/(p + p')^+$, and the momentum transfer squared $t = \Delta^2$ with $\Delta \equiv p' - p$ where the p and p' are initial and final nucleon momenta, respectively.

The quark GPDs relevant to the processes without the quark-helicity flip are given by (see, e.g., [2, 4])

$$\int \frac{dy^-}{4\pi} e^{ixP^+y^-} \left\langle p' \left| \bar{q}(-y/2)\gamma^+ q(y/2) \right| p \right\rangle \Big|_{y^+=\vec{y}_\perp=0}$$
$$= \frac{1}{2P^+} \bar{u}(p') \left[H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t)\frac{i\sigma^{+\alpha}\Delta_\alpha}{2\,m_N} \right] u(p), \tag{1}$$

and

$$\int \frac{dy^-}{4\pi} e^{ixP^+y^-} \left\langle p' \left| \bar{q}(-y/2)\gamma^+\gamma_5 q(y/2) \right| p \right\rangle \Big|_{y^+=\vec{y}_\perp=0}$$
$$= \frac{1}{2P^+} \bar{u}(p') \left[\tilde{H}^q(x,\xi,t)\gamma^+\gamma_5 + \tilde{E}^q(x,\xi,t)\frac{\gamma_5\Delta^+}{2\,m_N} \right] u(p), \tag{2}$$

for each quark flavor q, where $|p\rangle$ denotes the proton state with momentum p and mass m_N, $u(p)$ denote the Dirac spinor for the proton, $\sigma^{\alpha\beta}$ is given by $\sigma^{\alpha\beta} = (i/2)[\gamma^\alpha, \gamma^\beta]$, and the average momentum is denoted as $P\ (\equiv (p+p')/2\,)$. The gauge-link operator between the two quark fields for maintaining the gauge invariance is not explicitly written for simplicity. $H^q(x,\xi,t)$ and $E^q(x,\xi,t)$ are the unpolarized quark GPDs, and $\tilde{H}^q(x,\xi,t)$ and $\tilde{E}^q(x,\xi,t)$ are the polarized ones.

The factorization has been proven for the DVMP processes at the leading-twist, including the exclusive electroproduction of pion, $\gamma^* N \to \pi N$ [15]. The amplitude can be written in terms of the hard-scattering processes at parton level, combined with the pion DAs, ϕ_π, and also the nucleon GPDs, $\tilde{H}$ and $\tilde{E}$. By interchanging the initial γ^* and final π in the exclusive electroproduction of pion, and replacing the spacelike momentum of γ^* by the timelike momentum, the factorization at twist-two is argued to be applicable to the exclusive Drell-Yan process, $\pi(q)N(p) \to \gamma^*(q')N(p')$, with the same universal non-perturbative input [23].

The appropriate kinematical region is of large timelike virtuality $Q'^2 = q'^2$ at fixed $t = (p'-p)^2$ and fixed scaling variable $\tau \equiv Q'^2/(2p\cdot q)$ where the q, p and p' are the momenta of the pion, initial, and final nucleons, respectively. At the large Q' scaling limit, the corresponding leading-twist cross section of $\pi^- p \to \gamma^* n$ as a function of t and Q'^2 is expressed in terms of convolution integrals $\tilde{\mathcal{H}}^{du}$ and $\tilde{\mathcal{E}}^{du}$, as follows [23]

$$\frac{d\sigma_L}{dtdQ'^2}\bigg|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \Big[(1-\xi^2)|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)|^2$$
$$- 2\xi^2 {\rm Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^* \tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t) \right) - \xi^2 \frac{t}{4m_N^2} |\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)|^2 \Big], \tag{3}$$

where the scaling variable $\tilde{x}$ is given by [2, 4, 11, 22], $\tilde{x} = -(q+q')^2/(2(p+p')\cdot(q+q')) \approx -Q'^2/(2s - Q'^2) = -\xi$, and the pion decay constant f_π. The subscript "L" of the cross section indicates the contribution of the longitudinally polarized virtual photon.

The convolution integral $\tilde{\mathcal{H}}^{du}$ involves two soft objects: the nucleon GPD $\tilde{H}^{du}$ for $p \to n$ transition and the twist-two pion DAs ϕ_π. Using $\tilde{H}^{du}(x,\xi,t) = \tilde{H}^u(x,\xi,t) - \tilde{H}^d(x,\xi,t)$ to relate the transition GPD with the usual proton GPDs $\tilde{H}^q$ for quark flavor $q = u, d$, the expression of $\tilde{\mathcal{H}}^{du}$ is given, at the leading order in α_s, by [23]

$$\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t) = \frac{8}{3}\alpha_s \int_{-1}^{1} dz\, \frac{\phi_\pi(z)}{1-z^2} \times \int_{-1}^{1} dx \left(\frac{e_d}{\tilde{x}-x-i\epsilon} - \frac{e_u}{\tilde{x}+x-i\epsilon}\right)\left(\tilde{H}^d(x,\xi,t) - \tilde{H}^u(x,\xi,t)\right), \quad (4)$$

where $e_{u,d}$ are the electric charges of u, d quarks in units of the positron charge. The corresponding expression of $\tilde{\mathcal{E}}^{du}$ is given by (4) with $\tilde{H}^q$ replaced by the proton GPDs $\tilde{E}^q$. Because of the pseudoscalar nature of the pion, the cross section (3) receives the contributions of $\tilde{H}$ and $\tilde{E}$ only, among the GPDs in Eqs. (1) and (2).

To ensure a proper factorization and sensitivity to the partonic structure, Q' has to be larger than 1 GeV and $|t|$ is large enough. Both of these require a large center-of-mass energy ($\sqrt{s}$) for the reactions. Nevertheless the estimated hard exclusive Drell-Yan cross sections drop dramatically with an increase of $\sqrt{s}$. Furthermore the experimental determination of exclusiveness for the measured reactions through miss-mass technique favors the measurement of lepton tracks from the Drell-Yan process in an open apparatus and thus the charged multiplicity has to be low enough for good tracking. Considering various factors and constraints, it is found that the measurement of the exclusive Drell-Yan process in the high-momentum beam line at J-PARC with 10-20 GeV π^- beam ($\sqrt{s} =$ 4-6 GeV) is unique and optimized.

III. PROPOSED EXPERIMENT

The E50 experiment at J-PARC plans to investigate the charmed-baryon spectroscopy via the measurement of $\pi^- + p \to Y_c^* + D^{*-}$ reaction in the high-momentum beam line [34]. Spectroscopy of Y_c^* could reveal the essential role of diquark correlation in describing the internal structure of hadrons. The mass spectrum of Y_c^* will be constructed by the missing-mass technique following the detection of D^{*-} via its charged decay mode. A large acceptance for charged hadrons together with good momentum resolution is required. The E50 experiment received the stage-1 approval in 2014 [35].

Figure 3 shows the conceptual design of the E50 spectrometer. The spectrometer is composed of a dipole magnet and various detectors [34]. Since the secondary beams are unseperated, the

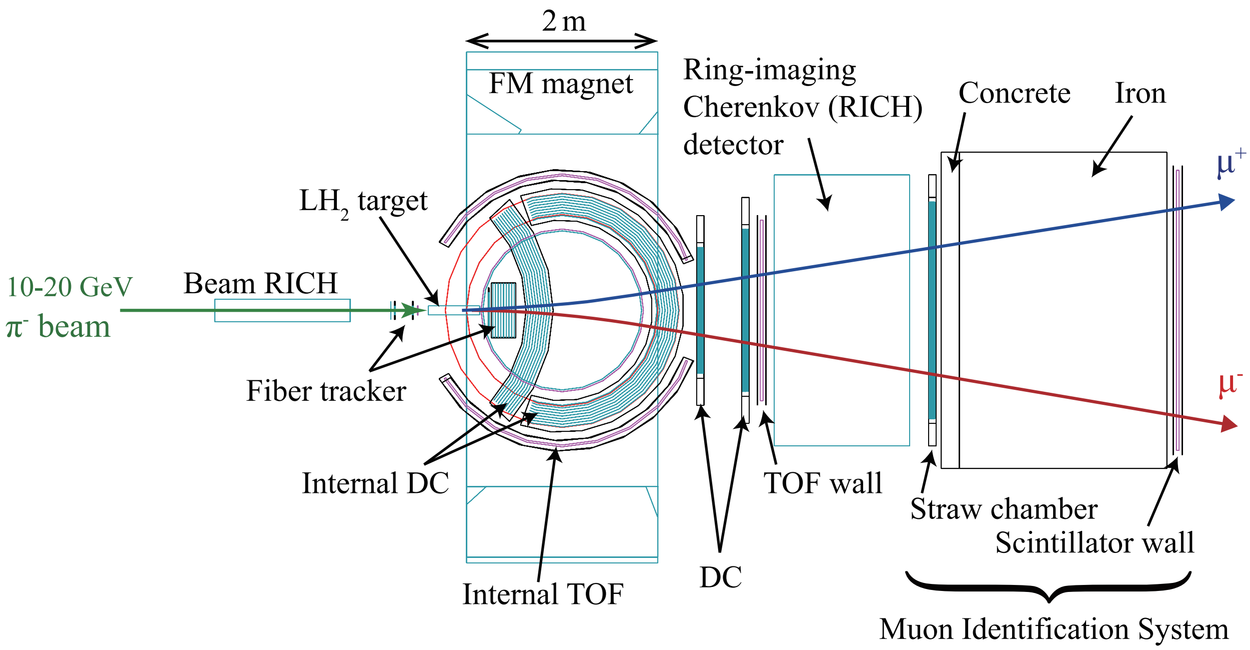


FIG. 3. Conceptual design of J-PARC E50 spectrometer with muon identification system.

beam pions are tagged by gas Cherenkov counters (Beam RICH) placed upstream of the target. Finely segmented particle trackers, silicon strip detectors (SSD) and scintillating fiber trackers (SFT) with designed spatial resolutions of 80 μm and 1 mm respectively, are placed immediately upstream and downstream of the target. The magnet has a circular pole of 2.12 m in diameter and a gap of 1 m. An integrated magnetic field of up to 2.3 Tesla-meter is expected. High-granularity drift chambers placed downstream of the magnet are for detection of charged tracks, e.g. kaons and pions from D^{*-} decay. Time-of-flight (TOF) counters and ring-imaging Cherenkov (RICH) 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 [34].

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 of E50 experiment, the measurement of Drell-Yan process could be operated without the installation of hadron absorber in front of the spectrometer. Exclusion of the multiple-scattering effect in the hadron absorber is very essential for achieving a good momentum determination of muon tracks so that the exclusive Drell-Yan process can be characterized via the missing-mass technique.

As for the final muon identification, we propose to install a dedicated muon identification (μID) system in the most downstream position as shown in Fig. 3. The current design of μID system consists of hadron absorber layers made of 20-cm concrete and 230-cm iron to absorb incoming hadrons, scintillator hodoscopes downstream of the absorber (3.5x2.5 m^2 active area with 5cm spatial resolution), and a straw chamber (or drift tube chamber) upstream of the absorber (2.4x1.8 m^2 active area with few mm spatial resolution). The thickness of concrete and iron should be optimized for the consideration of the stopping power for low-momentum tracks and penetrating efficiency for high-momentum ones. Muons are identified when the tracks can be reconstructed in both sets of stations. The threshold momentum of a penetrating muon is 3 GeV. The signals from the μID system could be used in the trigger decision. The major component of the background events is originated from the uncorrelated muons from the decay of hadrons, mostly pions, and kaons. These background muons arising from the decay-in-flight of hadrons produced on the target could be effectively identified by a kink of the decay vertex, bad ξ^2-probability in the reconstruction, and inconsistency of the trajectory between the spectrometer and the upstream tracking chamber in the μID system. The muons from the beam decay could be rejected with proper kinematics cuts. All these background-rejection considerations have to be carefully simulated and implemented into the high-level trigger system.

IV. ESTIMATIONS

We perform the Monte-Carlo simulations in the Geant4 simulation framework [36] using the detector configuration of E50 experiment together with μID system. Both inclusive and exclusive Drell-Yan events are generated together with the other dimuon sources like J/ψ and the random combinatorial from minimum-bias hadronic events in the event simulation. We assume the following experimental conditions: 4 g/cm^2 liquid hydrogen target, $1.83/1.58/1.00 \times 10^7$ π^-/spill for 10/15/20 GeV beams, and 50-days of beam time. In this study, the corresponding integrated luminosity with the event cuts of $M_{\mu^+\mu^-} > 1.5$ GeV and $|t - t_0| < 0.5$ GeV^2 is 3.66/3.16/2.00 fb^{-1}. The expected rate of dimuon trigger from μID system is $\sim$ 2/10/15 Hz for 10/15/20 GeV beams. Since the trigger rate is low compared to 6kHz for the trigger of charmed baryons, the measurement of exclusive Drell-Yan process and charmed-baryon spectroscopy could be carried out together in E50 experiment. In reality, the lower limit of the dimuon mass $M_{\mu^+\mu^-}$ could be further extended to 1 GeV. This would increase the expected number of events for the exclusive

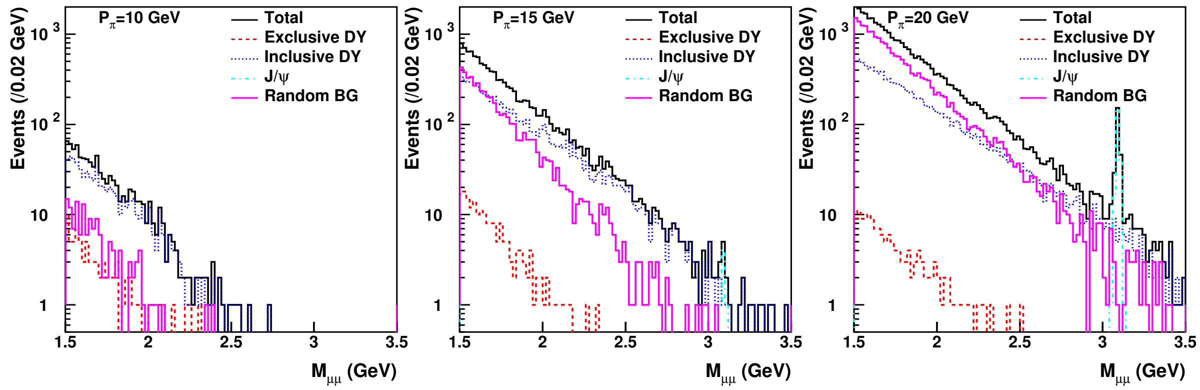
Drell-Yan and enable the study of ϕ meson production as well.

With the parametrization of GPDs $\tilde{H}^q(x, \xi, t)$ and $\tilde{E}^q(x, \xi, t)$, and pion DAs ϕ_π, the leading order differential cross sections of the exclusive Drell-Yan process could be evaluated by Eqs. (3) and (4) straightforwardly. Since the global analysis of GPDs is still at a premature stage, we use two sets of GPD modeling to estimate the uncertainty due to the GPD input. The first set of GPDs labeled as "BMP2001" is what was used in Refs. [22, 23] and the second set labeled as "GK2013" is constructed in a rather similar way as the first one [37]. In terms of consistency, the same pion DA is used for the modeling of $\tilde{E}^u - \tilde{E}^d$ and the convolution integrals of $\tilde{\mathcal{H}}^{du}$ and $\tilde{\mathcal{E}}^{du}$.

Using GK2013 GPDs for the exclusive Drell-Yan process, the Monte-Carlo simulated invariant mass $M_{\mu^+\mu^-}$ and 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_π=10, 15, and 20 GeV are shown in Figs. 4 and 5, where t_0 ($= -4m_N^2\xi^2/(1-\xi^2)$) is the limiting value of t corresponding to the scattering angle in the center-of-mass system $\theta^{CM} = 0$. Lines with different colors denote the contributions from various sources: exclusive Drell-Yan (red, dashed), inclusive Drell-Yan (blue, dotted), J/ψ (cyan, dash-dotted) and random background (purple, solid), respectively. Signals of J/ψ are only visible in the invariant mass distributions for P_π=15 and 20 GeV.

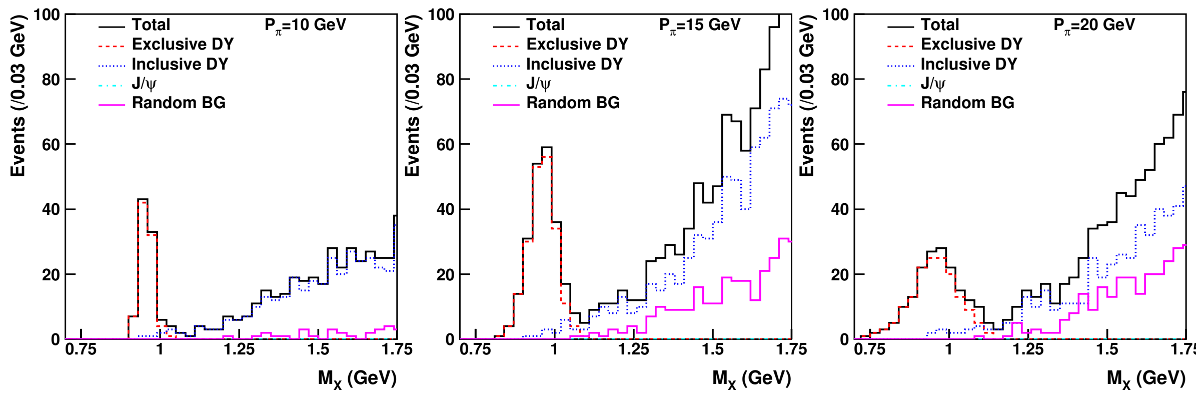
Fig. 5 clearly shows that the exclusive Drell-Yan events could be identified by the signature peak at the neutron mass ($M_n \sim 0.940$ GeV) in the missing-mass spectrum for all three pion beam momenta. The Q' range of the accepted exclusive Drell-Yan events is about $1.5 - 2.5$ GeV. For the case of lowest pion beam momentum P_π= 10 GeV, the momentum and the missing-mass resolution are best because of the relatively low momenta of produced muons. However the statistics of accepted $\mu^+\mu^-$ events is least due to the threshold momentum for the muon to penetrate through the μID system.

In Fig. 6 we show the expected statistic errors of exclusive Drell-Yan cross sections as a function of momentum transfer $|t - t_0|$. Under the current setting, the measurement with 15-GeV pion beam momentum is most feasible where the GPD modelings of BMP2001 and GK2013 could be differentiated by the experiment. We compare the kinematic regions of Q^2 versus x_B for spacelike processes and those of Q'^2 versus τ for timelike ones explored by the existing and coming experiments in Fig. 7. Testing the universality of nucleon GPDs through both the measurements of spacelike and timelike processes on the same kinematic region shall be very important.



(a) (b) (c)

FIG. 4. The Monte-Carlo simulated invariant mass $M_{\mu^+\mu^-}$ spectra of the $\mu^+\mu^-$ events with $|t - t_0| < 0.5$ GeV^2 for P_π=10, 15, and 20 GeV. Lines with different colors denote the contributions from various sources. The GK2013 GPDs is used for the GPDs input for the evaluation of exclusive Drell-Yan process.



(a) (b) (c)

FIG. 5. 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_π=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.

V. CONCLUSION

In the framework of the J-PARC E50 experiment, we addressed the feasibility of measuring the exclusive pion-induced Drell-Yan process in the coming high-momentum beam line of J-PARC. Detailed simulations on signal reconstruction efficiency as well as on rejection of the most severe random background channel were performed for the pion beam momentum in the range of 10−20

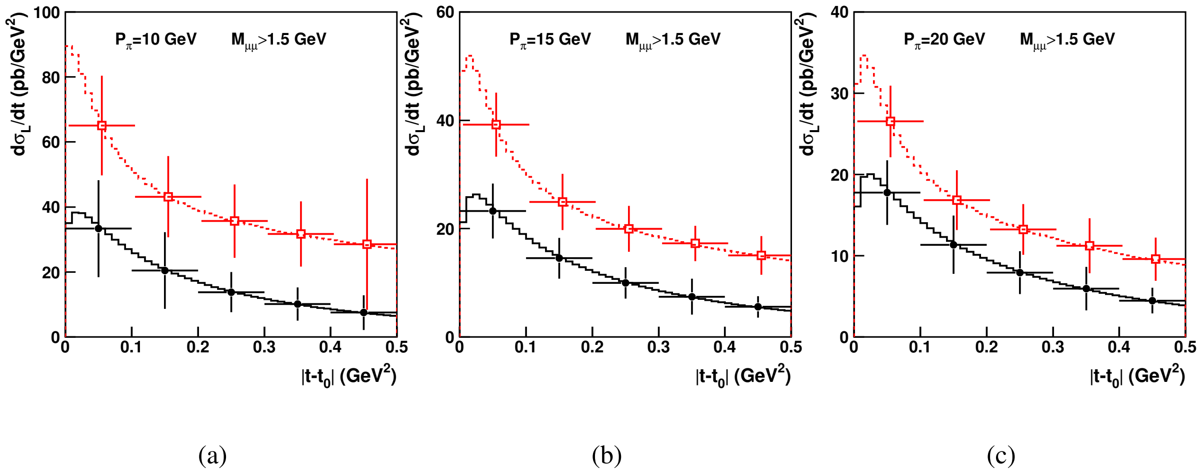


FIG. 6. The expected statistical errors of the exclusive Drell-Yan measurement for two GPDs inputs, BMP2001 (black) and GK2013 (red), as a function of invariant momentum transfer $|t - t_0|$ in the dimuon mass region of $M_{\mu^+\mu^-} > 1.5$ GeV for P_π=10, 15, and 20 GeV.

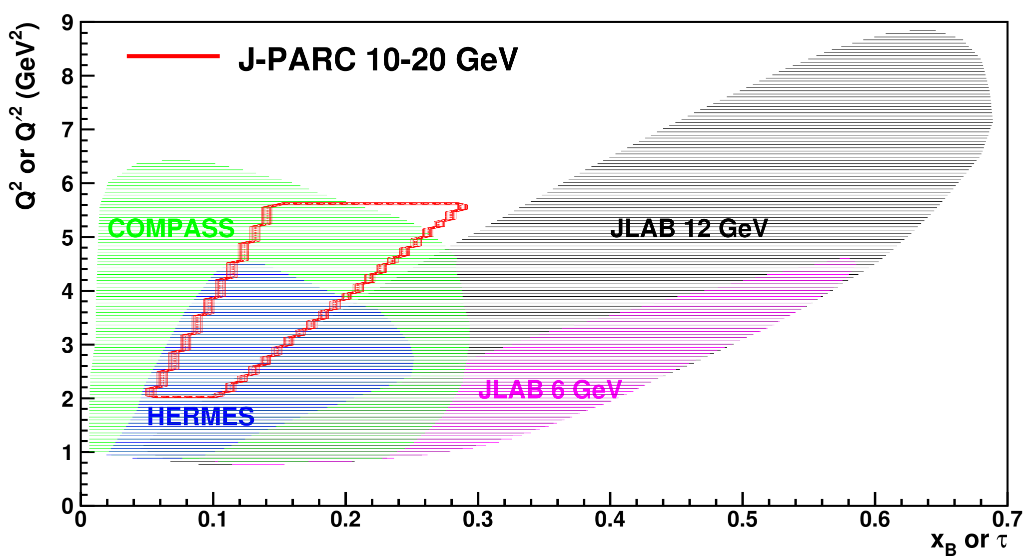


FIG. 7. The kinematic regions of GPDs explored by the experiments at JLab, HERMES and COMPASS (DVCS or DVMP) and J-PARC (exclusive Drell-Yan). The region is either [Q^2, x_B] for spacelike processes or [Q'^2, τ] for timelike ones.

GeV. 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 luminosity. The statistics accuracy is adequate for discriminating between the predictions from two current GPD modelings. The realization of this measurement will represent not only a new approach of accessing nucleon GPDs and pion DAs in the timelike process, but also novel tests of the factorization of an exclusive Drell-Yan process associated with timelike virtuality and the universality of GPDs in spacelike and timelike processes.

Since the dimuon events will be triggered, the production of inclusive Drell-Yan process and J/ψ could be studied as well. With this relatively low-momentum beam, the partonic structure of pion, kaon and proton at large-x region could be explored. The beam RICH detector is expected to identify the particle type in the secondary beams and it might enable the study of kaon and antiproton-induced Drell-Yan process. In 2014, the LHCb Collaboration reported the observation of two charmonium-pentaquark states, denoted as the P_c^+(4380) and P_c^+(4450) in the J/ψ-p invariant mass spectrum [38]. With high-flux pion beam, we could search for these or similar hidden-charm pentaquark states from the events with identified J/ψ and protons near the threshold region.

Finally it has been suggested to perform an experimental test of the onset of factorization by studying the A-dependence of the induced dilepton production [39] . An installation of additional thin nuclear targets will be considered to achieve this measurement. This feature could also lead to the formation and the study of charmed hypernucleus.

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