Semi-Exclusive Drell-Yan

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Same mechanism for high-pt photoproduction:
pQCD applicability

- Large momentum scale is required to make pQCD calculations applicable for specific processes
  - DIS, SIDIS, Drell-Yan: large $Q^2$
  - Elastic scattering: large $Q^2$ (form factors); large $p_T$ (2->2)
  - Deep-exclusive processes (DVCS, DVMP): large $Q^2$ and/or $p_T$
  - Wide-angle exclusive photoproduction (Compton, exclusive mesons): small or zero $Q^2$, large $p_T$
  - Inclusive photoproduction: small $Q^2$, large $p_T$
Berger’s Mechanism


Fig. 1. (a) Sketch of $uN \rightarrow \ell' \pi X$; $Q$ labels the exchanged $\gamma^*$ or $W$. The intermediate quark labeled $p_a$ is off-shell and timelike. The initial quark from the incident nucleon carries four momentum $p_b = x p_N$. (b) On the left is a diagram showing the dissociation of an off-shell virtual quark into a pion plus $X$. At large $p_b^\perp$, its behavior may be represented by the single gluon exchange diagram sketched on the right, in which the quark lines marked with crosses ($x$) are essentially on-shell. The unshaded oval in the diagram on the right-hand side of fig. 1b represents the unspecified small momentum behavior of the pion wavefunction, represented in this paper simply by the wavefunction at the origin, $\psi_n (r = 0)$. 

Andrei Afanasev, Physics at AMBER International Workshop, CERN, 18-20 March 2024
Berger Mechanism in Drell-Yan: $x_F \sim 1$


**Quark Structure Functions of Mesons and the Drell-Yan Process**

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(Received 18 January 1979)

For massive-lepton pair production in meson-induced reactions, we use quantum chromodynamics perturbation theory to predict that the decay angular distribution in the pair rest frame will change from predominantly $1 + \cos^2 \theta$ to $\sin^2 \theta$ as the longitudinal-momentum fraction of the pair $x_F \rightarrow \pm 1$. The two angular distributions are associated respectively with $(1-x)^2$ and $Q^{-2}(1-x)^0$ components of the valence-quark structure function of the meson.

![Diagram](image)

FIG. 1. Diagrams for $Mq \rightarrow q\gamma^*, \gamma^* \rightarrow \mu^+\mu^-$. Solid single lines represent quarks. Symbols $p_1, p_2, p_3$, and $p_c$ denote four-momenta of quarks, and $k$ is the four-momentum of the gluon.
Parton Model + pQCD for high-pT Photoproduction

- Similar to SIDIS, high-\( p_t \) photoproduction may be described by parton fragmentation; hadron is a part of a jet
- In addition, pQCD predicts existence of a short-distance process in which a hadron (pion) is produced kinematically isolated at high \( p_t \), balanced by a opposite-momentum quark jet

![Diagram](image1)

**FIG. 2.** One diagram for photproducing \( \pi \) mesons via fragmentation.

![Diagram](image2)

**FIG. 3.** One of four lowest order perturbative diagrams for direct photoproduction of mesons from a quark. The four diagrams correspond to the four places a photon may be attached to a quark line.

![Diagram](image3)

**FIG. 4.** A resolved photon process.
Implications for Experiment

- Direct production enhanced toward high pt


FIG. 5. Comparing fragmentation, direct, and resolved photon processes for $e + p \rightarrow \pi^+ + X$ with $E_e = 50$ GeV and $\theta_{lab} = 5.5^\circ$.

FIG. 9. The asymmetry $E$ for $\gamma + p \rightarrow \pi^- + X$, at $E_e = 50$ GeV and $\theta_{lab} = 5.5^\circ$. This time, the upper six curves are for $\pi^+$ production and the lower six curves are for $\pi^-$ production. As in Fig. 8, for each set of six, there are three curves with the full calculation, with the loose dotted curve using parton distributions from GRSV, the dashed curve using GS-A, and the tight dotted line using the CTEQ with the suggestion of Soffer et al. and the BBS polarized gluon distribution. The other three curves have $\Delta g$ set to zero, with the solid curve using GRSV, the dash-dotted curve using GS, and the dash-triple dot curve using the CTEQ with the suggestion of Soffer et al.
Pion Distribution Amplitude

- Subprocess calculable using pQCD and (arguably) known pion $q\bar{q}$ Fock component wave function.

Project parallel $q\bar{q}$ onto pion using
\[
\int_0^1 dy \, \phi_\pi(y) \times \frac{1}{\sqrt{2}} (u_\uparrow(yk)v_\downarrow((1-y)k) - (\uparrow\leftrightarrow\downarrow)) .
\]

Normalization comes from $\pi \to \mu\nu$:

, leading to $\int_0^1 dy \, \phi_\pi(y) = f_\pi/2\sqrt{3}$.

- Results shown use asymptotic wf: $\phi_\pi = \sqrt{3} f_\pi y(1-y)$.

- for $Q^2 = 0$ needs $I_{\pi} = \int_0^1 dy \, \frac{\phi_\pi(y)}{y}$.

(Same integral appears in pion FF calculation, (both for $\gamma^*\pi^+ \to \pi^+$ and $\gamma^*\gamma \to \pi^0$.)

$Q^2 \neq 0$ also requires
\[
I'_\pi = -t \int_0^1 dy \frac{\phi_\pi(y)}{(1-y)Q^2 - yt}
\]
Relevance to GPD measurements

- Exclusive pion electroproduction calculated using GPD’s involves the same hard subprocess.
Direct Pion Production vs Beam Energy

- For higher beam energies, higher $kT$ can be accessed, while suppressions VMD contributions
  - Semi-exclusive production mechanism has an order-of-magnitude higher cross section
- EIC can study these processes
Semi-Exclusive Drell Yan

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

60 GeV, 5°, \( Q^2 = 2 \text{ GeV}^2 \)

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

200 GeV, 5°, \( Q^2 = 2 \text{ GeV}^2 \)

AA, Carlson, in progress

Andrei Afanasev, Physics at AMBER International Workshop, CERN, 18-20 March 2024
Two-Photon Exchange in inclusive DIS

  - Asymmetry due to 2γ-exchange ~1/137 suppression
  - Addional suppression due to transversity parton density => predict asymmetry at ~10⁻⁴ level
  - EM gauge invariance is crucial for cancellation of collinear divergence in theory predictions
  - Hadronic non-perturbative ~1% vs partonic 10⁻⁴: Major disagreement
- Prediction consistent with HERMES measurements who set upper limits ~(0.6-0.9)x10⁻³ : Phys.Lett.B682:351-354,2010
Two-Photon Fragmentation for SIDIS

- Extending Kivel-Vanderhaeghen mechanism to SIDIS
  - Emission of an additional photon that converts into quark-antiquark pair leads to an additional mechanism for fragmentation
  - Produced hadron may be kinematically isolated (similar to higher-twist Berger’s mechanism)

(a) one of the photons generates a q-qbar pair to form a final-state meson
(b) two-photon exchange facilitates baryon production from current fragmentation
(c) two-photon mechanism for production of fast meson pairs
TPE in Drell-Yan

Single-photon, single-gluon exchange

Two-photon exchange

Interference of these two mechanisms generates C-odd asymmetries in angular distributions of muons vs antimuons

Note: C-odd asymmetries from TPE will also show in standard partonic picture of DY
Summary and Outlook

- **Deep-Exclusive Processes** – GPD can be accessed based on short-range gluon-exchange mechanism of meson production
  - This mechanism, “direct pion production”, can be studied separately in SIDIS and Drell Yan
- **Semi-Exclusive electroproduction**: kinematically isolated hadrons at high-z or at high-$p_T$
  - Feasibility studies for EIC are underway
- **Drell Yan process**: high-$x_F$ or at high-$p_T$
  - Can be studied at AMBER
- **Higher-order QED corrections**: would generate muon/antimuon angular asymmetries at per cent level in Drell Yan