Semi-Exclusive Drell-Yan

<u>Andrei Afanasev</u>

The George Washington University

Washington, DC

Electroproduction: Berger, *Higher-Twist Effects in Deep-Inelastic Scattering,* Phys.Lett B89 (1979) 241; Brandenburg, Khoze, Müller, *Semi-Exclusive Pion Production in Deep-Inelastic Scattering*, Phys.Lett. B347 (1995) 413

Brodsky, Diehl, Hoyer, Peigne, *Semi-exclusive processes: new probes of hadron structure*, Phys.Lett. B449 (1999) 306.

Same mechanism **for high-pt photoproduction**:

Carlson&Wakely, Phys.Rev.D48:2000-2006,1993

Afanasev, Carlson&Wahlquist, Phys.Lett.B398:393-399,1997; Phys.Rev.D58:054007,1998; Phys.Rev.D61:034014,2000;

Scaling and duality in semi-exclusive processes: Phys.Rev.D62:074011,2000

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, exlusive mesons): small or zero Q^2, large p_T
  - Inclusive photoproduction: small Q^2, large p_T

Berger's Mechanism

- Berger, Higher-Twist Effects in Deep-Inelastic Scattering, Phys.Lett B89 (1979) 241

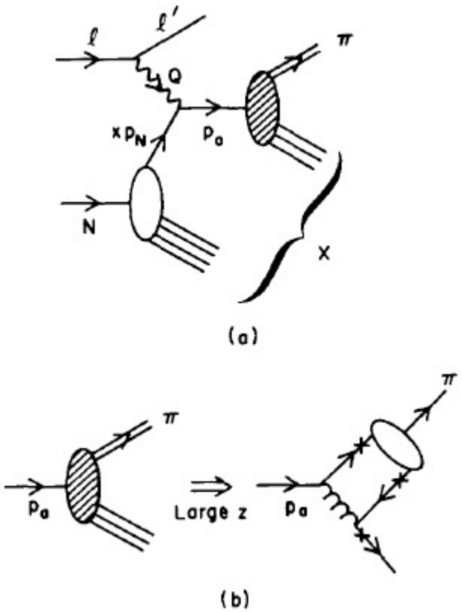


Fig. 1. (a) Sketch of $\ell N \to \ell' \pi X$; Q labels the exchanged γ^* or W. The intermediate quark labeled p_a is off-shell and timelike. The initial quark from the incident nucleon carries four momentum $p_b = xp_N$. (b) On the left is a diagram showing the dissociation of an off-shell virtual quark into a pion plus X. At large p_a^2, 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, $\psi_\pi(r = 0)$.

Berger Mechanism in Drell-Yan: $x_F \sim 1$

- K.J. Eskola, P. Hoyer, M. Vänttinen, R. Vogt, Phys.Lett. B333 (1994) 526-530
- E.L. Berger and S.J. Brodsky, Phys. Rev. Lett. 42, 940 (1979)

Quark Structure Functions of Mesons and the Drell-Yan Process

Edmond L. Berger[a] and Stanley J. Brodsky
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(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 $x_F \to +1$. 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.

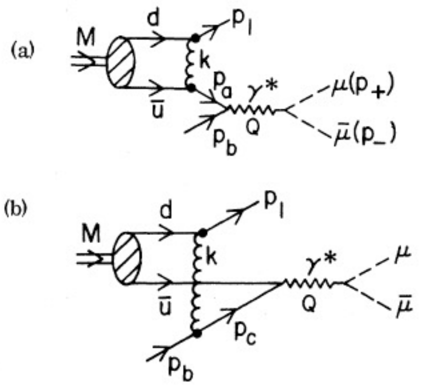


FIG. 1. Diagrams for $Mq \to q\gamma^*$, $\gamma^* \to \mu^+\mu^-$. Solid single lines represent quarks. Symbols p_1, p_a, p_b, and p_c denote four-momenta of quarks, and k is the four-momentum of the gluon.

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 pt, balanced by a opposite-momentum quark jet

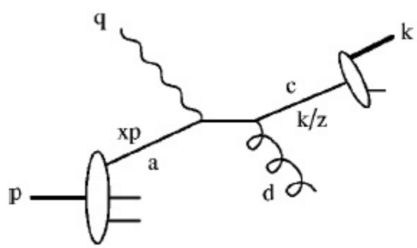


FIG. 2. One diagram for photoproducing π mesons via fragmentation.

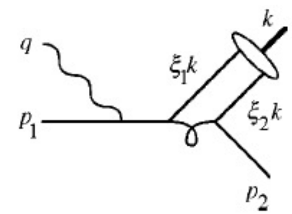


FIG. 3. One of four lowest order perturbative diagrams for direct photoproduction of mesons from a quark. The four diagrams correspond to the four places a photon may be attached to a quark line.

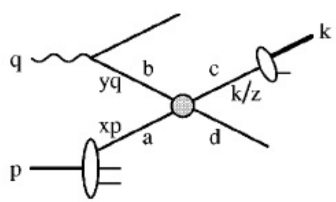


FIG. 4. A resolved photon process.

Implications for Experiment

- Direct production enhanced toward high pt

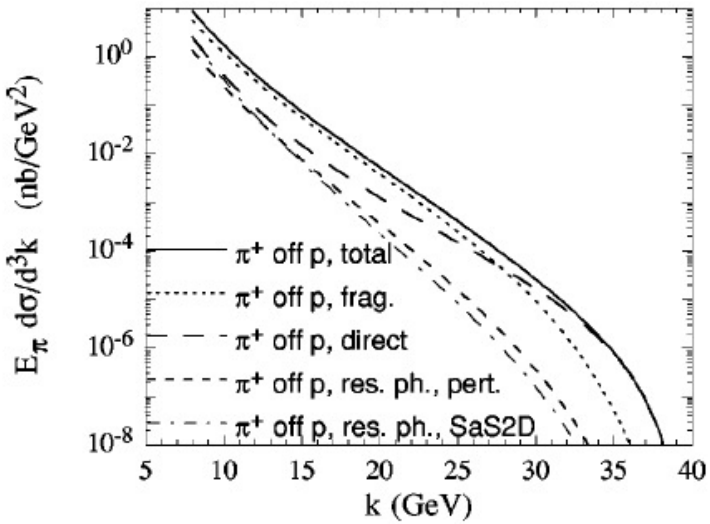


FIG. 5. Comparing fragmentation, direct, and resolved photon processes for $e+p\rightarrow\pi^+ + X$ with $E_e=50$ GeV and $\theta_{\rm lab}=5.5°$.

Afanasev, Carlson&Wahlquist, Phys.Lett.B398:393-399,1997; Phys.Rev.D58:054007,1998; Phys.Rev.D61:034014,2000

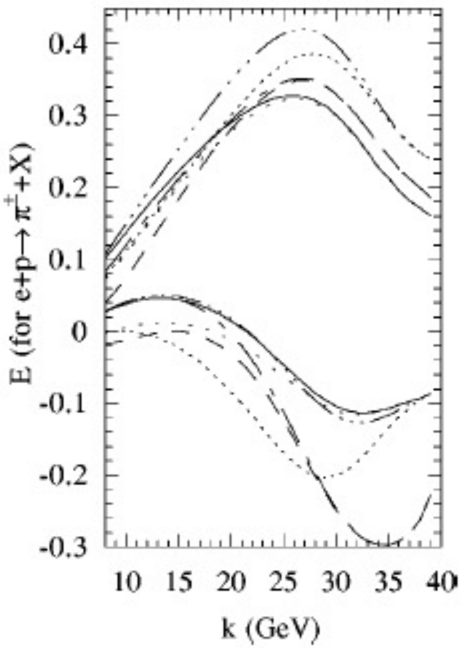
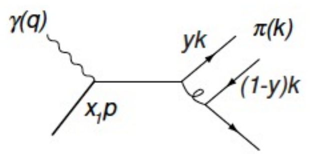


FIG. 9. The asymmetry E for $\vec{\gamma}+\vec{p}\rightarrow\pi^\pm+X$, at $E_e=50$ GeV and $\theta_{\rm lab}=5.5°$. This time, the upper six curves are for π^+ production and the lower six curves are for π^- production. As in Fig. 8, for each set of six, there are three curves with the full calculation, 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 Δg 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.*

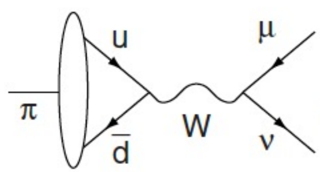
Pion Distribution Amplitude

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



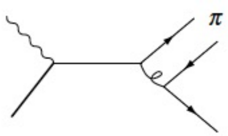
Project parallel $q\bar{q}$ onto pion using
$\int_0^1 dy\ \phi_\pi(y) \times$
$\frac{1}{\sqrt{2}} \left(u_\uparrow(yk) v_\downarrow((1-y)k) - (\uparrow \leftrightarrow \downarrow) \right)$.

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 $I_\pi = \int_0^1 dy\ \frac{\phi_\pi(y)}{y}$.

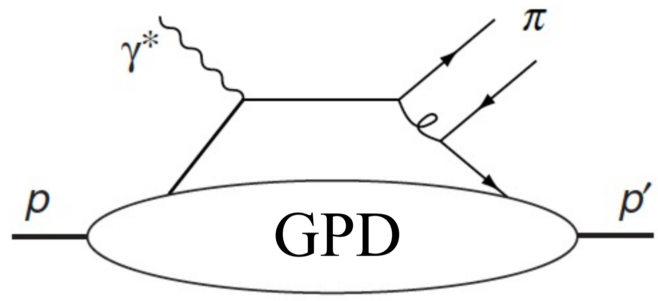
(Same integral appears in pion FF calculation,
(both for $\gamma^* \pi^+ \to \pi^+$ and $\gamma^* \gamma \to \pi^0$.)

$Q^2 \neq 0$ also requires

$$I'_\pi = -t \int_0^1 dy \frac{\phi_\pi(y)}{(1-y)Q^2 - yt}$$

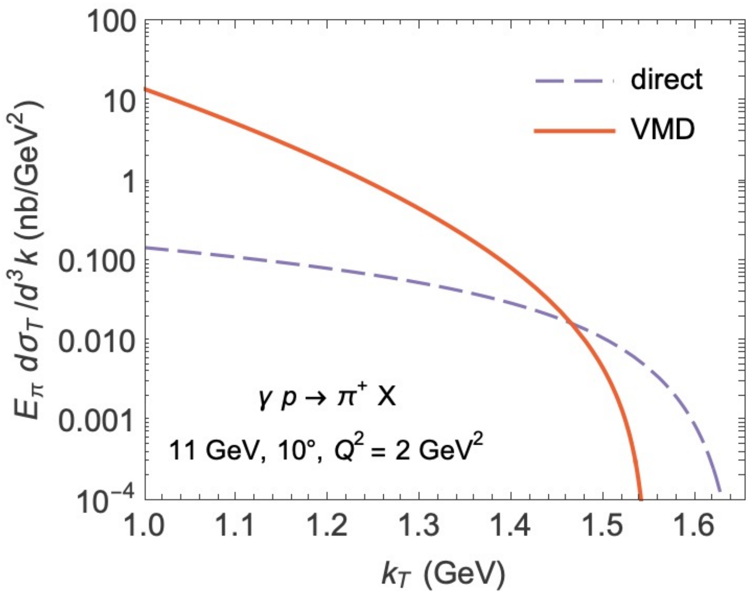
Relevance to GPD measurements

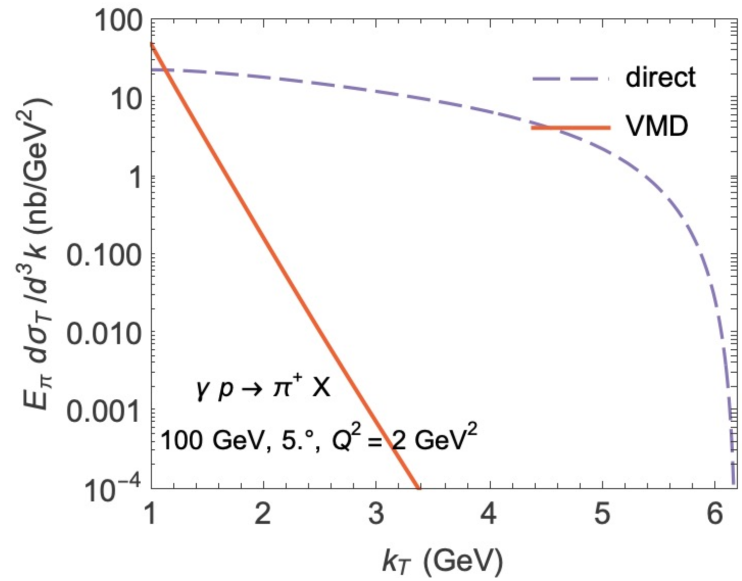
- Exclusive pion electroproduction calculated using GPD's involves the same hard subprocess.



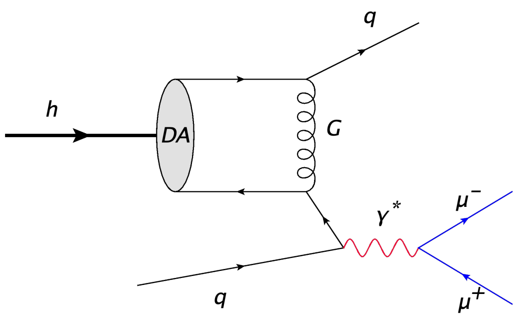
Direct Pion Production vs Beam Energy

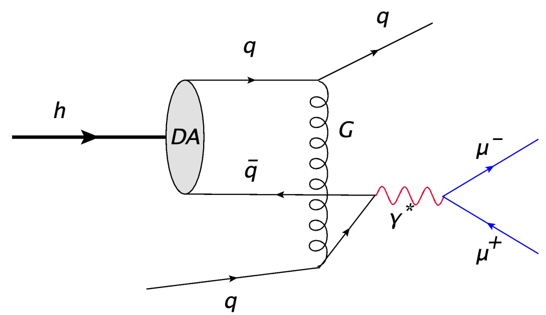
- For higher beam energies, higher kT can be accesses, while suppressions VMD contributions
  - Semi-exclusive production mechanism has an order-of-magnitude higher cross section
  - EIC can study these processes

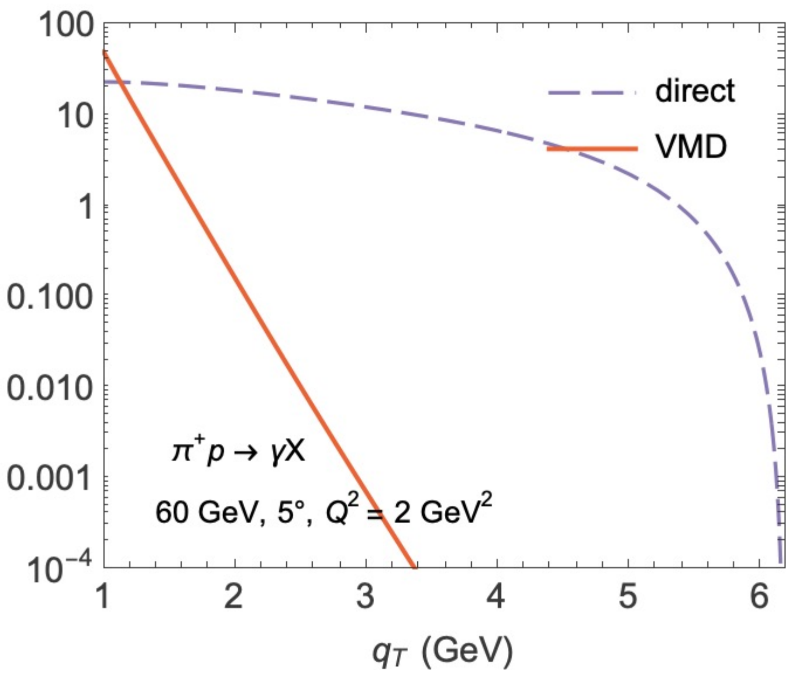


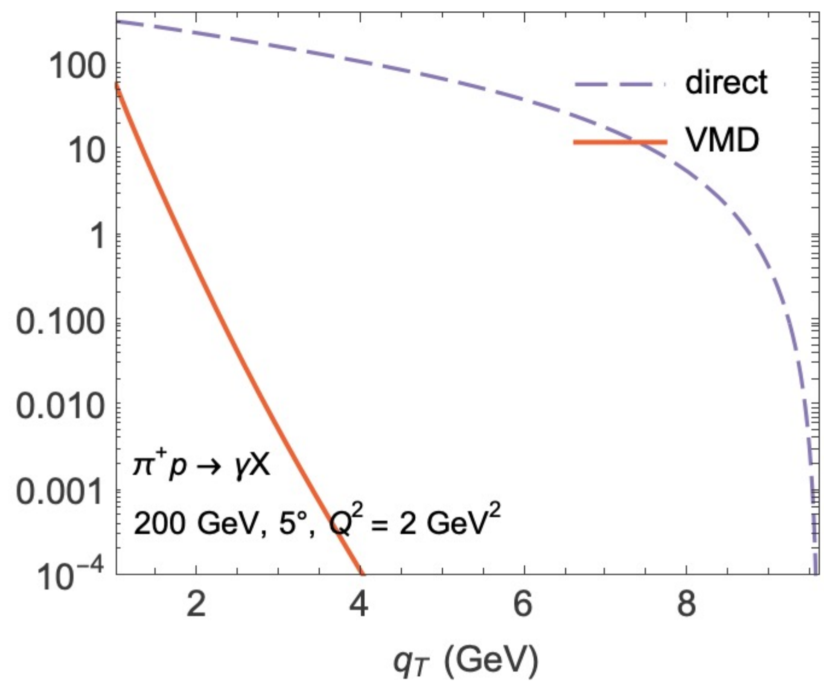


Semi-Exclusive Drell Yan



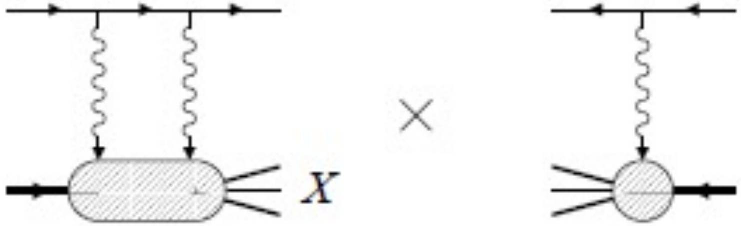




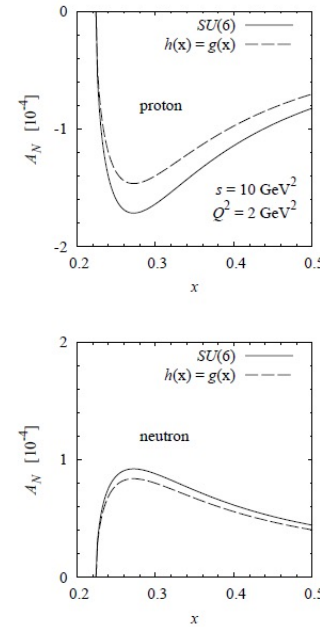


AA, Carlson, in progress

Two-Photon Exchange in inclusive DIS



- Theory: Afanasev, Strikman, Weiss, **Phys.Rev.D77:014028,2008**
  - 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**
- **In contradiction to JLAB observation of per-cent asymmetry**
  J. Katich et al. Phys. Rev. Lett. **113,** 022502 (2014).



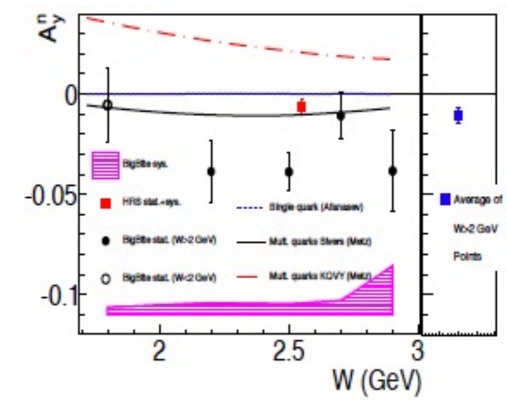
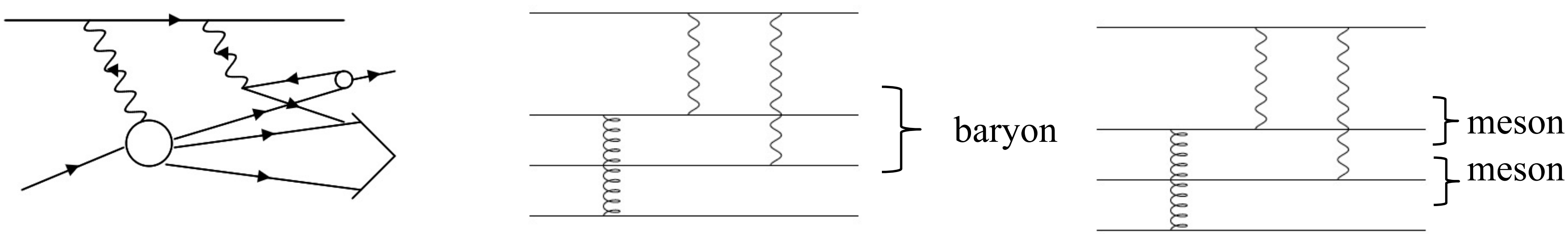


FIG. 3. Neutron asymmetry results (color online). **Left panel:** Solid black data points are DIS data ($W > 2$ GeV) from the BigBite spectrometer; open circle has $W = 1.72$ GeV. BigBite data points show statistical uncertainties with systematic uncertainties indicated by the lower solid band. The square point is the LHRS data with combined statistical and systematic uncertainties. The dotted curve near zero (positive) is the calculation by A. Afanasev *et al.* [11], The solid and dot-dashed curves are calculations by A. Metz *et al.* [12] (multiplied by −1). **Right panel:** The average measured asymmetry for the DIS data with combined systematic and statistical uncertainties.

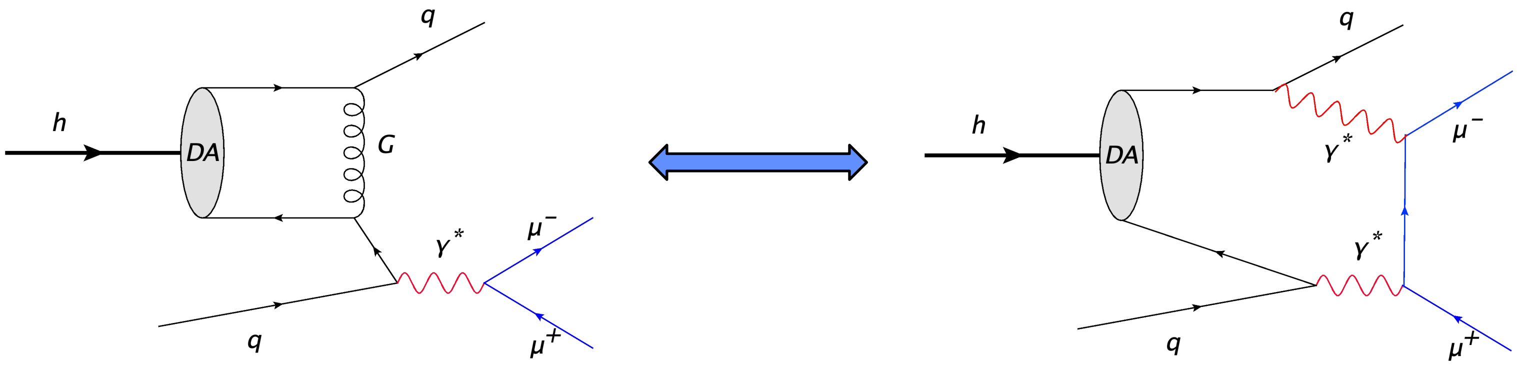
Two-Photon Fragmentation for SIDIS

- Extending Kivel-Vanderhaeghen mechanism to SIDIS
  - Emission of an additional photon that converts into quark-antiquark pair leads do 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