Physics with exclusive dilepton photoproduction

C. Weiss (JLab), Nucleon and nuclear structure through dilepton production, ECT* Trento, 24–28 Oct 2016

\[ \gamma + T \rightarrow (l^+ l^-) + T' \]

quasi two-body

\[ T = N, A, \quad l = e, \mu \]

- Crossing, BH-TCS interference, kinematic regions
- Vector meson region \( M_{l+l^-} \sim M_V \): Re/Im amplitude
- High-mass region \( M_{l+l^-} \gg 1 \text{ GeV} \): QCD description, GPDs
- \( J/\psi \) region \( M_{l+l^-} \sim M_{c\bar{c}} \): Gluon GPDs, \( J/\psi-N \) bound states
- Related processes: Electro- and hadroproduction of dileptons
Dileptons: Crossing

- Crossing: Relativity & analyticity

- Measure form factors $F(t < 0)$ with photon beam
  
  QED pair production process as “radiator/source”

- Advantages of pair production channel
  
  Lepton charge asymmetry $l^+ \leftrightarrow l^-$

  Different lepton species $l = e, \mu$

  Lepton universality in elastic scattering: Pauk, Vanderhaeghen 15
Dileptons: BH and TCS amplitudes

Exclusive dilepton production

\[ \gamma + T \rightarrow (l^+l^-) + T' \]

Quasi two-body

Kinematic variables \( M^2, s, t \)

- BH amplitude

Strong kinematic variation because lepton virtuality becomes small in collinear configurations \( p_{l+} \parallel q \) or \( p_{l-} \parallel q \)

Leading-order amplitude real, higher-order corrections give \( \text{Im}(\text{BH}) \neq 0 \)

- BH and TCS amplitudes interfere

Interference effect depends on relative size of amplitudes, width of \( M^2 \) window, polarization states

Use as tool for nucleonic and nuclear structure!
Dileptons: TCS kinematic regions

- Pair mass $M_{l^+ l^-}$
  - $M_{l^+ l^-} \sim M_V$ hadronic
  - $M_{l^+ l^-} \gg 1$ GeV QCD, quarks/gluons
  - $M_{l^+ l^-} \approx M_{c \bar{c}}$ QCD, gluons

- CM energy squared $s$
  - Reggeon ↔ pomeron exchange (hadronic)
  - Quark ↔ gluon GPDs (QCD)

- Momentum transfer $t$
  - $t < t_{\text{min}}(s, M^2)$ kinematic limit
VM region: Re/Im of $\phi$ amplitude

$+ \quad \quad \quad +$

- Charge asymmetry $l^+ \leftrightarrow l^-$ gives direct access to $\text{Re}M_\phi/\text{Im}M_\phi \equiv \beta$

- Method demonstrated

DESY71: $^{12}\text{C}$ nucleus, $\beta = -0.48^{+0.33}_{-0.45}$

Precise measurements possible with JLab12

CLAS12, GlueX?

- Re/Im important information on production mechanism

Exchange mechanisms?


- **Energy dependence puzzle**

  Non-uniform energy dependence of $d\sigma/dt(t = 0)$ observed near threshold LEPS05, CLAS 6 GeV

  Important to correct for $t_{\text{min}}$ effect!

  Exchange mechanisms: $\eta$ vs. Pomeron?

- **Nuclear targets**

  Helicity–flip suppressed in coherent production $\gamma + A \rightarrow \phi + A$:

  Nucleus has to stay intact! [Strikman]

  Nuclear FSI: Glauber approximation

- **$\phi$ electroproduction at $Q^2 \gg 1 \text{ GeV}^2$**

  Strange quark vs. gluon GPD?

  Intrinsic strangeness?
VM region: $\rho^0$ photoproduction

- $\rho^0$ reconstruction using $e^+e^-$ mode
  
  Complement/test reconstruction in $\pi^+\pi^-$ mode

  Wide resonance, pedestal subtraction specific to decay mode

- $\text{Re}/\text{Im}$ from BH–$\rho^0$ interference
  
  DESY 70 measurement, $\beta = 0.2 \pm 0.1$

  Precise measurements possible with JLab12
  
  CLAS12, GlueX?

- $\rho^0$ electroproduction puzzle $\rightarrow$ Talk Kroll
  
  What causes rise of cross section at $W < 4$ GeV?
  
  CLAS 6 GeV data. Guidal, Morrow 08

  $\text{Re}/\text{Im}$ can give new insight
High-mass region: Factorization, GPDs

- **Factorization (cf. DVCS)**
  Berger, Diehl, Pire 02

  $M^2$ as large scale, collinear approximation

  Quark-gluon process $\times$ GPD

  Crossing of quark-gluon process

- **Observables**

  Differential cross section (BH dominant)

  Photon SSA linear pol $A_{LU}$, circular pol $A_{\sigma U}$ ($BH = 0$)

  Target SSA linear pol $A_{Ux,y,z}$ ($BH = 0$)

  Double spin asymmetries

- **Use for GPD analysis**

  Sensitive to $\text{Re}(\text{TCS})$, D–term

  Boer, Guidal, Vanderhaeghen 15+
High-mass region: Questions

- **NLO QCD corrections**
  
  Apparently large in Re(TCS): Effective scale? Quark ↔ gluon GPDs?
  Pire, Szymanowski, Wagner 11; Moutarde, Sabatie, Szymanowski, Pire 13

  Crossing of partonic amplitudes
  Müller, Pire, Szymanowski, Wagner 12

- **Dispersion relations for TCS amplitude**
  
  $s$–channel dispersion relation (cf. DVCS)?
  Analyticity in $M^2$: Rich structure, Landau singularities

- **Higher-order QED corrections**
  
  Two-photon exchange makes $\text{Im}(BH) \neq 0$
  Soft-photon emission from BH and TCS amplitudes can generate asymmetries
- Charmonium production using $l^+l^-$ mode

- Charmonium size small on hadronic scale

  LQCD, potential models: $\langle r^2 \rangle^{1/2} \sim 0.2–0.3 \text{ fm}$

  EFT approach: Non–relativistic QCD, $\nu \ll 1$

  Lepage et al 92; Manohar 97; Brambilla 2000; Kniehl et al. 2002

  \[
  m \gg mv \gg mv^2
  \]

  mass \quad momentum, inverse size \quad binding energy

  “intermediate”

- $\bar{Q}Q$ couples to gluon field in nucleon/nucleus

  Multipole expansion: Dipole + ...

  Fields change with energy $s$, momentum transfer $t$

- Related process: Charmonium–nucleon scattering

  Theoretically simpler, difficult to realize in exp
• Light–cone variables

\[ \zeta \quad \text{"Plus" momentum transfer, cf. } x_B \]
large near threshold, but not \( \zeta \to 1! \)

\[ \Delta_T \quad \text{Transverse momentum transfer} \]

\[ t = -\left(\zeta^2 m_N^2 + \Delta_T^2\right)/(1 - \zeta) \]

• Invariant momentum transfer grows near threshold: \( |t_{\text{min,th}}| = 2.2 \text{ GeV}^2 \)

• Two regimes

\[ W \approx W_{\text{th}} \quad t_{\text{min}} = 1\text{–}2 \text{ GeV}^2, \zeta \text{ large} \]
cf. nucleon elastic form factors
Cornell, SLAC, JLab 12 GeV

\[ W \gg W_{\text{th}} \quad t_{\text{min}} \text{ negligible, } \zeta \ll 1 \]
cf. diffractive processes
FNAL, COMPASS, HERA, EIC
**J/ψ region:** Photoproduction at high $W$

- **Collinear factorization** \cite{Collins, Frankfurt, Strikman 96}
  
  Space-time picture in rest frame: $l_{\text{coh}} \gg 1 \text{ fm}$  
  
  Brodsky et al. 94

- **GPD as gluonic dipole moment of target**

- **HERA exp:** Kinematic dependences, absolute cross secns, comparison of diffractive channels $J/\psi \leftrightarrow \rho^0, \phi(Q^2)$
  
  More data: Ultraperipheral $pA$ at LHC $\rightarrow$ Talk Guzey

- **Transverse spatial distribution of gluons**
  
  Fourier $\Delta_T \rightarrow b$ impact parameter

  Distribution changes with $x$ and scale $\mu^2$:
  
  Parton diffusion, DGLAP evolution

  Fundamental gluonic size of nucleon in QCD:
  
  Gluon vs. quark radii, non–pert. dynamics

  Needed for small–$x$ physics, pp@LHC underlying event, multiparton processes, diffraction
  
  Frankfurt, Strikman, CW 04/11; Frankfurt, Hyde, Strikman, CW 07

  EIC: Gluon imaging’’
**J/ψ region: Photoproduction near threshold**

- **Kinematics near threshold**
  
  Large $|t_{\text{min}}|$, up to 2.2 GeV$^2$
  
  Large longit. momentum transfer $x_1 - x_2 = \zeta$

- **Reaction mechanism near threshold**
  
  GPD-based description at $t \sim 1–2$ GeV$^2$ and large skewness: Two-gluon form factor
  
  Frankfurt, Strikman 02
  
  Hard scattering mechanism, cf. high–$t$ FFs
  
  Brodsky, Chudakov, Hoyer, Laget 01
  
  Can be tested with JLab 12 GeV!

- **Theoretical questions**
  
  Behavior of two–gluon form factor?
  
  Correlations in nucleon LCWF?
**$J/\psi$ region: Bound states and nuclei**

- **$J/\psi$ nucleon bound states**
  - Hints seen in LHCb experiments, great interest
  - Can be studied in dilepton photoproduction
  - $J/\psi$ and $N$ fast in lab frame

- **$J/\psi$ photoproduction on nuclei**
  - $J/\psi$ fast in nucleus rest frame
  - Study $J/\psi$–$N$ interaction at $p_\psi \sim$ few GeV

- **Low-energy $J/\psi$–$N$ interaction**
  - Theoretical interest: Operator expansion, QCD Van–der–Waals force, nuclear bound states
  - Fuji, Kharzeev 99; Brodsky, Miller 97; Brodsky, de Teramond 90; Luke, Manohar, Savage 92
  - How to study it experimentally?

**Diagram:**
- Lab momenta $p_\psi$, $p_N$ at $\Delta T = 0$ [GeV]
- $E_\gamma$ [GeV]
Dileptons: Related processes

- Exclusive dilepton electroproduction $e + T \rightarrow e' + (l^+l^-) + T'$
  
  - $L/T$ amplitudes, $Q^2$ dependence
  
  - Antisymmetrization if $l = e$; effect minor if kinematically separated; absent if $l = \mu$

- Vector meson region: Re/Im in $\rho^0, \phi$ electroproduction

- High-mass region: DDVCS for GPD analysis, very challenging
  
  - JLab12 → Talks Guidal, Baltzel, Camsonne

- $J/\psi$ region: Electroproduction near threshold
  
  - JLab12 SOLID → Talk Meziani

- Inclusive dilepton photoproduction on nuclei $\gamma + A \rightarrow (l^+l^-) + X$
  
  - Vector mesons “in medium:” Mass shift, broadening, optical potential
  
  - CBELSA/TAPS, CLAS. Overview see V. Metag, Workshop Nuclear photoproduction with GlueX, JLab, April 28-29, 2016.

- Exclusive hadron production $\pi + T \rightarrow (l^+l^-) + T' \rightarrow$ Talk Chang
  
  - Timelike meson photoproduction, exclusive version of Drell-Yan
  
  - JPARC, COMPASS?
Dileptons: Summary

- Interesting physics in exclusive dilepton photo/electroproduction
  
  Vector meson region: Re/Im in $\rho^0, \phi$, test of universality
  
  High-mass region: Re/Im in GPD analysis, D–term
  
  Gluonic structure, $J/\psi-N$ bound states

- Much can be covered by approved JLab12 experiments or extensions
  
  Discuss need for $\mu^+\mu^-$ vs. $e^+e^-$

- Accurate treatment of QED radiative corrections essential
  
  Im(BH) \neq 0 in higher orders; real emissions change charge parity

- Photoproduction capabilities at EIC → Talk Hyde
  
  Small-angle electron tagger for photoproduction in JLEIC design
  
  What dilepton capabilities will be needed in central detector?