Plans to measure $J/\psi$ photoproduction and TCS on the proton at CLAS12

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Outline

Introduction

\( J/\psi \) photoproduction near threshold

- Gluonic structure of the nucleon at large \( x \)
- Behavior of cross section near threshold is unknown
  - CLAS12 will provide the first results
- Future measurements with nuclear targets?

Timelike Compton Scattering (TCS)

- Timelike-spacelike correspondence and universality of GPDs
- Real and imaginary parts of Compton form factors for valence quarks
Approved ep → e'pe^+e^- program for CLAS12

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- Unpolarized proton target will be first to run
- Experiment E12-12-001 for e^+e^- physics was approved at the last PAC meeting
- Spectroscopy (119 PAC days) and e^+e^- (100+20 days) experiments drive the total beam time for proton running (119+20 days), which can be shared by all.
- Approved beam time corresponds to more than a year of actual running
Partons in the nucleon

Elastic form factors
Transverse spatial distributions
(Naively Fourier transform of $Q^2$ or $t$)

Parton Distribution Functions
Longitudinal momentum distributions

Generalized Parton Distributions
A unified description of partons (quarks and gluons) in momentum and impact parameter space
Generalized Parton Distributions (GPDs)

**Experimental Kinematics**
- GPDs are measured in exclusive processes
- $Q^2$ is the momentum transfer from the electron
- $t$ is the momentum transfer to the nucleon
- $2\xi$ is the difference between initial and final momentum of the struck parton

**Elastic Form Factors**
\[
\int_{-1}^{1} dx \, H(x, \xi, t) = F_1(t) \quad \int_{-1}^{1} dx \, \tilde{H}(x, \xi, t) = g_A(t)
\]
\[
\int_{-1}^{1} dx \, E(x, \xi, t) = F_2(t) \quad \int_{-1}^{1} dx \, \tilde{E}(x, \xi, t) = h_A(t)
\]

**Parton Distribution Functions (PDFs)**
\[
H(x, \xi=0, t=0) = q(x)
\]
\[
\tilde{H}(x, \xi=0, t=0) = \Delta q(x)
\]

$E$, $\tilde{E}$ don't appear in DIS (nucleon helicity flip)
Charmonium as a probe of nucleon's color field

At high $Q^2$ $c\bar{c}$ is produced in small-size configurations

- c.f. color transparency
- Local probe of color field

$J/\psi$ photoproduction

- Probes distances $\approx 1/\sqrt{Q^2 + M_{J/\psi}^2} \approx 1/M_{J/\psi}$
- $J/\psi$ radius much smaller than nucleon: $r_{J/\psi} \sim 0.2 - 0.3$ fm $<< 1$ fm
- Transverse size in light-cone wave function: $<r_T^2> = 2/3 <r^2>$
- Small-size configurations dominate, but corrections could be important
Exclusive J/ψ kinematics near threshold

Four-momentum transfer to the nucleon

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

- \( \zeta \) is the „plus“ momentum transfer
  - light cone variables
- \( \Delta_T \) is the transverse momentum transfer
- \( t_{\min} \) at threshold is 2.2 GeV^2

C. Weiss, Non-perturbative forces in QCD, Temple U., 26-28 March 2012
**J/ψ production at high vs. low W (= \( \sqrt{s} \))**

**J/ψ production at high W**

- Access to nucleon's gluon GPD at small \( x \)
  - \( t_{\text{min}} \) and \( \zeta \) small, well understood diffractive process
  - Measurements at EIC, HERA, COMPASS, FNAL

**J/ψ production near threshold**

- \( t_{\text{min}} \) and \( \zeta \) large, implies large skewness \( x_1 - x_2 \)

- Natural interpretation in terms of a gluonic form factor sensitive to non-perturbative gluon field
  - analogous to high-\( t \) elastic \( eN \) scattering

- Amplitude constant, but cross section near threshold suppressed by large \( t_{\text{min}} \)

Weiss, Strikman
Enhancement instead of suppression near threshold?

- Based on the Cornell point, Brodsky et al. instead suggest a flattening out near threshold – diagram on the right?

- CLAS12 can easily answer this question.

- For rate predictions, a conservative estimate more akin to the red curve was used for E12-12-001.
Exclusive quasi-real photoproduction in CLAS12

- Low-$Q^2$ events are reconstructed by applying cuts on the transverse momentum of the missing beam electron.

- Exclusivity is ensured by detection of all produced final-state particles, and application of a missing mass cut.
Detection of the exclusive final state in CLAS12

- The leptons pairs are detected and identified using the High-Threshold Cherenkov Counter (HTCC) and the Forward Electromagnetic Calorimeter (FEC).

- Pairs with one lepton below the HTCC pion threshold of 4.9 GeV/c will have a pion pair rejection factor of $2 \cdot 10^7$.

- Proton kinematics and acceptance are shown on the right.
Acceptance and yields for J/ψ in CLAS12

- CLAS12 has excellent acceptance for photoproduction of lepton pairs with a large invariant mass over a wide range in s and t.

\[ E_\gamma > 9 \text{ GeV} \]

\[ 9.92 \text{ GeV} < E_\gamma < 11 \text{ GeV} \]

Bethe-Heitler + J/ψ

100 days at \(10^{35} \text{ cm}^{-2}\text{s}^{-1}\)
Projected results – exclusive J/ψ production

Statistical uncertainties for 100 days at a luminosity of $10^{35}$ cm$^{-2}$s$^{-1}$

Uncertainties for the total cross section assuming the most conservative prediction

$t$-dependence in narrow bins of $s$ for a total cross section given by the lower curve on the left
Projected results – “inclusive” $J/\psi$ production

Statistical uncertainties at a luminosity of $10^{35}$ cm$^{-2}$s$^{-1}$

Filled squares: 100 days   Open squares: 30 days

- Excellent benchmark for studies of detector efficiency
  - Nominal acceptance for $e^+ e^-$ final state identical for both torus polarities
## Approved CLAS12 beam time with nuclear targets

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Timelike Compton Scattering (TCS)

**Timelike-spacelike correspondence and the universality of GPDs**

- Of fundamental importance for the GPD program

**Real (and imaginary) part of Compton amplitude**

- Straightforward access through azimuthal asymmetry of lepton pair
- Input for global analysis of Compton Form Factors (and GPDs)
Deep Inelastic Scattering (DIS) and Drell-Yan

- The spacelike DIS and timelike Drell-Yan processes both factorize into a partonic cross section and a Parton Distribution Function (PDF)
  - Measurements of both demonstrated the universality of PDFs
DVCS and TCS

(spacelike) Deeply Virtual Compton Scattering

Timelike Compton Scattering

- In DVCS there is a similar factorization at the amplitude level into a partonic amplitude and a Generalized Parton Distribution (GPD)
  - Measuring both spacelike DVCS and Timelike Compton Scattering (TCS) can test the universality of GPDs
Real part at large $x$ important for GPD models

\[ \tau = \frac{Q'^2}{s - M_p^2} \]

\[ \eta = \frac{\tau}{2 - \tau} \]

$\tau$ and $\eta$ are the TCS equivalents of Bjorken $x$ and the skewness $\xi$.

$Q'^2 = M^2_{e^+e^-}$ is the timelike virtuality of the outgoing photon (→ hard scale).
Photoproduction of lepton pairs

- TCS and Bethe-Heitler (BH) processes contribute
- TCS cross section is smaller than BH in JLab 12 GeV kinematics
- The interference term is enhanced by the BH and easy to isolate
TCS-BH interference

\[
\frac{d \sigma^4}{dQ'^2 \, dt \, d(\cos \theta) \, d\phi} = |BH|^2 + I(BH \cdot TCS) + |TCS|^2
\]

- Under lepton charge conjugation:
  - Compton and BH amplitudes are even
  - Interference term is odd
    \[
    \text{Easy to project out only the interference term}
    \]

- Direct access to interference term through angular distribution of the lepton pair
  - cosine and sine moments
Kinematics

- $k, k' = \text{momentum of } e^-, e^+$
- $\theta = \text{angle between the scattered proton and the electron}$
- $\phi = \text{angle between lepton scattering- and reaction planes}$

\[
\frac{d\sigma_{BH}}{dQ'^2 dt d\cos \theta} \approx 2\alpha^3 \frac{1 + \cos^2 \theta}{-tQ'^4} \frac{1 - \cos^2 \theta}{1 - \cos^2 \theta} \left( F_1(t)^2 - \frac{t}{4M_P^2} F_2(t)^2 \right)
\]

- For $\theta$ close to 0 and $\pi$, BH becomes large. A cut is usually applied.
TCS cross section and the interference term

\[
\frac{d\sigma_{TCS}}{dQ'^2 \, d\Omega \, dt} \approx \frac{\alpha^3}{8\pi} \frac{1}{s^2} \frac{1}{Q'^2} \left( \frac{1 + \cos^2 \theta}{4} \right) 2(1 - \xi^2) |\mathcal{H}(\xi, t)|^2
\]

\[
\frac{d\sigma_{INT}}{dQ'^2 \, dt \, d\cos \theta \, d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{t} \frac{M}{Q'} \frac{1}{\tau \sqrt{1 - \tau}} \cos \varphi \frac{1 + \cos^2 \theta}{\sin \theta} \Re \tilde{M}^{--}
\]

\[
\tilde{M}^{--} \approx \frac{2\sqrt{t_0 - t}}{M} \frac{1 - \xi}{1 + \xi} [F_1(t) \mathcal{H}(\xi, t)]
\]

\[
\mathcal{H}(\xi, t) = \sum_q e_q^2 \int_{-1}^{1} dx \left( \frac{1}{\xi - x + i\epsilon} - \frac{1}{\xi + x + i\epsilon} \right) H^q(x, \xi, t)
\]
The D-term and the pressure balance in the nucleon

\[ H(x, \xi) = H_{DD}(x, \xi) + \theta(\xi - |x|) \frac{1}{N_f} D\left(\frac{x}{\xi}\right) \]

- The D-term contributes only to the real part of the Compton amplitude
First measurements at 6 GeV

• Cosine moment of weighted cross sections

\[
\frac{dS}{dQ^2 dt d \varphi} = \int \frac{L(\theta, \varphi)}{L_0(\theta)} \frac{d \sigma}{dQ^2 dt d \varphi} d \theta
\]

\[
R = \frac{2 \int_0^{2\pi} d \varphi \cos \varphi \frac{dS}{dQ^2 dt d \varphi}}{\int_0^{2\pi} d \varphi \frac{dS}{dQ^2 dt d \varphi}}
\]

• Numerator is proportional to \( \overline{M} \cdot \overline{M} \)
  - \( \cos \varphi \) part of interference term

• \( R \) can be compared directly with GPD models

• Analysis of 6 GeV data with tagged real photons is underway

Comparison of results by R. Paremuzyan et al from e1-6/e1f with calculations by V. Guzey.
From 6 to 12 GeV

- 6 GeV kinematics are limited to $M_{e^+e^-} < 2$ GeV.
- 12 GeV extends this mass ($Q'$) range up to 3 GeV

- 6 GeV data were important for developing methods

- 12 GeV will provide
  - A much larger reach in $s$ and $Q'^2$
  - Higher luminosity and more statistics for multi-dimensional binning
  - A possibility to avoid meson resonances in the $e^+e^-$ final state
    - Data can be taken in the resonance-free region between the $\rho'$ and $J/\Psi$
Projected results – cosine moment $R'$

Statistical uncertainties for 100 days at a luminosity of $10^{35}$ cm$^{-2}$s$^{-1}$

- Uncertainties for $R'$, integrated over the CLAS12 acceptance, for two bins in photon energy, for the lowest $Q'^2$ bin above the $\rho'$ resonance.
- Different values of the D-term are only shown for the double distribution.
Summary

CLAS12 experiment E12-12-001 will measure TCS and J/Ψ

**J/Ψ photoproduction near threshold**

- Establish reaction mechanism
- Access to gluonic structure of the nucleon at large x

**Timelike Compton Scattering (TCS)**

- Test universality of GPDs
- Straightforward access to real part of Compton form factors
Backup
Jefferson Lab PAC 39 Proposal
Timelike Compton Scattering and $J/\psi$ photoproduction on the proton in $e^+e^-$ pair production with CLAS12 at 11 GeV


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(Dated: May 4, 2012)

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Probing GPDs through Compton scattering

(Im, $x=\xi$)
DVCS: spin asymmetries
(TCS with polarized beam)

(DVCS: charge asymmetry)

(Re)
TCS: azimuthal asymmetry
DVCS: charge asymmetry

$H(x, \xi, 0)$

(Im, $x \neq \xi$, $x < |\xi|$)
Double DVCS

(|Re|^2)
DVCS: cross section
Interference term

To leading order, in terms of helicity amplitudes:

\[
\frac{d\sigma_{INT}}{dQ'^2 dt d(cos \theta) d\varphi} = -\frac{\alpha^3_{em}}{4\pi s^2} \frac{1}{-t} \frac{M}{Q'} \frac{1}{\tau \sqrt{1-\tau}} \frac{L_0}{L} \left[ \cos \varphi \frac{1 + \cos^2 \theta}{\sin \theta} \text{Re} \tilde{M}^{--} + \cos 2\varphi \sqrt{2} \cos \theta \text{Re} \tilde{M}^{0-} + \cos 3\varphi \sin \theta \text{Re} \tilde{M}^{+-} + O\left(\frac{1}{Q'}\right) \right],
\]

\[
-\frac{\alpha^3_{em}}{4\pi s^2} \frac{1}{-t} \frac{M}{Q'} \frac{1}{\tau \sqrt{1-\tau}} \frac{L_0}{L} \left[ \sin \varphi \frac{1 + \cos^2 \theta}{\sin \theta} \text{Im} \tilde{M}^{--} - \sin 2\varphi \sqrt{2} \cos \theta \text{Im} \tilde{M}^{0-} - \sin 3\varphi \sin \theta \text{Im} \tilde{M}^{+-} + O\left(\frac{1}{Q'}\right) \right],
\]

\[\nu:\text{ circular polarization of incoming photon also gives access to imaginary part}\]

\[
\frac{1}{2} \sum_{\lambda, \lambda'} |M_{\lambda', \lambda^-}^{\lambda^-}|^2 = (1 - \eta^2) \left( |\mathcal{H}_1|^2 + |\mathcal{H}_1^*|^2 \right) - 2\eta^2 \text{Re} (\mathcal{H}_1^* \mathcal{E}_1 + \mathcal{H}_1 \mathcal{E}_1^*) - \left( \eta^2 + \frac{t}{4M^2} \right) |\mathcal{E}_1|^2 - \eta^2 \frac{t}{4M^2} |\bar{\mathcal{E}}_1|^2.
\]
• CLAS12 has excellent acceptance for photoproduction of lepton pairs with a large invariant mass over a wide range in $s$ and $t$. 
Acceptance in the TCS angles $\theta_{\text{CM}}$ and $\phi_{\text{CM}}$

$E_\gamma = 9.39$ GeV, $Q^2 = 4.5$ GeV$^2$

Generated events. Regions dominated by BH fall outside of the contour indicating the CLAS acceptance.

Accepted events for four t-bins. The observable $R'$ is integrated over the CLAS acceptance.
Projected results – cross section

Statistical uncertainties for 100 days at a luminosity of $10^{35}$ cm$^{-2}$s$^{-1}$

- The unpolarized and polarized four-fold differential TCS+BH cross sections will provide input for global analysis of Compton Form Factors.

- The narrow $J/\psi$ peak on the right is very prominent.