Extraction of the cross-section of the near-threshold photoproduction of J/ψ with the CLAS12 experiment

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Motivations and previous results

Motivations and previous results
Photoproduction of the J/ψ meson near its production threshold

J/ψ photoproduction near the energy threshold

\[
\gamma p \rightarrow J/\psi \ p' \rightarrow e^+ e^- p'
\]

- At the energy production threshold, the t-dependence of the cross-section allows to access gluon Gravitational Form Factors (GFFs) and the mass radius of the nucleon.

**Cross-section**

\[
\frac{d\sigma_{\gamma p \rightarrow J/\psi p}}{dt} = \frac{1}{64\pi s} \left| \frac{1}{|p_{cm}|^2} M_{\gamma p \rightarrow J/\psi p}(t) \right|^2
\]

**Amplitude**

\[
M_{\gamma p \rightarrow J/\psi p}(t) \propto \langle p' | T^g_{\mu\nu} | p \rangle
\]

**Matrix element**

\[
\langle p', s' | T^a_{\mu\nu}(x) | p, s \rangle = \bar{u}' \left[ A^a(t) \frac{\gamma_{\nu}(p_\nu)}{2} + B^a(t) \frac{iP_{\mu} \sigma_{\nu\lambda} \Delta_{\mu\nu}}{4m} + D^a(t) \Delta_{\mu\nu} - g_{\mu\nu} \Delta^2 + m \bar{c}^\alpha(t) g_{\mu\nu} \right] u(p' - p)\alpha
\]

Coupled channels and pentaquarks

- The previous considerations rely on the application of Vector Meson Dominance.
- Thus the contribution from open-charm meson channels and potential pentaquark must be understood or ruled-out.

Recent results from JLab

Figure from “Measurement of the $J/\psi$ photoproduction cross section”, S. Adhikari et al. (GlueX Collaboration), Phys. Rev. C 108, 025201, 2023, arXiv:2304.03845

Figure from “Determining the gluonic gravitational form factors of the proton”. Duran, B., Meziani, ZE., Joosten, S. et al. Nature 615, 813–816 (2023)


Figure from S. Prasad presentation at the APS/JPS 2023 meeting

Extraction of the cross-section of the near-threshold photoproduction of $J/\psi$ with the CLAS12 experiment – Pierre Chatagnon – 10th of July 2024 – QNP2024
Experimental setup and analysis strategy
The CLAS12 detector package

**Beam**
- 85% longitudinally polarized $e^-$
- Max. luminosity: $10^{35}$ s$^{-1}$cm$^{-2}$
- Energy up to ~10.6 GeV

**Target**
- Proton
- Deuterium
- Longitudinally pol. H/D
- Nuclear targets

**Central Detector**
- Solenoid magnet
- Tracker
- Time-of-Flight
- Neutron detector

**Forward Detector**
- Torus magnet
- Drift Chambers
- Time-of-Flight
- Calorimeters
- Cherenkov counters

**Forward Tagger**
- Calorimeter
- Time-of-Flight
- Tracker

**Extraction of the cross-section of the near-threshold photoproduction of $J/\psi$ with the CLAS12 experiment – Pierre Chatagnon – 10th of July 2024 – QNP2024**
Exclusive dilepton event selection

What we want to measure

\[ \gamma p \rightarrow e^+ e^- p' \]

What we can measure with CLAS12

\[ ep \rightarrow (e') \gamma p \rightarrow (e') e^+ e^- p' \]
Exclusive dilepton event selection: Exclusivity variables

1) CLAS12 PID + Positron NN PID

\[ e^+ p \rightarrow (e') \gamma p \rightarrow (X) e^+ e^- p' \]

\[ p_X = p_{beam} + p_{p} - p_{e^-} - p_{e^+} - p_{p'} \]

2) \(|M_X^2| < 0.4 \text{GeV}^2\)

3) \(Q^2 < 0.5 \text{ GeV}^2\)

Proton identification

Lepton identification

Cherenkov counters + Calorimeter energy deposition

Sampling Fraction = \(\frac{E_{dep}}{P}\)
Exclusive dilepton invariant mass spectrum

\[ ep \rightarrow (e')\gamma p \rightarrow (X)e^+e^-p' \]

Counts

Timelike Compton Scattering
Motivations and previous results ●● Analysis strategy ●●●●● Results and interpretation ●●●

Total cross section computation

\[ \sigma_j = \frac{N_{J/\psi,j}}{F_j \cdot \mathcal{L} \cdot \omega_{c,j} \cdot B_r \cdot \epsilon_j \cdot \epsilon_{Rad/j}} \]

- Number of photons and Number of targets
- Normalization factor
- Branching ratio
- Number of J/\(\psi\) from data
- Radiative corrections from MC
- Reconstruction efficiency from MC

Extraction of the cross-section of the near-threshold photoproduction of J/\(\psi\) with the CLAS12 experiment – Pierre Chatagnon – 10th of July 2024 – QNP2024
1) Number of $J/\psi$ from data

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Number of $J/\psi$</th>
<th>Integrated $\mathcal{I}$ (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GlueX</td>
<td>2270</td>
<td>320</td>
</tr>
<tr>
<td>Hall C - 007</td>
<td>~2K</td>
<td>1</td>
</tr>
<tr>
<td>CLAS12</td>
<td>707</td>
<td>114</td>
</tr>
</tbody>
</table>
II) Normalization factor - Overall strategy for the background modelization

1) Event mixing procedure from data:
   - Randomly select electron, positron, proton (from different events)
   - Construct kinematics and make sure they are within the region of interest:
     \( M_{ee} > 2 \text{ GeV}, |MM| < 0.4 \text{ GeV}^2, Q^2 < 2 \text{ GeV}^2 \)


3) Validate the weights on the validation region.

4) Apply weights on the signal region and obtained BG-subtracted yields
Motivations and previous results

Analysis strategy

Results and interpretation

II) Normalization factor - Data/MC comparison in the signal region

- Normalization factor can be computed as:

\[ \omega_C = \frac{N_{Data} - N_{BG}}{N_{SIM} \cdot BH} = 68.6\% \pm 16.9\% \]

Assigned as systematic error on normalization
Results from the CLAS12 experiment
Kinematic coverage and binning

Region of the dip observed by GlueX
Only the dominant normalization systematic (17%) is included in the CLAS12 results.

Both cross-sections are in agreement and errors (statistical and systematics) are of similar size.

No clear conclusion concerning a potential dip in the open charm threshold region.
Differential cross section coverage and binning
Preliminary differential cross-section results

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Dipole fit and interpretation in term of mass radius

\[ \frac{d\sigma}{dt} = \frac{d\sigma}{dt}_0 \cdot \frac{1}{(1-t/m_s^2)^4} \]

\[ \sqrt{\langle r^2 \rangle / m} = \frac{\sqrt{12}}{m_s} \]

Toward GFF extraction including CLAS12 data (work in progress)

Motivations and previous results

- **Analysis strategy**

Results and interpretation

---

Model dependent extraction of GFFs

- **Holographic QCD model**


\[
\frac{d \sigma}{dt} = \mathcal{N}^2 \frac{e^2}{64\pi(s-M_{K}^2)^2} \left[ A(t) + \eta^2 D(t)^2 \right] F(s) \cdot 8
\]

- **Generalized Parton Distribution model**

QCD analysis of near-threshold photon-proton production of heavy quarkonium, Yuxun Guo, Xiangdong Ji, and Yizhuang Liu, Phys. Rev. D 103, 096010, 2021

\[
\frac{d \sigma}{dt} = \frac{\alpha_{EM} e_Q^2}{4(W^2-M_N^2)^2} \left( \frac{16\pi\alpha_s}{3M_V^2} \right)^2 |\phi_{NR}(0)|^2 |G(t, \xi)|^2
\]

- **GFF parametrization**

\[ D(t) = \frac{D(0)}{\left(1 - \frac{t}{m_D^2}\right)^3} \quad A(t) = \frac{A(0)}{\left(1 - \frac{t}{m_A^2}\right)^3} \]

\[ A(0) = 0.414 \]

See T.-J. Hou et al., Phys. Rev. D 103, 014013 (2021) for A(0) value
Take-aways and outlook

- Photoproduction of J/ψ has become a *flagship* measurement for *current and future* JLab experiments.

- New *cross-section results* from the CLAS12 experiment have now been released.

- Current work is dedicated to wrapping-up the analysis note for *publication in the next few months*.

- Strong efforts to *interpret these data*, and *expand upon the capabilities of CLAS12* (measurement on deuterium target and muon final state analysis).

Thank you for your attention
BACK-UPs
Positron PID

One important challenge: a clean positron identification

Al identification of the positrons

Performances of AI identification of the positrons

Strategy and discriminating variables:

- Lepons produce electromagnetic showers and tend to deposit energy in the first layers of the detectors.
- Electrons penetrate deeper into the detectors, hence they deposit a smaller amount of energy along their path.

Two characteristics to use:

\[ S_{Elec} \frac{\sigma_{Elec} \Delta \rho}{\rho} \]

\[ M_2 = \frac{1}{2} \sum_{i=1}^{N} \frac{1}{x_{i,1}} \frac{1}{x_{i,2}} \sum_{j=1}^{N} (x_{i,1} - x_{j,1}) \sum_{k=1}^{N} (x_{i,2} - x_{j,2}) \]
One important challenge: a clean positron identification

Pion background at large momenta

At high momenta (typically above the HTCC threshold at 4.5 GeV), both pions and leptons will emit Cherenkov light.

\[ ep \rightarrow ep\pi^+\pi^- \quad \text{VS} \quad ep \rightarrow e\pi^+\pi^- \]

\[ \gamma p \rightarrow e^+e^-p \quad \text{M} \geq 1.5 \text{ GeV} \]
**AI identification of the positrons**

**Strategy and discriminating variables**

- Leptons produce electromagnetic showers and tend to deposit energy in the first layers of the calorimeters.
- Pions are **Minimum Ionizing Particles** in the GeV region, they deposit small amounts of energy all along their path.

- Two main characteristics to use:
  1. \[ S_{\text{EC Layer}} = \frac{E_{\text{dep(EC Layer)}}}{P} \]
  2. \[ M_2 = \frac{1}{3} \sum_{U,V,W} \frac{\sum_{\text{strip}} (x-D)^2 \cdot \ln(E)}{\sum_{\text{strip}} \ln(E)} \]
Performances of AI identification of the positrons

Strategy and discriminating variables

- Leptons produce electromagnetic showers and tend to deposit energy in the first layers of the calorimeters.
- Pions are Minimum Ionizing Particles in the GeV region, they deposit small amounts of energy all along their path.

Two main characteristics to use:

1. \[ SF_{EC\ Layer} = \frac{E_{dep}(EC\ Layer)}{P} \]

2. \[ M_2 = \frac{1}{3} \sum U,V,W \frac{\sum_{strip} (x-D)^2 \cdot \ln(E)}{\sum_{strip} \ln(E)} \]
J/ψ analysis

Data and MC samples
- Analysis is for 2012, all full LHC run on barrel calorimeter and Spring (1% runs are processed).
- Production are performed on MC and with full configuration.
- The CLAS12 rate were used in the simulation and assume the corrected charge per DCA line.
- The CLAS12 samples at full rates were used instead of template correction for each one.
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- Bias on samples without radiation does not considered.
- The radiative effects are coherent along the full production.

Radiative effects
- Radiation correction is taken in all generations according to formula in Figure 1 and Simulation procedure for the radiative corrections which is in figure 2.
- The cross section at jet parent needs to be corrected.
- The cross section at jet parent needs to be corrected.
- The correction is applied for each event.
- The correction is applied for each event.

Photon flux
- Not all events have gone through the same electron.
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- The proton has a mass of 804.6 MeV/c^2.
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- The number of events is the number of photons in the beam and is found.
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Detection efficiency
- The detection efficiency is shown in the upper right corner of the graph.
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Radiative correction
- The radiative correction is performed along the full production.
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Selection cut systematics
- The systematic uncertainties on the selection are shown in different cuts.
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Bin volume correction
- The bin volume correction is shown in different bins.
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Deuteron target and muon final state
- The deuteron target is shown in different cuts.
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- The deuteron target is shown in different cuts.
- The deuteron target is shown in different cuts.

Tagged J/ψ quasi-photoproduction with CLAS12
- The tagged J/ψ quasi-photoproduction with CLAS12 is shown.
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Data and MC samples

- Analysis on Pass 2 data. All main Fall 18 (Inbending and outbending) and Spring 19 runs are processed.
- Simulations are processed through OSG with pass 2 configuration
- The QADB tool is used to clean-up data and retrieve the accumulated charge per DST files
- The RCDB interface of clas12root is used to retrieve the beam current for each run
- Accumulated charge is computed per beam current for each configuration

### Config / Beam currents / Charge

<table>
<thead>
<tr>
<th>Generator</th>
<th>Fall 18 In.</th>
<th>Fall 18 Out.</th>
<th>Sp. 19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grape</td>
<td>45 nA 26.312 mC</td>
<td>50 nA 4.000 mC</td>
<td>8.2M each</td>
</tr>
<tr>
<td></td>
<td></td>
<td>55 nA 5.355 mC</td>
<td>40 nA 11.831 mC</td>
</tr>
<tr>
<td>TCSGen</td>
<td></td>
<td>2M each</td>
<td>1.5 M</td>
</tr>
<tr>
<td>JPsiGen</td>
<td></td>
<td>2M each</td>
<td></td>
</tr>
<tr>
<td>JPsiGen (No rad.)</td>
<td></td>
<td>3M each</td>
<td></td>
</tr>
</tbody>
</table>

Total of 24 MC samples and 3 Data samples
Radiative effects

- Inclusion of radiative effect is done in all generators according to formulas in: *Matthias Heller et al. Soft-photon corrections to the bethe-heitler process in the $\gamma p \rightarrow l^+l^- p$ reaction. PRD*
- The JpsiGen, TCSGen generator with radiative effect are on Github, as well as an event converter for Grape
  …not yet on OSG
- A full note on the algorithm is ready and will be included in the analysis note.
- The work was presented at the CLAS collaboration meeting in July 23.
1) Real and virtual flux are provided event by event by the \textbf{JPsiGen Generator}.

2) The integral over the range of energy of the bin $j$ is done using the integral/mean theorem:

$$\mathcal{F}_{c/j} = \int_j \mathcal{F}_c dE = \Delta E \sum_{i=1}^{N} \frac{\mathcal{F}_c(E_{GEN/i}) \cdot \omega_i}{\sum_{i=1}^{N} \omega_i}$$

3) Each flux (one per configuration) is multiplied by the corresponding accumulated charge:

$$\mathcal{F}_j = \sum_c C_c \cdot \mathcal{F}_{c/j}$$

Total number of photon in the bin $j$ in unit of e

4) The results is multiplied by the luminosity factor to recover the correct normalizing factor:

$$\mathcal{L} = \frac{l \cdot \rho \cdot N_A \cdot C}{e}$$

\textbf{Plots from Richard Tyson}
Detection efficiency

1) From the data fit a second order polynomial background function is extracted.
2) Events are generated according to this background function and added to the Jpsi signal MC sample.
3) The obtained distribution is fitted with the same function as the data.
4) The acceptance correction is then:

$$\epsilon_j = \left. \frac{N_{J/\psi}}{N_{J/\psi}} \right|_{j/REC} \left/ \left. \frac{N_{J/\psi}}{N_{J/\psi}} \right|_{j/RAD} \right.$$ 

Acceptance is of the order of 5-10%
1) Jpsi samples without radiative effects are produced

2) The radiative correction is defined using the GEN kinematics as:

\[ \epsilon_{Rad/j} = \frac{N_{J/\psi}}{N_{J/\psi}} \bigg| \frac{j/\text{RAD}}{j/\text{GEN}} \]
Selection cut systematics

- Every step of the analysis, except normalization factor, is repeated with different cuts:
  - $Q^2$ **DONE**
  - $|\text{MM}|^2$ **DONE**
  - Fit function **DONE**
  - Lepton momenta cut **To be done**
  - Lepton ID cut **To be done**
  - Proton PID **To be done**

→ Implementation of ad-hoc smearing to reproduce resolution in MC and reduce this systematic

→ Variation of the signal function to be added
Radiative correction effect

- The standard CS is extracted using the Radiated Jpsi MC samples and radiative correction
- The alternate is using non-radiated MC samples
- The effect is of the order of 10% (GlueX quoted 8.5%)

+ Closure test (Implemented but not presented here)
Bin volume correction

\[ \frac{d\sigma}{dt} \mid j = \frac{N_j / \psi / j}{F_j \cdot L \cdot \omega_c / j \cdot B_r \cdot \epsilon_j \cdot \epsilon_{Rad} / j \cdot V_j \cdot \Delta t_j} \]

\( V = \text{Ratio Area within boundary / Area rectangle} \)

- In practice is this readily done using integral of functions in root

\[ f_{\text{Bin limit T min function}} \]

\( E_\gamma \in [9.28, 10.36] \text{GeV} \)
\( -t \in [4, 6] \text{GeV}^2 \)
Integrated $t$-dependent cross-section

- The integral of the $t$-dependent cross section is done bin-by-bin:
- And compared to the total CS

$$\sigma = \sum_j \left. \frac{d\sigma}{dt} \right|_j \cdot \Delta t_j$$

- Good agreement between integrated $t$-dependent CS and $E_\gamma$-dependent CS
Deuterium target and muon final state

- Deuterium data were taken by CLAS12 in 2019/2020.
- Opportunity to measure $J/\psi$ production on (bound) neutron and (bound) proton.
- Alongside this analysis, a framework to explore the muon decay channel was developed.
- This effort is lead by R. Tyson from University of Glasgow.
Tagged $J/\psi$ quasi-photoproduction with CLAS12

\[ ep \rightarrow e' J/\psi \ p' \rightarrow e' l^+ l^- (X) \]

- Analysis conducted by M. Tenorio Pita, ODU.
- In this case, one electron in the Forward Tagger (Low lab angle < 5°) and a lepton pair in CLAS12.
- Excellent cross-check of the quasi-photoproduction approach.
- Early results show low statistics, the new data “cooking” including better tracking efficiency will be beneficial for this analysis.
- Other event topologies will be explored.

Other potential $J/\psi$ analysis using CLAS12 data
- Available data for longitudinally polarized proton target