Near-threshold exclusive $J/\psi$ photoproduction with GlueX

$\gamma p \rightarrow J/\psi p$

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(GLueX Collaboration)

- Why study threshold $J/\psi$ production?
- New results from Jefferson Lab - total and differential cross section in the full near threshold kinematic region - based on full GlueX Phase-I dataset
  - Total cross section (from threshold $E_\gamma=8.2-11.44$ GeV)
  - Differential cross sections: three $E_\gamma$ slices, each $t_{\min}(E_\gamma) - t_{\max}(E_\gamma)$
- Interpretation of the results
  - Phenomenology - forward cross section at threshold ($t \rightarrow 0$, $E_\gamma \rightarrow E_{thr.}$)
  - Gluon exchange: VMD, GPD factorization models
  - Open-charm exchange
  - Discussion: relevance to the mass properties of the proton
- Outlook
Threshold $J/\psi$ photoproduction ↔ mass properties of proton?

- VMD reduces $\gamma p \to J/\psi p$ to $J/\psi p \to J/\psi p$
- If $m_c \to \infty$ interaction via gluon exchange, at threshold sensitive to trace anomaly - quantum fluctuations (Kharzeev, Satz, Syamtomov, Zinovjev 1996-1999) contributing to proton mass (Ji 1995)
- GPD factorization valid for $m_c \to \infty$ at threshold (Gun, Ji, Liu 2021)
- At threshold large difference in gluon rapidity (skewness $\xi$), 2g dominated by $2^{++}$ exchange (graviton) allows to study mass properties of the proton (Hatta, Ji et al. 2021)
- $t$-dependence of the amplitudes - gravitational form factors $\to$ mass radius of the proton (Hatta, Kharzeev, Ji et al. 2018-2021)

- At large $t$ pQCD approach - no direct relation to gravitational FF? (Sun, Tong, Yuan 2021,2022)
- Is the $J/\psi$ mass large enough for the above assumptions to be valid? New results from Jefferson Lab - Hall C (J/psi-007) and GlueX - what the data say about this?
• Photon beam from coherent Bremsstrahlung off thin diamond
• Photon energy tagged by scattered electron: 0.2% resolution
• Beam collimated at 75m, <35 µrad
• Intensity: \( \sim 2 \times 10^7 \) - \( 5 \times 10^7 \) \( \gamma \)/sec above \( J/\psi \) threshold (8.2 GeV) – total \( \sim 320 \) pb\(^{-1} \) in GlueX phase-I runs
Hermetic detector: $1 - 120^\circ$ polar and full azimuthal acceptance

- Tracking: $\sigma_p/p \sim 1 - 5\%$
- Calorimetry: $\sigma_E/E \sim 6\%/\sqrt{E} + 2\%$

GlueX detector

2T-solenoid, LH target

Tracking (FDC,CDC), Calorimetry (BCAL,FCAL), Timing (TOF,SC)
Exclusive reaction $\gamma p \rightarrow J/\psi p \rightarrow e^+e^-p$

- GlueX detector has full acceptance for this reaction - direct measurement of the total cross section - no need to extrapolate to low/high $t$

- Electrons separated from pions by $E/p$ – energy deposition in the calorimeters over measured momentum (pions >$10^3$ times more than electrons)
e$^+e^-$ invariant mass spectrum

- Tagged photon beam (0.2% energy resolution) and exclusivity of the reaction:
- Kinematic fit (constrained mostly by the recoil proton): 13 MeV mass resolution; no radiative tail
- $J/\psi$ yields extracted from fits of $M(e^+e^-)$ distributions
- BH(1.2 – 2.5 GeV) used for normalization
Differential cross-sections

\[
\frac{d\sigma}{dt}(E,t) = \frac{N_{J\psi}}{L(E_\gamma)[nb^{-1}]/0.045 GeV \cdot \text{area}(E,t)[GeV \cdot GeV^2] \cdot \varepsilon(E,t)}
\]

- Event-by-event weighting by luminosity
- Dots - mean energy and t-value for the corresponding bin
- Results reported at mean energy for corresponding slice
- Deviations due to bin averaging included in the systematic errors
GlueX preliminary results compared to Hall C (J/psi-007):

- Three GlueX energies compared to closest Hall C energies (shown only 4 out of 10 energies in J/psi-007)
- Scale uncertainties: 20% in GlueX and 4% in Hall C results
- Good agreement within the errors; note also differences in average energies
Differential cross-sections - forward extrapolation

\[ \frac{d\sigma}{dt}(0) = 3.121 \pm 2.23 \]
\[ m_s = 1.089 \pm 0.1722 \]

\[ \chi^2 / \text{ndf} = 0.2182 / 3 \]

\[ \frac{d\sigma}{dt}(0) = 2.303 \pm 0.3997 \]
\[ m_s = 1.453 \pm 0.07444 \]

\[ \chi^2 / \text{ndf} = 3.712 / 7 \]

\[ \frac{d\sigma}{dt}(0) = 4.184 \pm 0.5407 \]
\[ m_s = 1.314 \pm 0.04871 \]

\[ \chi^2 / \text{ndf} = 9.777 / 9 \]

\[ \frac{d\sigma}{dt}(0) = 2.23 \pm 3.121 \]
\[ m_s = 0.1722 \pm 1.089 \]

\[ \chi^2 / \text{ndf} = 0.2182 / 3 \]

\[ \frac{d\sigma}{dt}(0) = 1.0 \pm 1.0 \]
\[ m_s = 0.04871 \pm 1.314 \]

<table>
<thead>
<tr>
<th>( E_\gamma, \text{GeV} )</th>
<th>8.93</th>
<th>9.86</th>
<th>10.82</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_{c.m.}, \text{GeV} ) (( J/\psi p ) c.m.)</td>
<td>0.499</td>
<td>0.767</td>
<td>0.978</td>
</tr>
<tr>
<td>( \frac{d\sigma}{dt}(0), \text{nb/GeV}^2 )</td>
<td>3.121 ± 2.23</td>
<td>2.303 ± 0.400</td>
<td>4.184 ± 0.541</td>
</tr>
<tr>
<td>( m_s, \text{GeV} )</td>
<td>1.089 ± 0.172</td>
<td>1.453 ± 0.074</td>
<td>1.314 ± 0.049</td>
</tr>
</tbody>
</table>
Forward differential cross-sections - threshold extrapolation

1/ Even-power polynomial fit

\[
\frac{d\sigma}{dt}(q,0) = \frac{\alpha \pi}{\gamma^2} \frac{1}{64\pi\skyp^2} \cdot |T^{\psi p}(q,0)|^2
\]

using VMD

\[
\frac{\skyp^2}{\skyp^2}_{\text{thr.}} [p_0 + p_2q^2 + p_4q^4]
\]

2/ Gryniuk, Vanderhaeghen PRD94 (2016)

dispersive relation:

\[
ReT^{\psi p}(\nu) = T(0) + \frac{2}{\pi} \nu^2 \int_{\nu_{\text{th.}}}^{\infty} \nu' \frac{ImT^{\psi p}(\nu')}{\nu'(\nu^2 - \nu'^2)} dv' + \frac{p_0}{p_1^2} [p_1 + DI(q)]^2 \frac{(skyp^2)_{\text{thr.}}}{skyp^2} \]

\(p_1\) - subtraction constant \(T(0)\)

\[\left. \frac{d\sigma}{dt}(0) \right|_{\text{thr.}} = 1.14 \pm 0.57 \quad 2.04 \pm 0.38 \text{ nb/GeV}^2\]

\(q_{\text{c.m.}} = 1.35 \text{ GeV}\)
Forward differential cross-sections - model dependent applications

1/ $J/\psi - p$ scattering length:
13.4 ± 3.8 $m_{fm}$, 17.9 ± 1.7 $m_{fm}$
very weak $J/\psi - p$ interaction

$$|\alpha_{J/\psi p}| = \sqrt{\frac{d\sigma}{dt}(0)}_{thr} \gamma_{\psi}^2 k_{\gamma p}^2 \frac{\alpha}{\pi} \frac{1}{\pi}$$

using VMD

2/ \begin{align*}
\text{proton mass radius, fm} \\
E_\gamma, \text{GeV} \\
& \text{GlueX 2018} \\
& \text{GlueX this work} \\
& \text{lattice calculations} \\
& \text{charge radius}
\end{align*}

$$r_m = \left. \frac{6}{m_p} \frac{dG}{dt} \right|_{t=0} = \frac{12}{m_s^2}$$

D.Kharzeev PRD104(2021)

3/ Other quantities - trace anomaly, scalar/mass radius of the proton ...
Preliminary results: total cross-section

- 20% scale uncertainty
- Statistical significance of the two “dip” points 2.6\sigma; if include look-elsewhere effect - 1.3\sigma

\[
s_{J/\psi}(E_{\gamma}) = \frac{N_{J/\psi}(E_{\gamma})}{N_{BH}(E_{\gamma})} \cdot \frac{\sigma_{BH}(E_{\gamma})}{\mathcal{B}_{J/\psi}} \cdot \frac{\varepsilon_{BH}(E_{\gamma})}{\varepsilon_{J/\psi}(E_{\gamma})}
\]
QCD factorization models

Total cross section

Comparison at $t = t_{\text{min}}$ → advantages:
- Data: SLAC measurements done at $t = t_{\text{min}}$ - using GlueX $d\sigma/dt(t = t_{\text{min}})$
- Theory: less dependence on lattice FF parameters, better factorization, connection to gravitational FF?

Ivanov, Sznajder, Szymanowski, Wagner (2022)
- GPD LO calculations
Guo, Ji, Liu PRD103 (2021), in $m_c \to \infty$ limit, $\xi \to 1$ extension:
  - factorization valid near threshold
  - connection to gravitational FFs: $A_g(t)$ and $C_g(t)$
Du, Baru, Guo, Hanhart, Meissner, Nefediev, Strakovsky EPJ C80 (2020)

FIG. 3. Feynman diagram for the proposed CC mechanism. The dashed blue line pinpoints the open-charm intermediate state.
# Open-charm or gluon exchange dominates?

## Experimental observations

<table>
<thead>
<tr>
<th></th>
<th>open-charm exchange</th>
<th>gluon exchange</th>
</tr>
</thead>
<tbody>
<tr>
<td>possible structures in total cross section</td>
<td>cusp-like structures at $\bar{D}^{(*)}\Lambda_{c}$ thresholds ✓</td>
<td>no structures ✗</td>
</tr>
<tr>
<td>$d\sigma/dt$ enhancement at high t</td>
<td>s,u -channel contribution? ✓</td>
<td>Not likely in t-channel ✗</td>
</tr>
<tr>
<td>sharp t-slope</td>
<td>expect shallow t-dependance due to high mass exchange ✗</td>
<td>consistent with gluon FFs as predicted on lattice ✓</td>
</tr>
<tr>
<td>$d\sigma/dt$ - weak energy dependence especially at high t (approx.)</td>
<td>?</td>
<td>expected from power counting rules ✓</td>
</tr>
<tr>
<td>helicity conservation ?</td>
<td>?</td>
<td>yes?</td>
</tr>
<tr>
<td>Naturality ?</td>
<td>unnatural $\bar{D}$ exchange ?</td>
<td>2g - natural parity exchange</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3g - unnatural (C-parity violation)</td>
</tr>
</tbody>
</table>

## Diagrams

- Double-exponent fits: $p_0 e^{t p_1} + p_2 e^{t p_3}$

### Graphs
- $\sigma(p\bar{p} \to J/\psi \gamma)$, nb
- $d\sigma/dt$, nb/GeV$^2$
Conclusions

• Threshold $J/\psi$ production and mass properties of the proton? - new GlueX data poses more questions than answers:
• Proximity of the reported total/differential cross sections to threshold in the full kinematic space allows (more reliable) extrapolation to $t = 0$ and $E_{thr.}$ and gives access to very important physics - mass properties of the proton - however
  … assuming VMD, QCD factorization
  … assuming relation of the measured cross sections and the gluon FFs
  … assuming gluon exchange over open-charm exchange mechanism:
• Total cross section - in agreement with open-charm exchange, while QCD predictions underestimate the data
• Differential cross section - generally consistent with gluon exchange and predicted by lattice QCD
• More precise measurements near threshold (including polarization quantities) are needed to better understand the reaction mechanism - expect x4 more data from Phase-II
• Important input from theorists is expected
Back-ups
Charmonium studies in Hall D with the CEBAF energy upgrade

Substantial increase of the flux in the coherent peak allows precise cross section measurements covering the whole region down to threshold

$$E_{el} = 17 \text{ GeV}$$

Significant increase of the linear polarization allows to do important polarization measurements in the threshold region

$$E_{el} = 17 \text{ GeV}$$

![Graphs and plots showing luminosity and cross sections for $\gamma p \rightarrow J/\psi p$](image)
Total cross section asymptotic - power counting

\[ \frac{d\sigma_{np}}{dt} = N_n (1-x)^{2n_s} \cdot F_{n_s}^2(t), \quad n_s \text{ is number of spectators in proton;} \]

\[ n_s = 0 \text{ associated with 3g exchange} \]

Brodsky et al. PLB498 (2001)

Sun, Tong, Yuan PRD 105.054032 (2021):

3g exchange is violating C-parity, all 2g and \( n_s = 0 \)

<table>
<thead>
<tr>
<th>Twist-4</th>
<th>Twist-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>no energy dependance</td>
<td>vanishes at threshold</td>
</tr>
<tr>
<td>( 1/t^5 )</td>
<td>( 1/t^4 )</td>
</tr>
<tr>
<td>proton spin flip</td>
<td>no spin flip</td>
</tr>
<tr>
<td>( \sim E_g(t, x, \xi) )</td>
<td>( \sim H_g(t, x, \xi) )</td>
</tr>
</tbody>
</table>
$e/\pi$ separation

- Pion contamination $\sim$50% in the continuum (using p/E fits to estimate it)
BH e.m. calculations vs data

BH(1.2-2.5 GeV) calculations

BH(1.2-2.5 GeV) data/MC ratio

BH yields extracted from fits of E/p distributions
\( \gamma p \rightarrow (p\bar{p})p \) with \( M(p\bar{p}) \sim M_{J/\psi} \)
QCD: high-\( t \) asymptotic

Sun, Tong, Yuan PRD105 (2022)

Asymptotic \( t \)-dependance \( 1/t^5 \) (vs \( 1/t^4 \)) due to helicity flip

Not enough statistics to test the \( t \)-asymptotic

However we can check \( J/\psi \) helicity conservation/flip, naturality?