Dynamical Model of J/ψ photoproduction on nucleon

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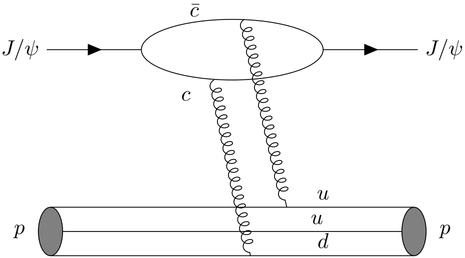
backgrounds

- To understand hadron-hadron interaction, phenomenological charm quark-nucleon (c-N) potential v_{cN} is needed to construct



- Several attempts had been made to determine $J/\psi - N$ interactions, such as Lattice QCD (LQCD) calculation using the approach of Kawanai and Sasaki obtained $J/\psi - N$ potential

Introduction

- To extract the J/ψ-N scattering amplitudes from the data of $\gamma + N \to J/\psi + N$ reactions, specifically from the experiments at Jefferson Laboratory
- The Final State Interaction effects has sensitivity testing of the predicted J/ψ-N scattering amplitudes.
- The dynamical model construct by following amplitudes

$$T^{\mathrm{D}}_{\gamma N,J/\psi N} = B_{\gamma N,J/\psi N} + T^{(\mathrm{fsi})}_{\gamma N,J/\psi N},$$

- $B_{\gamma N,J/\psi N}$ is the $\gamma + N \to J/\psi + N$ transition amplitude and $V_{J/\psi N}$ is the $J/\psi + N \to J/\psi + N$ potential, are defined by $c\bar{c}$-loop mechanisms
- By using the determined c-N potential $v_{cN}(r)$ and the wavefunctions generated from the same CQM we can predict the $\eta_c(1S)$ and $\psi(2S)$ photoproduction

Dynamical model

The Dynamical model of J/ψ photoproduction is using the following Hamiltonian

$$H = H_0 + \Gamma_{\gamma,c\bar{c}} + v_{c\bar{c}} + v_{cN},$$

by solving the bound state equation

$$(H_0 + v_{c\bar{c}})\,|\phi_V\rangle = E_V\,|\phi_V\rangle\,.$$

We assume a simple s-wave wavefunction defined in momentum-space as

$$\phi^{J_V m_V}_{V,\mathbf{p}_V}(\mathbf{k} m_{s_c}, \mathbf{k}' m'_{s_c}) \;=\; \langle J_V m_V | \frac{1}{2}\frac{1}{2} m_{s_c} m'_{s_{\bar{c}}}\rangle\, \phi(\mathbf{k}) \times \delta(\mathbf{p}_V - \mathbf{k} - \mathbf{k}')\,,$$

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[1] The wavefunction $\phi(\mathbf{k})$ is constructed by the Constituent Quark Model provided by J. Segovia, et. al [Int. J. Mod. Phys. E **22**, 1330026 (2013)]

Dynamical model

By the following Lippmann-Schwinger equation,

$$T(W) = H' + T(W)\frac{1}{W - H_0 + i\epsilon}H'.$$

the $J/\psi - N$ potential can be constructed by

$$V_{VN,VN}(W) = \langle \phi_V, N| \sum_c v_{cN} |\phi_V, N\rangle \, .$$

end the J/ψ photo-production process with the following form

$$B_{VN,\gamma N}(W) \quad = \quad \langle \phi_V, N| \left[\sum_c v_{cN} \frac{|c\bar{c}\rangle \langle c\bar{c}|}{E_{c\bar{c}} - H_0} \Gamma_{\gamma, c\bar{c}} \right] |\gamma, N\rangle \, ,$$

The loop-Integrations

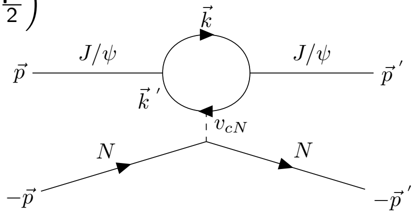
The V_{VN} potential explicitly write as

$$\langle \mathbf{p} | V_{VN} | \mathbf{p}' \rangle = 2 \int d\mathbf{k}\, \phi^* \left(\mathbf{k} - \tfrac{\mathbf{p}}{2}\right) \langle q \,|\, v_{cN} \,|\, q' \rangle\, \phi \left(\mathbf{k} - \tfrac{\mathbf{p}'}{2}\right)$$

where **q** is the relative momenta of quark or Nucleon are defined by

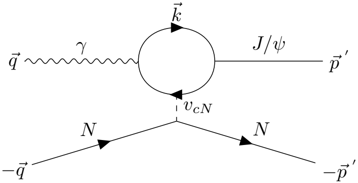
$$q = \frac{m_N \mathbf{k} - m_c \mathbf{p}}{m_N + m_c}$$

$$q' = \frac{m_N \mathbf{k}' - m_c \mathbf{p}'}{m_N + m_c}$$



The loop-Integrations

The $B_{VN,\gamma N}$ transition amplitude explicitly write as



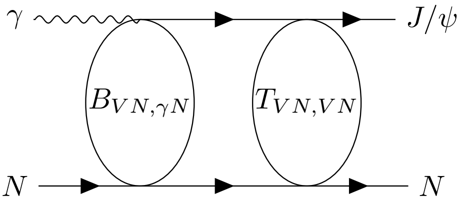
$$\left\langle \mathbf{p}' m_V m_s' \,\middle|\, B_{VN,\gamma N}(W) \,\middle|\, \mathbf{q}\lambda m_s \right\rangle = \sum_{m_c, m_{\bar{c}}} \frac{1}{(2\pi)^3} \frac{e_c}{\sqrt{2|\mathbf{q}|}} \int d\mathbf{k} \left\langle J_V m_V \middle| \tfrac{1}{2}\tfrac{1}{2} m_c m_{\bar{c}} \right\rangle \phi\left(\mathbf{k} - \tfrac{1}{2}\mathbf{p}'\right)$$

$$\times\, \delta_{m_s, m_s'} \left\langle \mathbf{p}'_{\mathbf{rel}} \,\middle|\, v_{cN} \,\middle|\, \mathbf{p}_{\mathbf{rel}} \right\rangle \frac{1}{W - E_N(\mathbf{q}) - E_c(\mathbf{q}-\mathbf{k}) - E_c(\mathbf{k}) + i\epsilon}$$

$$\times\, \bar{u}_{m_c}(\mathbf{k})[\epsilon_\lambda \cdot \gamma] u_{m_{\bar{c}}}(\mathbf{q}-\mathbf{k}).$$

Final State Interaction

The illustration of J/ψ photoproduction Final State Interaction



The $T^{(\mathrm{fsi})}_{VN,\gamma N}$ potential explicitly write as

$$\left\langle \mathbf{p}' m_V m_s' \,\middle|\, T^{(\mathrm{fsi})}_{VN,\gamma N}(W) \,\middle|\, \mathbf{q}\lambda m_s \right\rangle = \sum_{m_V'', m_s''} \int d\mathbf{p}'' \left\langle \mathbf{p}\, m_V m_s' \,\middle|\, T_{VN,VN}(W) \,\middle|\, \mathbf{p}'' m_V'', m_s'' \right\rangle$$

$$\times \frac{1}{W - E_N(p'') - E_V(p'') + i\epsilon} \left\langle \mathbf{p}'' m_V'' m_s'' \,\middle|\, B_{VN,\gamma N}(W) \,\middle|\, \mathbf{q}\lambda, m_s \right\rangle .$$

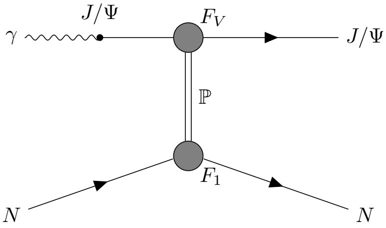
Final State Interaction

The total amplitude of Dynamical model is written as

$$\left\langle \mathbf{p}' m_V m'_s \,\middle|\, T^{D}_{VN,\gamma N}(W) \,\middle|\, \mathbf{q}\lambda m_s \right\rangle = \langle \mathbf{p}' m_V m'_s \,|\, B_{VN,\gamma N}(W) \,|\, \mathbf{q}\lambda m_s \rangle + \langle \mathbf{p}' m_V m'_s | T^{(\mathrm{fsi})}_{VN,\gamma N} | \mathbf{q}(W)\lambda m_s \rangle ,$$

Pomeron-Exchange Model

Following the approach of Donnachie and Landshoff, the Pomeron-exchange amplitude is constructed within Regge Phenomenology and is of the following



$$
\begin{aligned}
&\langle \mathbf{k}, m_V m'_s | T^{\rm Pom}_{VN,\gamma N}(W) | \mathbf{q}, \lambda_\gamma m_s \rangle \\
&= \frac{1}{(2\pi)^3} \sqrt{\frac{m_N m_N}{4E_V(\mathbf{k})E_N(\mathbf{p}')|\mathbf{q}|E_N(\mathbf{p})}} \\
&\times [\bar{u}(p', m'_s)\epsilon^*_\mu(k, \lambda_V)\mathcal{M}^{\mu\nu}_{\mathbb{P}}(k, p', q, p)\epsilon_\nu(q, \lambda_\gamma)u(p, m_s)].
\end{aligned}
$$

Pomeron-Exchange Model

The amplitude $\mathcal{M}^{\mu\nu}_{\mathbb{P}}(k, p', q, p)$ is given by

$$\mathcal{M}^{\mu\nu}_{\mathbb{P}}(k, p', q, p) = G_{\mathbb{P}}(s, t)\mathcal{T}^{\mu\nu}_{\mathbb{P}}(k, p', q, p), \tag{1}$$

and

$$\begin{aligned} \mathcal{T}^{\mu\nu}_{\mathbb{P}}(k, p', q, p) &= i\,2\frac{e\,m_V^2}{f_V}[2\beta_{q_V}F_V(t)][3\beta_{u/d}F_1(t)] \\ &\quad \{\not{q}g^{\mu\nu} - q^\mu\gamma^\nu\}\,, \end{aligned}$$

where m_V is the mass of the vector meson, and $f_V = 5.3,\ 15.2,\ 13.4,\ 11.2,\ 40.53$ for $V = \rho, \omega, \phi, J/\psi, \Upsilon$

Pomeron-Exchange Model

a form factor for the Pomeron-vector meson vertex is also introduced with

$$F_V(t) = \frac{1}{m_V^2 - t}\left(\frac{2\mu_0^2}{2\mu_0^2 + m_V^2 - t}\right),$$

where $t = (q-k)^2 = (p_f - p_i)^2$. By using the Pomeron-photon analogy, the form factor for the Pomeron-nucleon vertex is defined by the isoscalar electromagnetic form factor of the nucleon as

$$F_1(t) = \frac{4m_N^2 - 2.8t}{(4m_N^2 - t)(1 - t/0.71)^2}. \quad (2)$$

Here t is in the unit of GeV^2, and m_N is the proton mass

Pomeron-Exchange Model

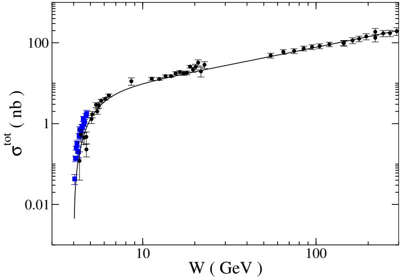
The propagator $G_{\mathbb{P}}$ of the Pomeron in Eq. (1) follows the Regge phenomenology form:

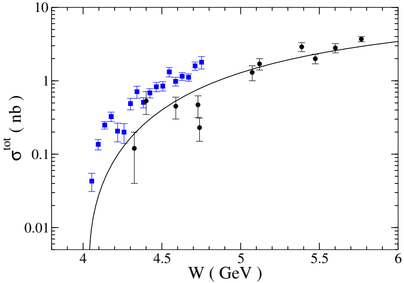
$$G_{\mathbb{P}} = \left(\frac{s}{s_0}\right)^{\alpha_P(t)-1} \exp\left\{-\frac{i\pi}{2}\left[\alpha_P(t)-1\right]\right\},$$

where $s = (q+p_i)^2 = W^2$, $\alpha_P(t) = \alpha_0 + \alpha'_P t$, and $s_0 = 1/\alpha'_P$. We use the value of $s_0 = 0.25$ GeV from Donnachie and Landshoff

Pomeron-Exchange Model

Total cross sections from Pomeron-exchange amplitude $\gamma + N \to J/\psi + N$ compared with experimental data by JLab, Zeus, act





Determination of quark-Nucleon potential v_{cN}

We consider the following parameterization using the Yukawa form to determine the quark-nucleon potential

$$v_{cN}(r) = \alpha \left(\frac{e^{-\mu r}}{r} - c_s \frac{e^{-\mu_1 r}}{r} \right).$$

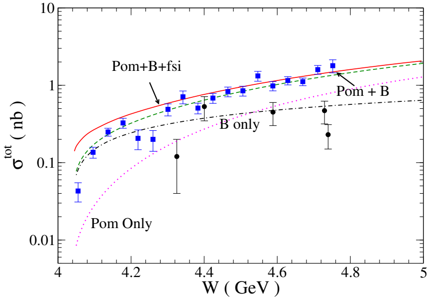


Figure. 1: Total cross sections for $4 \leq W \leq 5$ GeV from the 1Y model ($C_s = 0$) at $\alpha = -0.067$ and $\mu = 0.3$

2Y and 1Y comparision

$\gamma + N \rightarrow J/\psi + N$ total cross section

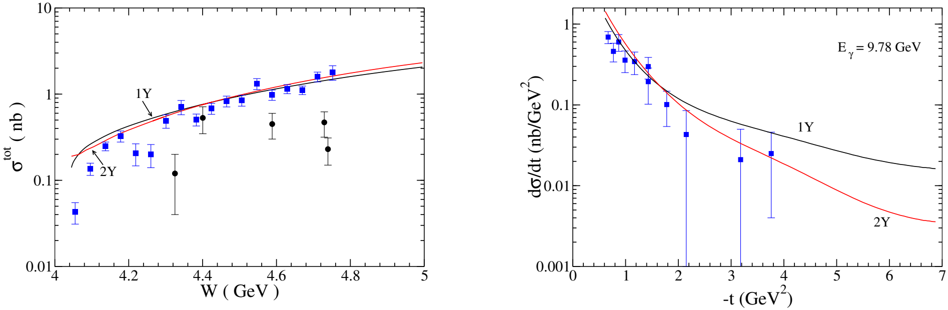
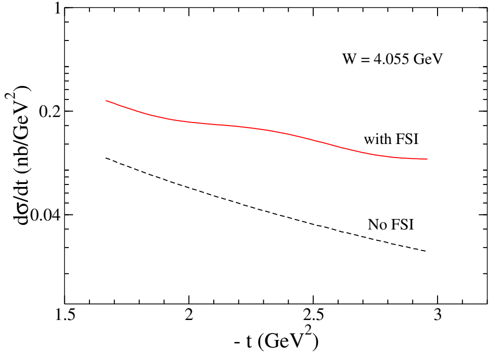


Figure. 2: Total cross sections of the 1Y model ($C_s = 0$) at $\alpha = -0.067$ and $\mu = 0.3$ and the 2Y model ($C_s = 1$) for $\alpha = -0.145$ and $N = 5$

$\gamma + N \to J/\psi + N$ differential cross-sections very near threshold, $W = 4.055$GeV



2Y and 1Y comparision

$\gamma + N \to J/\psi + N$ Differential cross sections

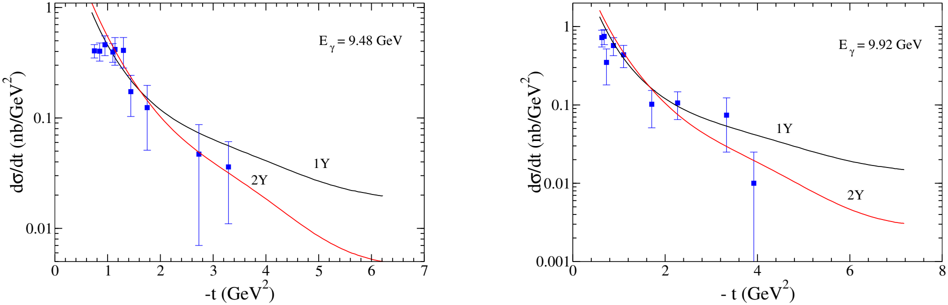


Figure. 3: Differential cross sections from the 1Y model and 2Y model

LQCD constrains

We next consider the models constructed by imposing LQCD constraints on the calculations of the FSI

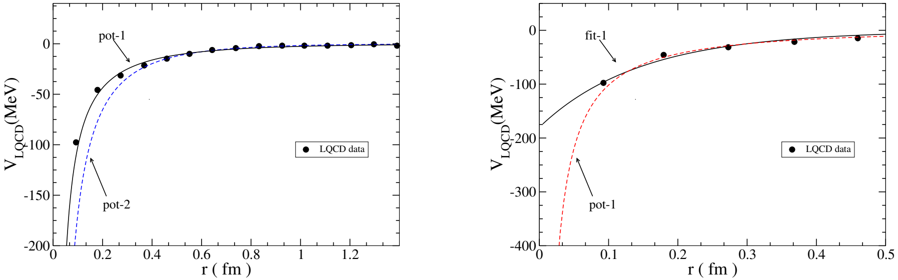
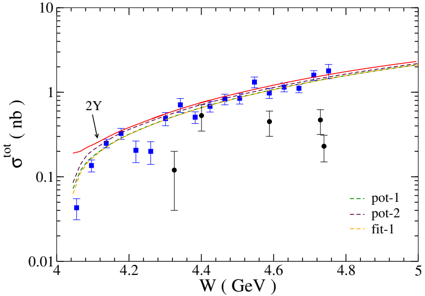
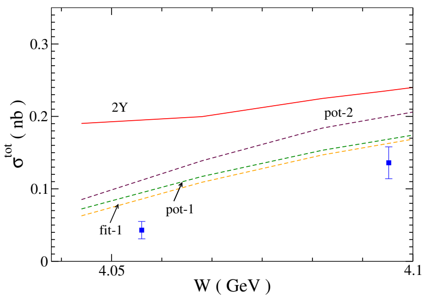


Figure. 4: $J/\psi - N$ potential extracted by the LQCD calculation using the 1Y form with two different sets of parameters as pot-1 and pot-2, and using the 2Y form as fit-1

LQCD constrains

The same B parameter as 2Y model and parameter sets of FSI calculation, (α_L, μ_L), namely $(\alpha_L, \mu_L) = (-0.06, 0.3)$ and $(-0.11, 0.5)$, which we denote as "pot-1" and "pot-2, respectively. the fit-1 is another form of FSI using the 2Y model with parameter $(\alpha_L, \mu_L, N) = (-0.2, 0.9, 2)$

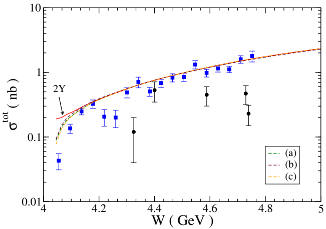


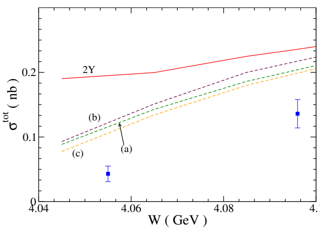


LQCD constrains

Table. 1: The parameters for the models (a), (b), (c) imposing LQCD constraints on FSI.

Model	$\alpha_{\rm FSI}$	μ (GeV)	μ_1 (GeV)	a(fm)	α_B
(a)	-0.03	0.3	–	-0.15	-0.162
(b)	-0.055	0.5	–	-0.233	-0.152
(c)	-0.1	0.9	1.8	-0.057	-0.163





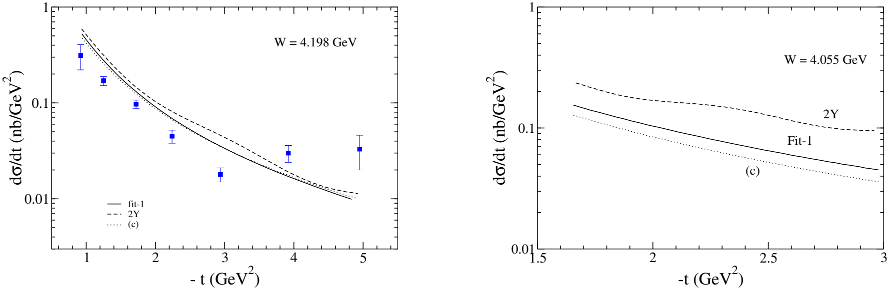
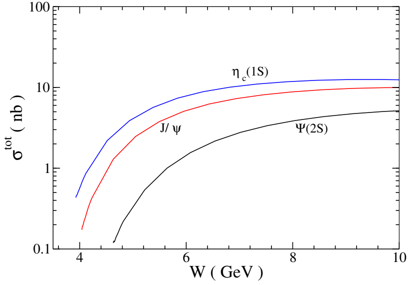


Figure. 5: The Differential cross section of the 2Y model, fit-1 and (c) model at $W = 4.198$GeV and the prediction of differential cross section very near threshold

Photo-production of $\eta_c(1S)$ and $\psi(2S)$

Total cross section comparison of J/ψ, $\eta_c(1S)$ and $\psi(2S)$ photoproduction



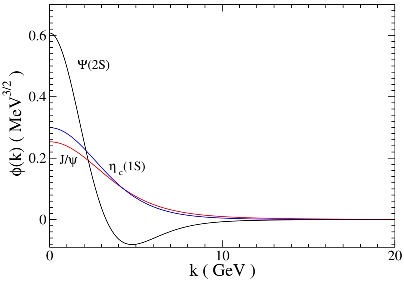
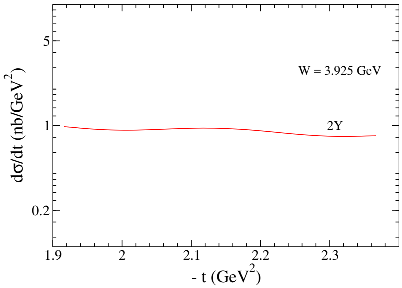


Photo-production of $\eta_c(1S)$ and $\psi(2S)$

Differential cross section of $\eta_c(1S)$ at near threshold and large energy



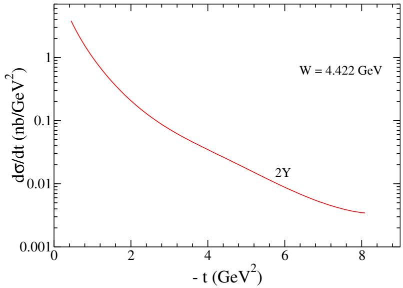
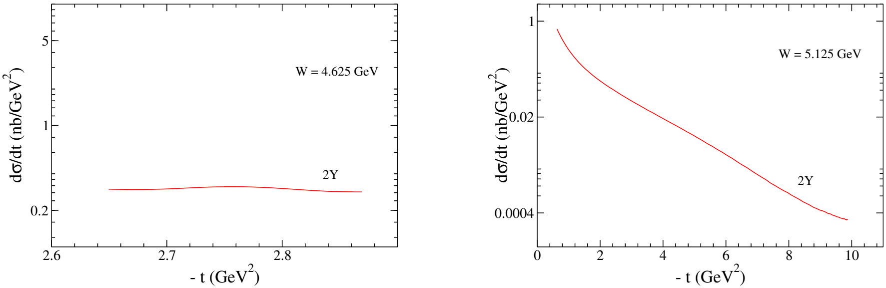


Photo-production of $\eta_c(1S)$ and $\psi(2S)$

Differential cross section of $\psi(2S)$ at near threshold and large energy



Summary and Conclusion

- a dynamical model based on the Constituent Quark Model (CQM) and a phenomenological charm quark-nucleon potential $v_{cN}(r)$ is constructed to investigate the J/ψ photo-production on the nucleon at energies near threshold.
- The parameters of v_{cN} are determined by fitting the total cross section data by performing calculations that include J/ψ-N final state interactions
- the FSI effects dominate the cross section in the very near-threshold region
- By imposing the constraints of J/ψ-N potential extracted from the LQCD calculation of Sasaki et all, we have three J/ψ-N potentials which fit the JLab data well
- The constructed dynamical model has been used to predict the cross sections of photo-production of $\eta_c(1S)$ and $\psi(2S)$ mesons. It will be interesting to have data from experiments at JLab and EIC to test our predictions

Thanks!