Exclusive charmonium production and gluonic structure

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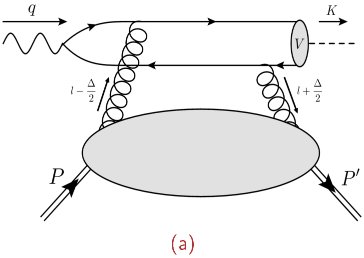
Near threshold J/ψ production based on gluonic GPDs



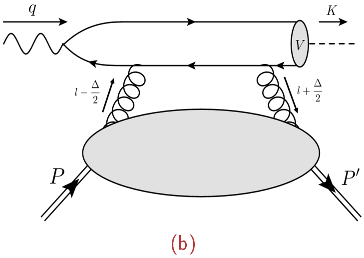


Figure: Photoproduction of J/ψ probing gluon GPDs.

- the differential cross section for J/ψ photoproduction in terms of gluon GPDs is given by [Guo, Ji, and Liu, 2021]

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

Near threshold J/ψ production based on gluonic GPDs

- where the function $G(t,\xi)$ is written in terms of gluon GPDs $F_g(x,\xi,t)$ as

$$G(t,\xi) = \frac{1}{2\xi}\int_{-1}^{1} \mathrm{d}x \mathcal{A}(x,\xi) F_g(x,\xi,t)$$

where the hard kernel $\mathcal{A}(x,\xi)$ reads

$$\mathcal{A}(x,\xi) \equiv \frac{1}{x+\xi-i0} - \frac{1}{x-\xi+i0}$$

Near threshold J/ψ production based on gluonic GPDs

- after summing/averaging over the final and initial proton spin

$$|G(t,\xi)|^2 = \frac{1}{\xi^4}\left\{\left(1-\frac{t}{4M_N^2}\right)E^2 - 2E(H+E) + \left(1-\xi^2\right)(H+E)^2\right\}$$

where we have defined

$$\int_0^1 dx H_g(x,\xi,t) = A(t) + \xi^2 D(t) \equiv H\ ,$$
$$\int_0^1 dx E_g(x,\xi,t) = B(t) - \xi^2 D(t) \equiv E$$

Holographic photoproduction of vector mesons

- Witten diagram showing the couplings of the graviton with bulk Dirac fermions and vector mesons [K.M., and Zahed, 2019]

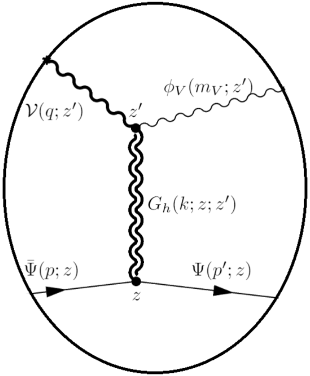


Figure: Witten diagram.

Holographic photoproduction of vector mesons

- the main elements of the Witten diagram are composed of:

1/ the bulk-to-boundary propagator of the vector mesons (or virtual photons for space-like momenta $q^2 = -Q^2$) as

$$V(q,z) = \mathcal{V}(q = iQ, z) = g_5 \sum_n \frac{F_n \phi_n(z)}{Q^2 + m_n^2},$$

where $\phi_n(m_n, z)$, m_n, $f_n \equiv -F_n/m_n$, and $g_5 \sim \frac{1}{\sqrt{N_c}}$ are the bulk wave function, mass, decay constant, and hadronic coupling constant of each meson resonances, respectively

2/ the bulk-to-boundary propagator of the spin-2 glueballs (for space-like momenta $k^2 = -K^2$)

$$h(k,z) = \mathcal{H}(K,z) = \sqrt{2}\kappa \sum_n \frac{F_n \psi_n(z)}{K^2 + m_n^2} ,$$

where $\psi_n(m_n, z)$, m_n, $f_n \equiv -F_n/m_n$, and $\kappa \sim \frac{1}{N_c}$ are the bulk wave function, mass, decay constant, and hadronic coupling constant of each glueball resonances

3/ the bulk-to-bulk propagators of the vector meson and glueball resonances

$$G_V(q', z, z') = \sum_n \frac{\phi_n(z)\phi_n(z')}{q'^2 - m_n^2},$$

and

$$G_h(k, z, z') = \sum_n \frac{\psi_n(z)\psi_n(z')}{k^2 - m_n^2}$$

Holographic photoproduction of vector mesons

- the normalized bulk wave function of one of the vector meson resonances $\phi_{n=0} \equiv \phi_V$ takes the form

$$\phi_V = c_V z J(M_V z) = \frac{f_V}{M_V} \times M_V z J(M_V z)$$

where $J(M_V z)$ is a special function that depends on the details of the holographic model
- the decay constant f_V, for a meson at rest, defined as

$$< 0|J_{V,i}|V_j >= f_V M_V \delta_{ij}$$

is calculable in a given holographic model to QCD, and can be extracted experimentally from the leptonic width as

$$\Gamma(V \to \ell^+ \ell^-) = \frac{4\pi}{3} \alpha_{QED}^2 e_V^2 \frac{f_V^2}{M_V}$$

where e_V is the electric charge of the constituent quarks of the vector meson, and for $V = (J/\psi, \Upsilon)$: $e_V = (2/3, 1/3)$, $M_V = (3.097, 9.460)$ GeV and $e_V f_V = (270, 238)$ MeV

Kinematics of the $\gamma^* p \to Vp$ Process

- the differential cross section for the photoproduction process $\gamma^* p \to Vp$ is given by

$$\frac{d\sigma}{dt} = \frac{e^2}{64\pi s |\mathrm{q}_\gamma|^2} |\mathcal{A}_{\gamma * p \to Vp}(s, t)|^2 \,,$$

where

$$|\mathrm{q}_\gamma| = \frac{1}{2\sqrt{s}} \sqrt{s^2 - 2(-Q^2 + m_N^2)s + (-Q^2 - m_N^2)^2} \,,$$

with $s = W^2 = (p_1 + q_1)^2$, and $t = (p_1 - p_2)^2 = (q_1 - q_2)^2$ where $q_{1,2}$ are the four-vectors of the virtual photon and vector meson, respectively

J/ψ photoproduction near threshold: a probe to gluonic gravitational form factors of proton

- for heavy vector meson photoproduction the bulk-to-bulk propagators of glueball resonances factorizes as

$$G_h(k,z,z') = \sum_n \frac{\psi_n(z'\to 0)\psi_n(z)}{k^2 - m_n^2} = \frac{\psi_n(z'\to 0)}{\sqrt{2}\kappa F_n} \times \sum_n \frac{\sqrt{2}\kappa F_n \psi_n(z)}{k^2 - m_n^2}$$

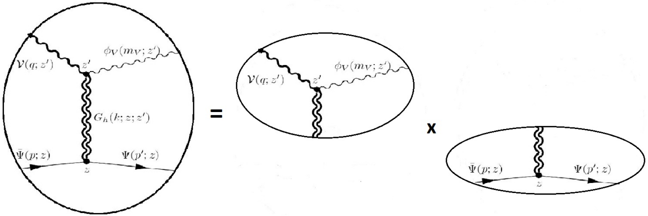


Figure: Factorization of Witten diagram.

The differential cross section for photoproduction of J/ψ near threshold

- after summing over the photon, J/ψ, and proton polarizations and spin, the differential cross section for photoproduction of J/ψ near threshold is [K.M., Zahed, 2019-2022]

$$\left(\frac{d\sigma}{dt}\right) = \mathcal{N}^2 \times \left[A(t) + \xi^2 D(t)\right]^2 \times \frac{1}{A^2(0)} \times \frac{1}{128\pi(s - m_N^2)^2} \times F(s, t, M_V, m_N) \times \left(1 - \frac{t}{4m_N^2}\right)$$

- the normalization factor $\mathcal{N}$ is defined as

$$\mathcal{N}^2 \equiv e^2 \times \left(\frac{f_V}{M_V}\right)^2 \times \mathbb{V}_{hAA}^2 \times 2\kappa^2 \times A^2(0) = 7.768\,\mathrm{GeV}^{-4}$$

- we also have $F(s,t) \sim s^4 \sim 1/\xi^4$ with $\frac{d\sigma}{dt} \sim s^2 \times (A(K) + D(K)/s^2)$

Pentaquarks at LHCb

- The masses and total widths of the three charm pentaquark states recently reported by LHCb [Aaij:2019] are

$$
\begin{aligned}
m_{P_c} &= 4311.9 \pm 0.7\,\mathrm{MeV} \qquad \Gamma_{P_c} = 9.8 \pm 2.7\,\mathrm{MeV} \\
m_{P_c} &= 4440.3 \pm 1.3\,\mathrm{MeV} \qquad \Gamma_{P_c} = 20.6 \pm 4.9\,\mathrm{MeV} \\
m_{P_c} &= 4457.3 \pm 0.6\,\mathrm{MeV} \qquad \Gamma_{P_c} = 6.4 \pm 2.0\,\mathrm{MeV}
\end{aligned}
$$

- the bulk interaction vertex between the Dirac fermion ψ and the pentaquark field Ψ is [Liu, K.M., Nowak, and, Zahed, 2021]

$$
\eta_X \int dz d^4x \sqrt{|g(z)|}\, e^{-\phi_N(z)} \sum_{\xi=1,2} \bar{\Psi}_\xi e^M_A e^N_B \sigma^{AB} F_{MN} \psi_\xi \,,
$$

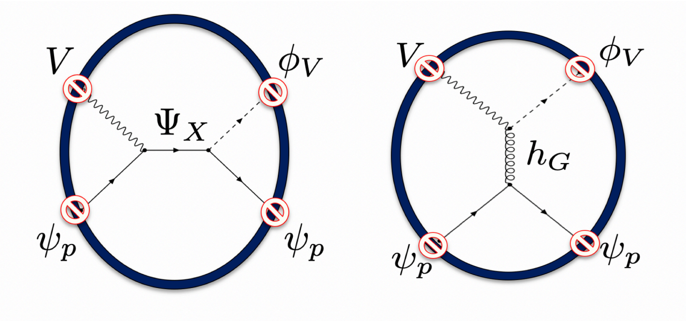


Figure: The s- and t-channel contribution to near threshold photoproduction of J/ψ.

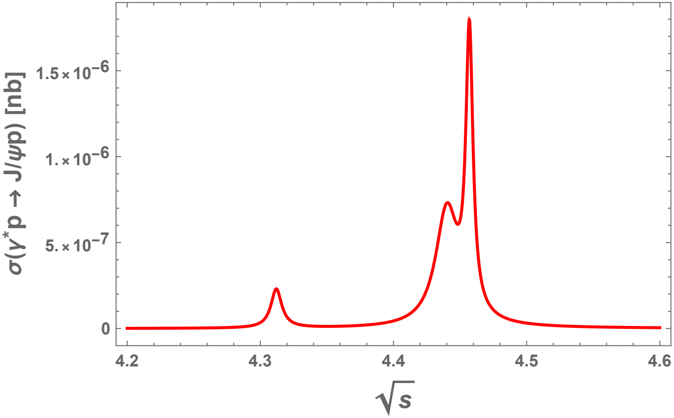


Figure: s-channel contribution to the photo-production cross section for $V = J/\psi$ versus $\sqrt{s}$, showing the three charm pentaquarks.

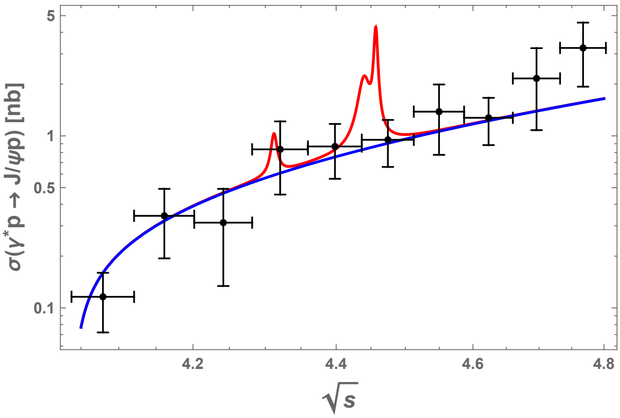


Figure: Total cross section for $V = J/\psi$ photo-production: the blue-solid curve is the t-channel contribution from [Mamo:2019], the red-solid curve is the sum of t- and s-channel contribution showing the three holographic pentaquarks times $\mathcal{N}_s = 2.0 \times 10^6$ to make them visible, and the data are from GlueX [GlueX:2019].

The differential cross section for photoproduction of J/ψ near threshold: comparison to experiment

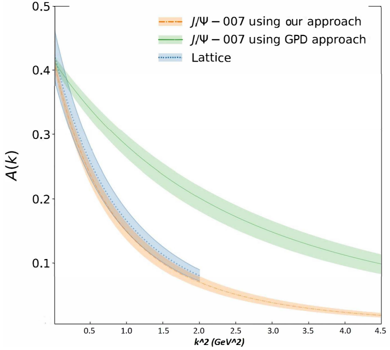


Figure: The $A(k^2)$ form factor extracted from the two-dimensional cross section data of $J/\psi - 007$ collaboration (Duran, et al., 2022) using our holographic QCD approach (orange dash-dot curve) and the GPD+VMD approach [Guo, et al., 2021] (green solid curve), compared to the latest lattice calculation [Pefkou, et al., 2021] (blue dotted curve).

The differential cross section for photoproduction of J/ψ near threshold: comparison to experiment

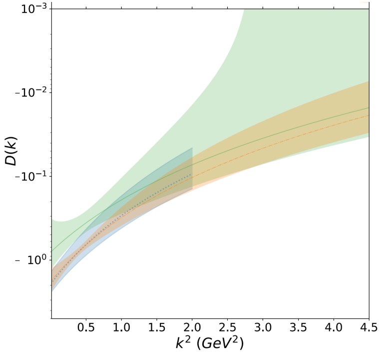


Figure: The $D(k^2) = 4C(k^2)$ form factor extracted from the two-dimensional cross section data of $J/\psi - 007$ collaboration (Duran, et al., 2022) using our holographic QCD approach (orange dash-dot curve) and the GPD+VMD approach [Guo, et al., 2021] (green solid curve), compared to the latest lattice calculation [Pefkou, et al., 2021] (blue dotted curve).

The differential cross section for photoproduction of J/ψ near threshold: comparison to experiment

Table: Gluonic GFF parameters and the corresponding proton mass and scalar radii, determined by $J/\psi - 007$ collaboration through a two-dimensional fit following the holographic QCD and GPD+VMD approach, compared to the latest lattice results.

Theoretical approach	χ^2/n.d.f	m_A (GeV^2)	m_C (GeV^2)	$C_g(0)$	$\sqrt{\langle r_m^2 \rangle}$ (fm)	$\sqrt{\langle r_s^2 \rangle}$ (fm)
Holographic QCD	0.925	1.575±0.059	1.12±0.21	-0.45±0.132	0.755±0.035	1.069±0.056
GPD + VMD	0.924	2.71±0.19	1.28± 0.50	-0.20 ± 0.11	0.472±0.042	0.695±0.071
Lattice		1.641± 0.043	1.07± 0.12	-0.483± 0.133	0.7464±0.025	1.073±0.066

Photoproduction of J/ψ from near threshold to far from threshold

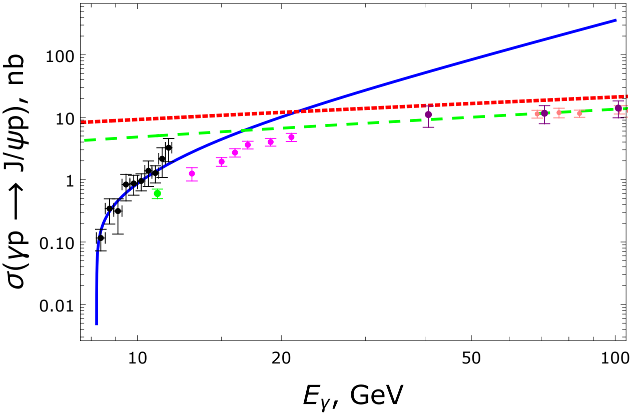


Figure: The total cross section for J/ψ photoproduction.

Thank You!