

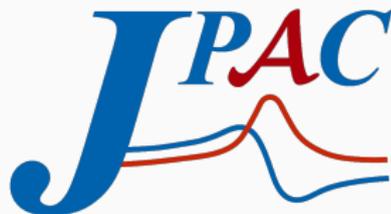
XYZP Spectroscopy in Photoproduction

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12 Oct 2020 — JLab Theory Seminar

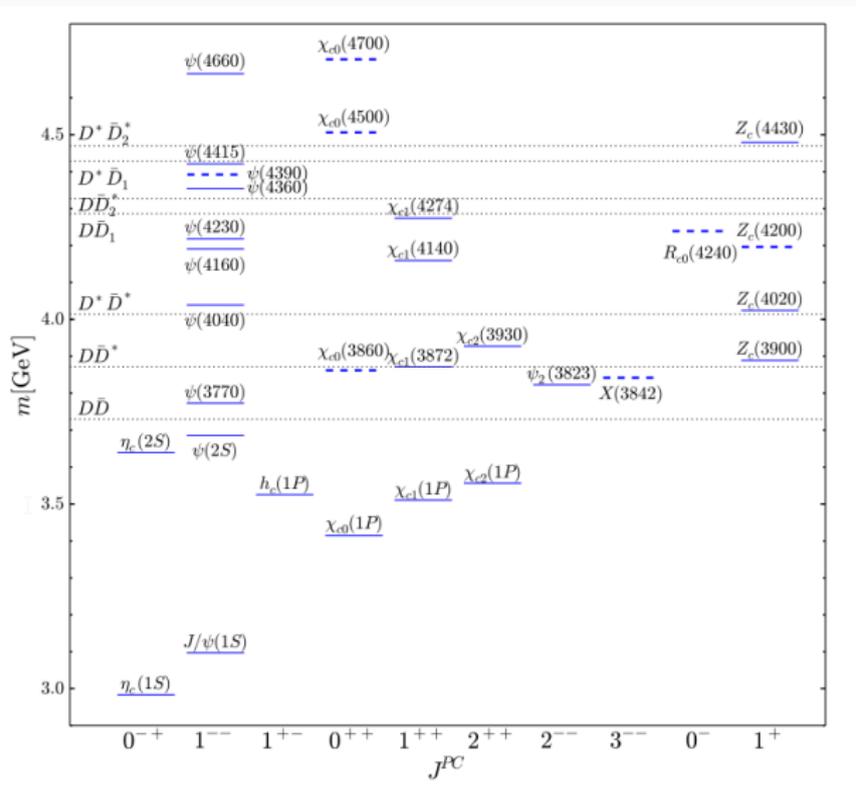


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1. Overview of *XYZP* spectroscopy
2. Overview of exclusive photon-induced production
3. JPAC Results:
 - "Double polarization observables in pentaquark photoproduction"
DW, Fanelli, Pilloni, Hiller Blin, and JPAC [1907.09393]
 - "XYZ spectroscopy at electron-hadron facilities: Exclusive processes"
Albaladejo, Hiller Blin, Pilloni, DW, and JPAC [2008.01001]
4. Summary and outlook

Charmonium landscape



Brambilla et al. [1907.07583]

The XYZ's

Plethora of states have been observed by experiments since 2003.

We focus on those best established in experiment.

(See *Olsen et al. [1708.0401]* or *Brambilla et al.[1907.07583]*)

X(3872) or $\chi_{c1}(3872)$

First observed by Belle in $B \rightarrow (\pi\pi J/\psi)K$ spectrum.

Confirmed in variety of production modes (B decay, pp , $p\bar{p}$ and e^+e^- collisions)

$$J^{PC} = 1^{++} \quad m_X = 3871.69 \pm 0.17 \quad \Gamma_X = 1.19 \pm 0.19$$

Mass coincidence with $D\bar{D}^*$ threshold, narrow width, and large observed isospin violation (decays mostly into isospin-1 final states) point to beyond $c\bar{c}$ structure.

molecular? compact tetraquark?

The XYZ's

$Y(4260)$ or $\psi(4260)$

First seen in electron-positron collisions with ISR by BaBar.

$$J^{PC} = 1^{--} \quad m_Y = 4220 \pm 15 \quad \Gamma_Y = 44 \pm 9$$

Part of "supernumeracy" states not predicted by quark model below 4500 MeV and no observed decays to open-charm final states.

hadrocharmonium? hybrid?

$Z_c(3900)^+$

Simultaneously discovered by BESIII and Belle in subsequent decays of $Y(4260) \rightarrow J/\psi\pi\pi$.

$$J^{PC} = 1^{+-} \quad m_Z = 3888.4 \pm 2.5 \quad \Gamma_Z = 28.3 \pm 2.5$$

Charged $c\bar{c}$ -like resonance, also very close to $\bar{D}D^*$ threshold.

tetraquark? molecule? triangle-singularity?

P_c states

Series of states observed in $\Lambda_b \rightarrow (J/\psi p)K$ decays.

First 2015 analysis suggested two states:

$$P_c(4380)^+ \text{ and } P_c(4450)^+$$

but follow-up analysis in 2019 with larger data set reported three narrow states:

$$P_c(4312)^+, P_c(4440)^+, \text{ and } P_c(4457)^+$$

Spin parities currently unknown and close proximity to $\Sigma_c \bar{D}$ and $\Sigma_c \bar{D}^*$.

compact pentaquark? molecule? triangle singularity?

Heavier states

$Z_b(10610)^+$ **and** $Z'_b(10650)^+$

Analogues of the charged Z_c states in the $b\bar{b}$ -like spectrum.

Two best established exotic candidates so far in the bottomonium sector.

$X(6900)$

Recently observed peak in the di- J/ψ spectrum by LHCb.

Four charm valence quarks, may be indication of tetraquark-like structure.

Theoretical landscape

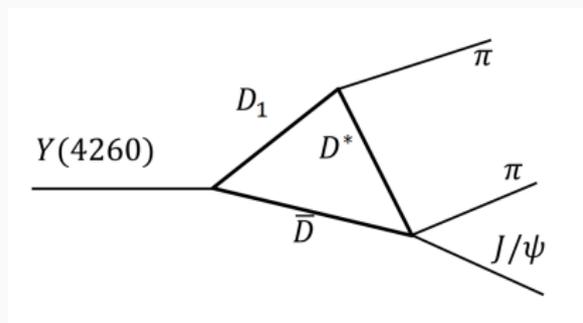
Variety of phenomenological and theoretical tools available. e.g.:

- QCD Sum Rules
- NRQCD
- Potential Models
- Quark / diquark models
- Lattice QCD
- HQET

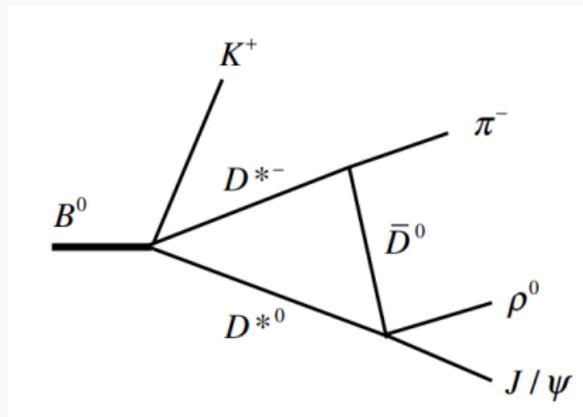
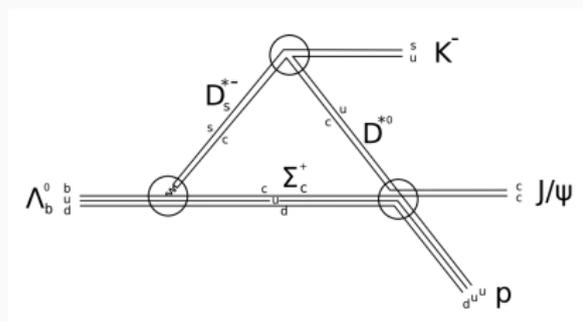
No single approach particularly conclusive on the substructure of exotic candidates.

Exploring alternative production mechanisms in experiment can further help disentangle the various interpretations of exotic candidate signals.

Triangle Singularities

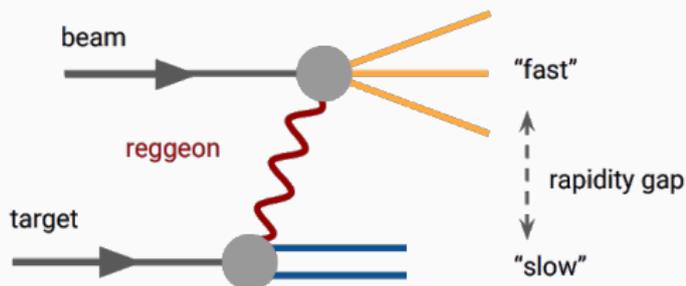


Resonance-like peaks generated by kinematic singularities in rescattering of on-shell particles. Multitude of open thresholds makes separating kinematic effects difficult.



Exclusive Photoproduction

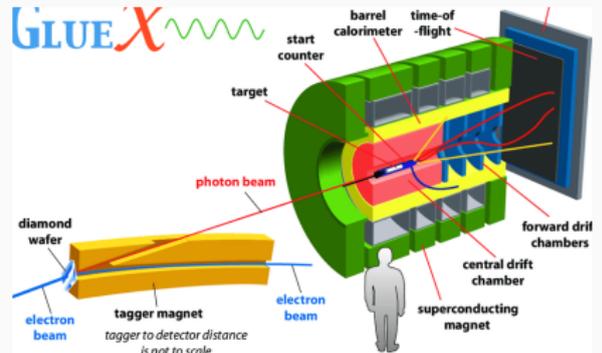
Allows direct production with no spectator particles in the final state (insensitive to complications from 3-body dynamics).



Constrained kinematics means less ambiguous signal and precise determination of production mechanism.

Well understood in terms of Regge phenomenology: forward production dominated by beam fragmentation by exchanges with meson quantum numbers.

Existing photoproduction experiments



Photoproduction already being employed in Hall D to illuminate the light hadron spectrum.

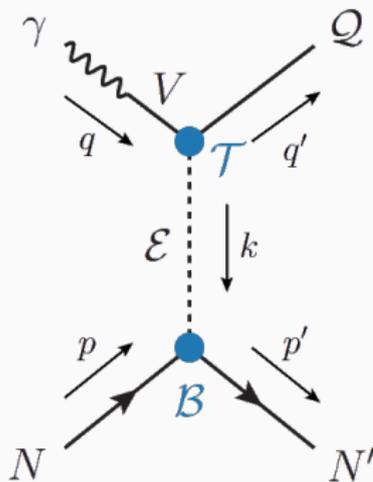
Exclusive Photoproduction

Production amplitudes in terms of exchanges determined by quantum numbers. Couplings may be estimated by available experimental data.

$$\langle \lambda_Q \lambda'_N | T \varepsilon | \lambda_\gamma \lambda_N \rangle = \sum_V \frac{e f_V}{m_V} \mathcal{T}_{\lambda_V = \lambda_\gamma, \lambda_Q}^{\alpha_1 \dots \alpha_j} \mathcal{P}_{\alpha_1 \dots \alpha_j; \beta_1 \dots \beta_j} \mathcal{B}_{\lambda_N, \lambda'_N}^{\beta_1 \dots \beta_j}$$

Recipe:

- Bottom vertex, $\mathcal{B}_{\lambda_N, \lambda'_N}$, known from Regge phenomenology
- Use VMD to relate incoming photon to lowest lying vector quarkonium
- Top vertex, $\mathcal{T}_{\lambda_V, \lambda_Q}$, from $\Gamma_{Q \rightarrow V \varepsilon}$ partial width
- Use Feynman amplitudes to fix couplings at low-energies, then Reggeize propagators to get high-energy behavior.



Exchanges

Q	V	\mathcal{E}	$\mathcal{B}(Q \rightarrow V\mathcal{E})$ (%)
$X(3872)$		ρ	4.1
	J/ψ	ω	4.4
$Z_c(3900)^+$		π	10.5
	$\Upsilon(1S)$		0.54
$Z_b(10610)$	$\Upsilon(2S)$	π	3.30
	$\Upsilon(3S)$		9.22
$Z'_b(10650)^+$	$\Upsilon(1S)$		0.21
	$\Upsilon(2S)$	π	1.47
	$\Upsilon(3S)$		4.8

Y and J/ψ (primary background for pentaquark production) proceed through Pomeron exchange and are treated separately.

Nucleon vertices

Based on standard forms of vector meson-nucleon interactions:

$$\mathcal{B}_{\lambda_N \lambda'_N}^\mu = \beta(t) \bar{u}(p', \lambda'_N) \left(g \gamma^\mu + g' \frac{\sigma^{\mu\nu} (p - p')_\nu}{2m_N} \right) u(p, \lambda_N)$$

and πNN interactions:

$$\mathcal{B}_{\lambda_N \lambda'_N} = \sqrt{2} g_{\pi NN} \beta(t) \bar{u}(p', \lambda'_N) \gamma_5 u(p, \lambda_N)$$

Couplings g & g' known from nucleon potential models and $g_{\pi NN}$ from πN and NN scattering data.

Additional form factor $\beta(t) = e^{t/\Lambda}$ suppress large t behavior to match experimentally observed behavior. Momentum cutoffs, Λ for each exchange also take usual values.

See for example:

Matsinos [1901.01204] and *Chiang et al. [nucl-th/0110034]*

Propagators

At low energies (near threshold) we expect the partial wave sum of the full amplitude to be $\propto (p(s)q(s))^j$ such that only the lowest j contributes. Thus, we consider fixed-spin, *Feynman propagators* which contain full energy dependence at low energies.

Easily written in terms of Feynman rules:

$$\mathcal{P}^0 = \frac{1}{t - m_{\mathcal{E}}^2}, \quad \mathcal{P}_{\alpha,\beta}^1 = \frac{g_{\alpha\beta} - k_{\alpha}k_{\beta}/m_{\mathcal{E}}^2}{t - m_{\mathcal{E}}^2}$$

Equivalently contracting all Lorentz structures evaluated in the t -channel CM frame we may match this to a helicity amplitude proportional to

$$\frac{d_{\mu\mu'}^j(\theta_t)}{t - m_{\mathcal{E}}^2} = \frac{\text{polynomial of order } j \text{ in } s}{t - m_{\mathcal{E}}^2}$$

Reggeization

At high energies, the above will like s^j which for $j \geq 1$ exceeds unitarity bounds. Therefore we restrict fixed-spin exchanges heuristically to a few GeV above threshold.

Beyond that, we must consider the re-summed (Reggeized) tower of arbitrary spin with the replacement

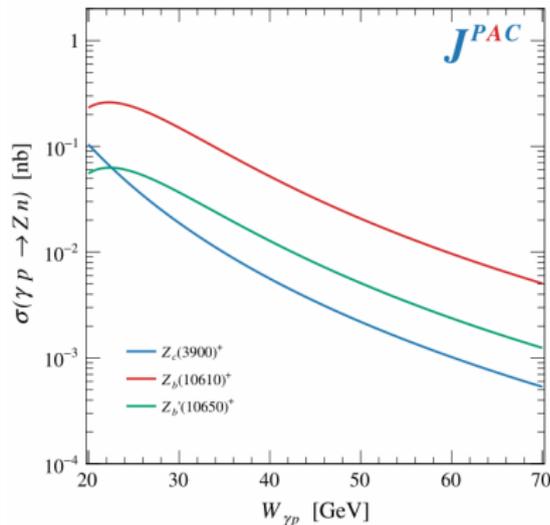
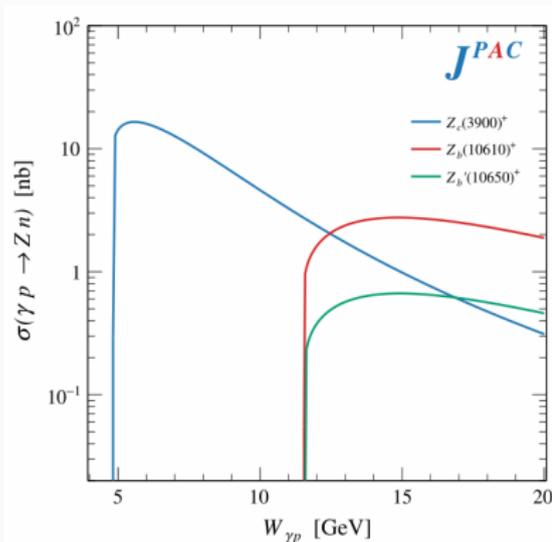
$$\mathcal{N}_{\mu\mu'}^j \left(\frac{4p(t)q(t)}{s_0} \right)^{j-M} \frac{d_{\mu\mu'}^j(\theta_t)}{\xi_{\mu\mu'}^{(t)}(s,t)} \frac{1}{t - m_{\mathcal{E}}^2} \rightarrow -\alpha' \Gamma(j - \alpha(t)) \left[\frac{1 + \tau e^{-i\pi\alpha(t)}}{2} \right] \left(\frac{s}{s_0} \right)^{\alpha(t) - M}$$

We use usual real, linear parameterizations for the $\rho - \omega$ and π Regge trajectories:

$$\alpha_{\rho}(t) = 1 + 0.9(t - m_{\rho}^2) \quad \alpha_{\pi}(t) = 0.7(t - m_{\pi}^2) .$$

Note an intercept $\alpha_0 = \alpha(t=0) < 1$ forces the Reggeized amplitude to decrease at high energies.

Results: Z's



Minimally gauge invariant A-P-V interaction:

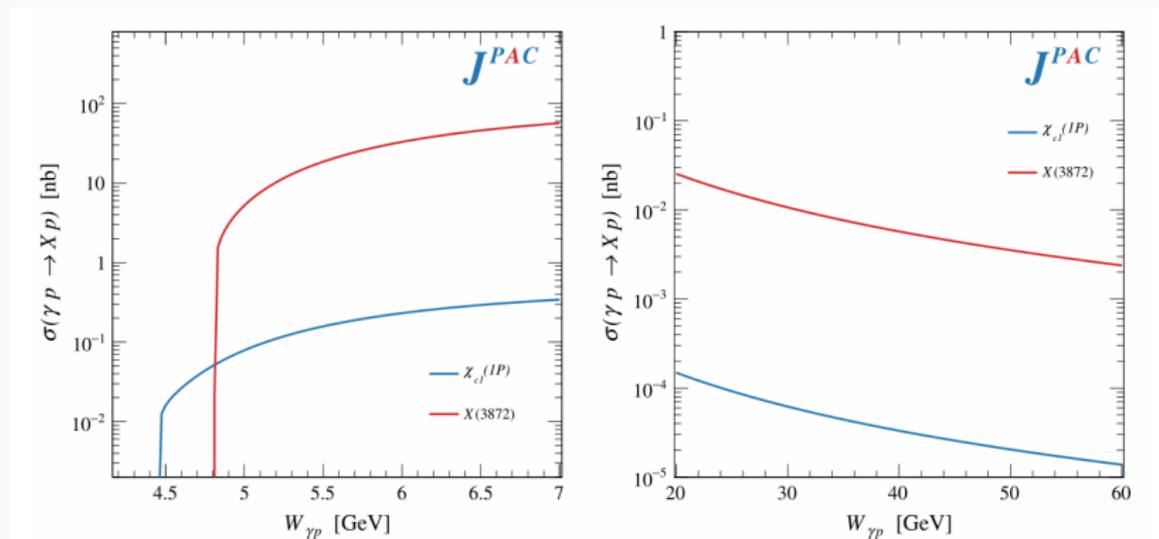
$$\mathcal{T}_{\lambda_V \lambda_Z} = \frac{g_{VZ\pi}}{m_Z} \varepsilon_\mu(q, \lambda_V) \varepsilon_\nu^*(q', \lambda_Z) [(q \cdot (q - q')) g^{\mu\nu} - (q - q')^\mu q^\nu]$$

Couplings fixed by saturating Z width by observed decay modes.

Results: X(3872)

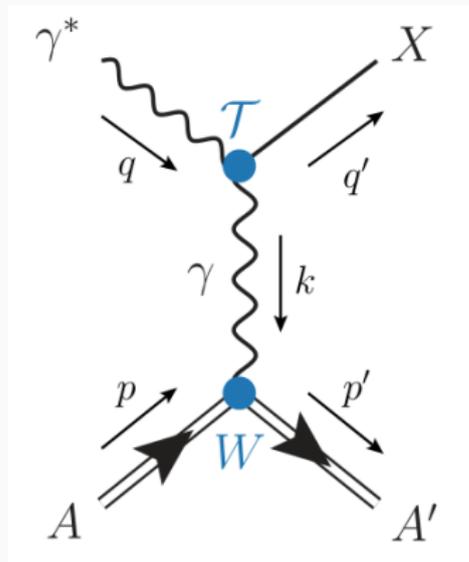
Gauge invariant V-V-A interaction. Coupling fixed by fits to differential decay widths to $X \rightarrow J/\psi\rho \rightarrow J/\psi\pi\pi$ and $X \rightarrow J/\psi\omega \rightarrow J/\psi\pi\pi\pi$.

$$T_{\lambda\varepsilon\lambda_X}^\mu = g_{\psi X \varepsilon} \epsilon_{\sigma\nu\alpha\beta} [g^{\sigma\mu} \varepsilon^{*\nu}(q', \lambda_X) q^\alpha \varepsilon^\beta(q, \lambda_\varepsilon)]$$



High energy cross-sections highly-suppressed by Reggeization!

Aside: Primakoff Production of X(3872)



Although the decay $X(3872) \rightarrow 2\gamma$ is forbidden by Landau-Yang theorem, recent measurement of $X(3872)$ in two-photon interactions by Belle gives the reduced width:

$$\tilde{\Gamma}_{\gamma\gamma}^X = \lim_{Q^2 \rightarrow 0} \frac{m_X^2}{Q^2} \Gamma_{\gamma\gamma^*}^X(Q^2).$$

Can use this to estimate coupling of X to two photons. At small (but finite) Q^2 we expect quasi-elastic Primakoff production.

Can take advantage of EIC's ability to accelerate high Z beams.

Aside: Primakoff Production of X(3872)

Squared amplitude given in terms of spin-summed tensors and photon propagator:

$$\sum_{\lambda_X, \lambda'_A} |\langle \lambda_X \lambda'_A | T | \lambda_\gamma \lambda_A \rangle|^2 = \frac{e^2}{t^2} T_{\lambda_\gamma}^{\mu\nu} W_{\mu\nu}$$

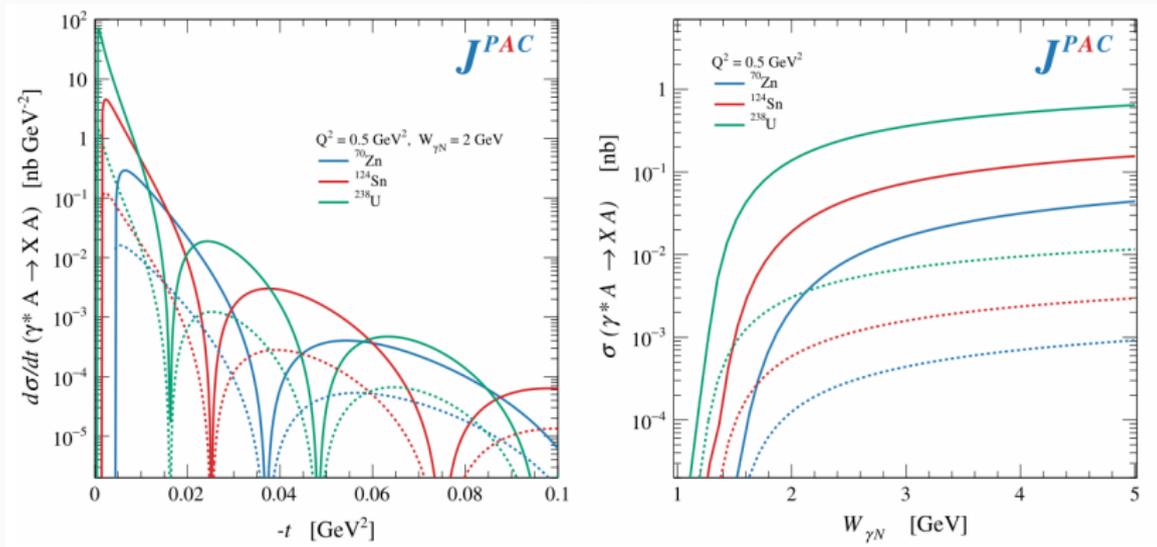
Top tensor $T_{\lambda_\gamma}^{\mu\nu}$ given in terms of our X(3872) A-V-V interaction, and the nuclear tensor is assumed to be dominated by the nuclear electric field:

$$W_{\mu\nu} \simeq 16\pi \left(p_\mu + \frac{1}{2} k_\mu \right) \left(p_\nu + \frac{1}{2} k_\nu \right) \frac{Z^2}{4\pi} \frac{16m_A^4 F_0^2(t)}{(4m_A^2 - t)^2}$$

The form factor, $F_0(t)$, accounts for the finite size of the nucleus and is parameterized by a Fermi model:

$$F_0(t) = \frac{\rho_0}{Z} \int d^3x \frac{\sin |\vec{k}| |\vec{x}|}{|\vec{k}| |\vec{x}|} \left[1 + \exp\left(\frac{|\vec{x}| - R}{a} \right) \right]^{-1}$$

Results: Primakoff



Differential and integrated cross-sections for longitudinal (solid) and transverse (dotted) photons respectively.

Pomeron Exchange

At high-energies, vector-meson photoproduction is well described by Pomeron exchange.

$$\langle \lambda_Q \lambda'_N | T_P^{(HE)} | \lambda_\gamma \lambda_N \rangle = F(s, t) \delta_{\lambda_Q \lambda_\gamma} \delta_{\lambda_N \lambda'_N}$$

At energies near threshold, vector production may be realized by the explicit multi-gluon (*Brodsky et al. [hep-ph/0010343]*) or open-charm exchanges (*Du et al. [2009.08345]*).

To be as agnostic as possible to the microscopic dynamics, we use a phenomenological model of that realizes the vector-like coupling of a Pomeron at low energies.

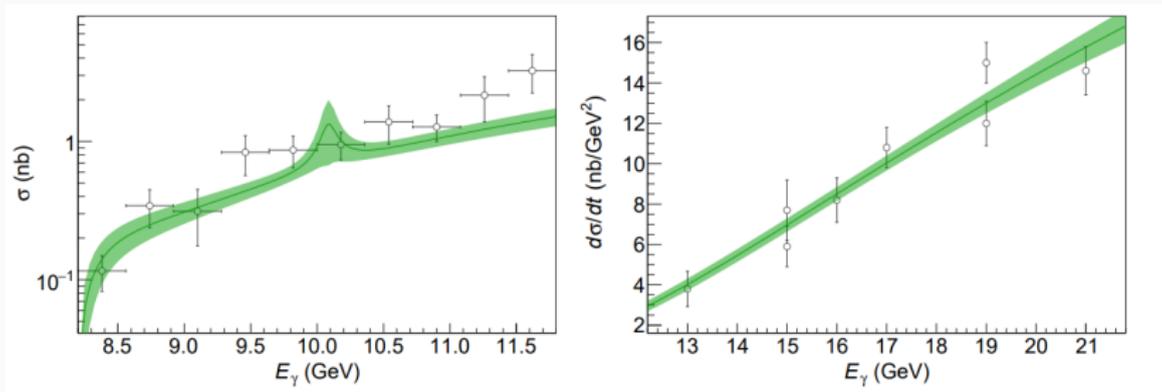
$$\langle \lambda_Q \lambda'_N | T_P^{(LE)} | \lambda_\gamma \lambda_N \rangle = \frac{F(s, t)}{s} [\bar{u}(p', \lambda'_N) \gamma_\mu u(p, \lambda_N)] \varepsilon_\nu^*(q', \lambda_Q) [\varepsilon^\mu(q, \lambda_\gamma) q^\nu - \varepsilon^\nu(q, \lambda_\gamma) q^\mu]$$

In both cases the function $F(s, t)$ contains all the dynamical s and t dependence of the Pomeron and must be fit to data:

$$F(s, t) = ie A \left(\frac{s - s_{\text{th}}}{s_0} \right)^{\alpha(t)} e^{b_0 t'}$$

J/ψ photoproduction

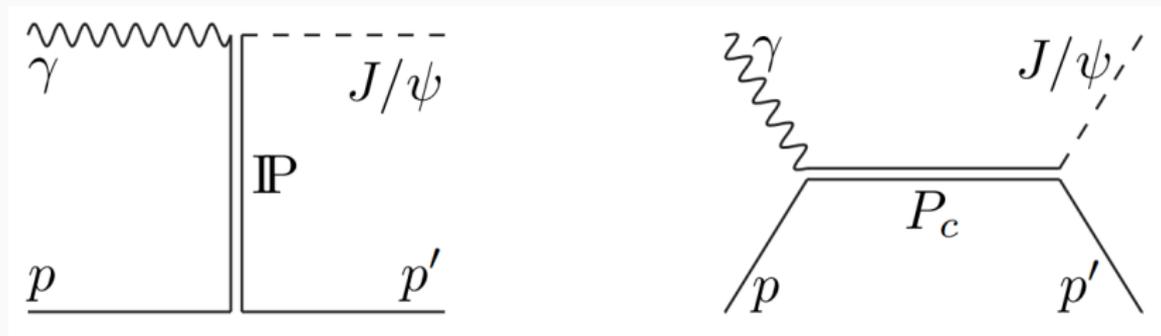
Fits to recent near-threshold data from GlueX and moderate energy SLAC data allow us to extract $\gamma\psi$ -Pomeron couplings.



No observation of peaks consistent with pentaquark states places upper bounds of $< 4\%$ on branching fractions $\mathcal{B}(P_c \rightarrow J/\psi p)$.

Aside: P_c production in polarization observables

Able to study the sensitivity of polarization observables to pentaquark-like peaks in the coherent sum of J/ψ production and direct-channel Breit-Wigner resonances.

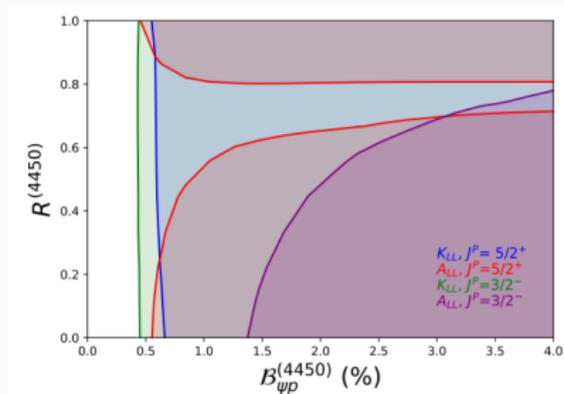
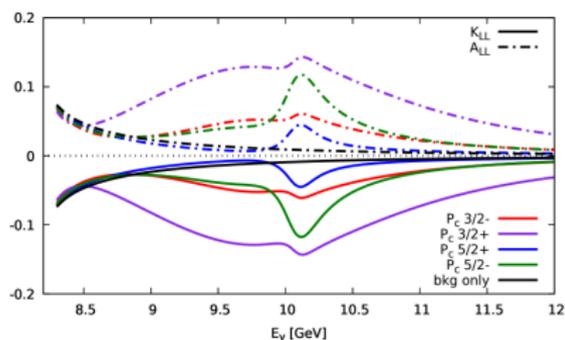


Pentaquark candidates amplitude in terms of usual nucleon resonance parameterization:

$$\langle \lambda_\psi \lambda_{p'} | T_R | \lambda_\gamma \lambda_p \rangle = f_{\text{th}}(s) \frac{\langle \lambda_\psi \lambda_{p'} | T_{\text{dec}} | \lambda_R \rangle \langle \lambda_R | T_{\text{em}}^\dagger | \lambda_\gamma \lambda_p \rangle}{M_R^2 - s - i\Gamma_R M_R}$$

Aside: P_c production in polarization observables

Couplings estimated with nominal branching fractions,
 $\mathcal{B}(P_c \rightarrow J/\psi p) = 1\%$ and VMD to fix overall photo-coupling strength.



Proposed measurement of beam-target polarization asymmetry A_{LL} and beam-recoil polarization asymmetry K_{LL} in Hall A at JLab sensitive to many pentaquark scenarios.

$$A(K)_{LL} = \frac{1}{2} \left[\frac{d\sigma(++)-d\sigma(+-)}{d\sigma(++)+d\sigma(+-)} - \frac{d\sigma(-+)-d\sigma(--)}{d\sigma(-+)+d\sigma(--)} \right]$$

Rescaling couplings for higher charmonia

We may relate the previously fit coupling A_ψ to $\psi(2S)$ production by a scale factor:

$$A_{\psi'} = R_{\psi'} A_\psi .$$

Assuming the Pomeron exchange is dominated by 2-gluon exchange:

$$R_{\psi'} = \sqrt{\frac{g^2(\psi' \rightarrow \gamma gg)}{g^2(\psi \rightarrow \gamma gg)}} \sim 0.55$$

where the the coupling are computed from known partial widths of the three-body process divided by the corresponding phase space (PS) by:

$$g^2(\psi \rightarrow \gamma gg) = 6m_\psi \frac{\Gamma_\psi \mathcal{B}(\psi \rightarrow \gamma gg)}{\text{PS}(\psi \rightarrow \gamma gg)}$$

$Y(4260)$ coupling

Radiative $Y \rightarrow \gamma gg$ decays have not yet been measured.

Instead we appeal to factorization arguments of *Voloshin and Zakharov* [*Phys. Rev. Lett.*45, 688 (1980)]:

$$g^2(Y \rightarrow \psi\pi\pi) = g^2(Y \rightarrow \psi gg) \times g^2(gg \rightarrow \pi\pi)$$

$$g^2(\psi' \rightarrow \psi\pi\pi) = g^2(\psi' \rightarrow \psi gg) \times g^2(gg \rightarrow \pi\pi)$$

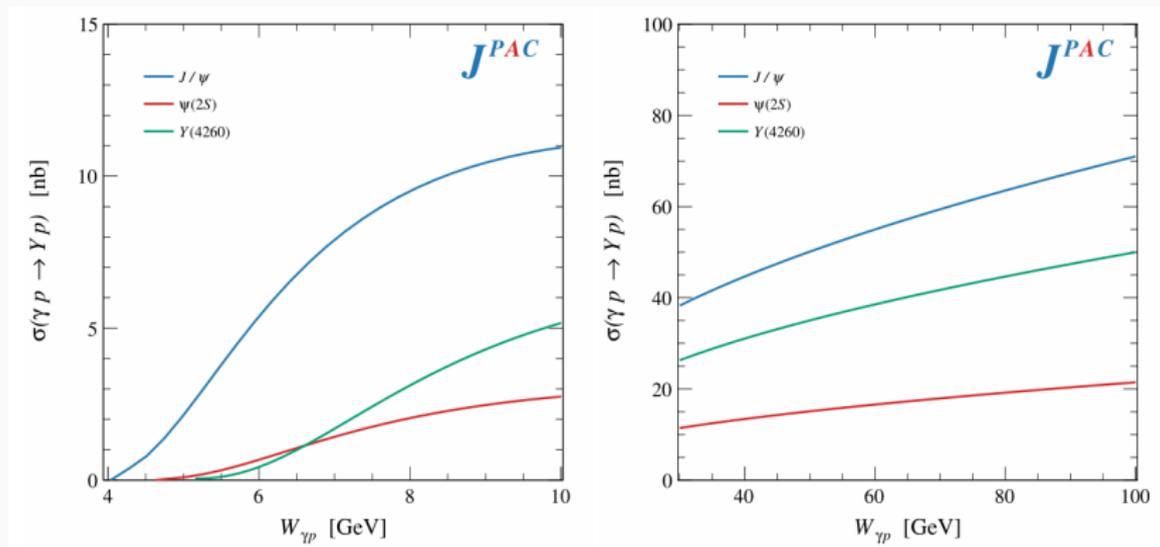
Furthermore use VMD to relate $g(Y \rightarrow \gamma gg) = \frac{ef_\psi}{m_\psi} g(Y \rightarrow \psi gg)$,

$$R_Y = \frac{ef_\psi}{m_\psi} \sqrt{\frac{g^2(Y \rightarrow \psi\pi\pi)}{g^2(\psi \rightarrow \gamma gg)} \frac{g^2(\psi' \rightarrow \psi gg)}{g^2(\psi' \rightarrow \psi\pi\pi)}}$$

Everything known up to coupling $g(Y \rightarrow \psi\pi\pi)$ which depends on the electromagnetic decay width $\Gamma_{e^+e^-}^Y$. Compare with high-energy HERA data to put an upper limit on this value and $R_Y = 0.84$.

Results: $Y(4260)$

Unlike meson exchanges, diffractive production *increases* with energy.



Photoproduction toolkit

Code implementations of all amplitudes to be available on the JPAC website or at <https://github.com/dwinney/jpacPhoto>.

Array of observables (cross-sections, asymmetries, SDME's) also available. Future plans to incorporate other JPAC models into centralized toolkit for amplitude analysis in photoproduction.

Easily interface-able to Monte-Carlo tools for simulation.

Helping motivate spectroscopy detector requirements for the EIC, feasibility studies for current experiments such as SBS and GlueX at JLab.

Summary and Outlook

Observation of exotic candidates in photoproduction would be important step towards understanding their structure. As such, photoproduction cross-sections for more robust exotic candidates predicted at two regimes of interest: near threshold and at high energies.

Future electron-ion colliders ideal laboratories for diffractive production of $Y(4260)$, high-mass states such as the Z_b 's, and Primakoff production of $X(3872)$ utilizing heavy ion beams.

Ongoing JPAC studies into semi-inclusive production will further motivate the XYZP spectroscopy program at next-generation electron-hadron facilities.