# Exotic Spectroscopy (in Photoproduction) @ EIC

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**[arXiv:2008.01001]**

**IR2 @ EIC**

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JPAC

# Exotic Hadrons

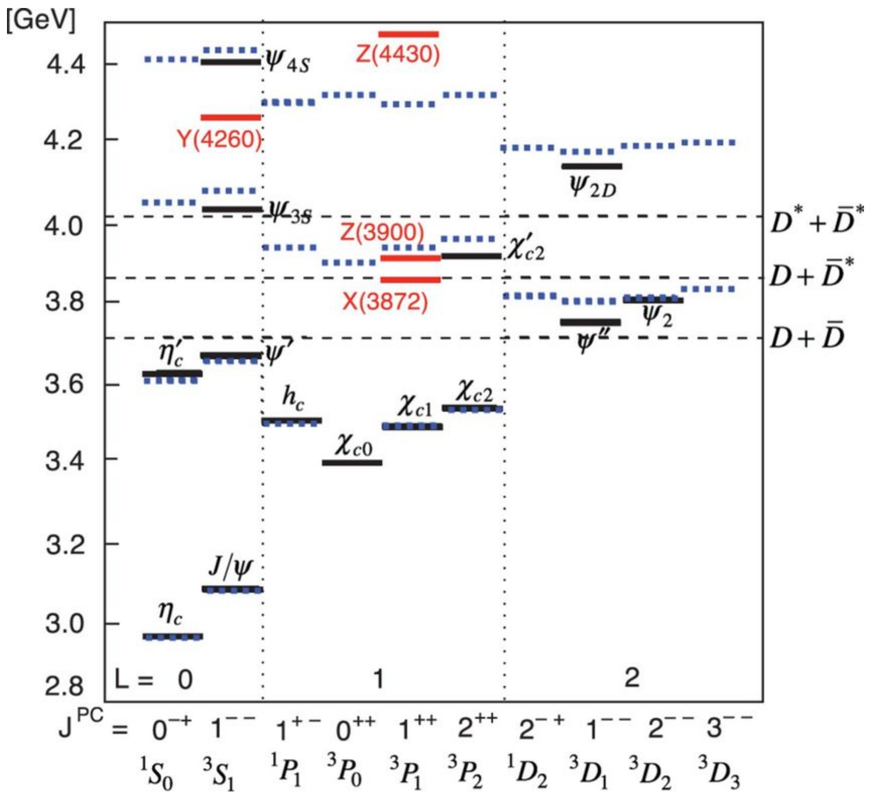
Plethora of quarkonium-like states observed since 2003 which do not fit into conventional qqbar models.

**X(3872)** - large isospin violation
**Y(4260)** - anomalous coupling to open charm channels
**Z(3900)** - charged, charmonium-like state

Ambiguous interpretation of signals:

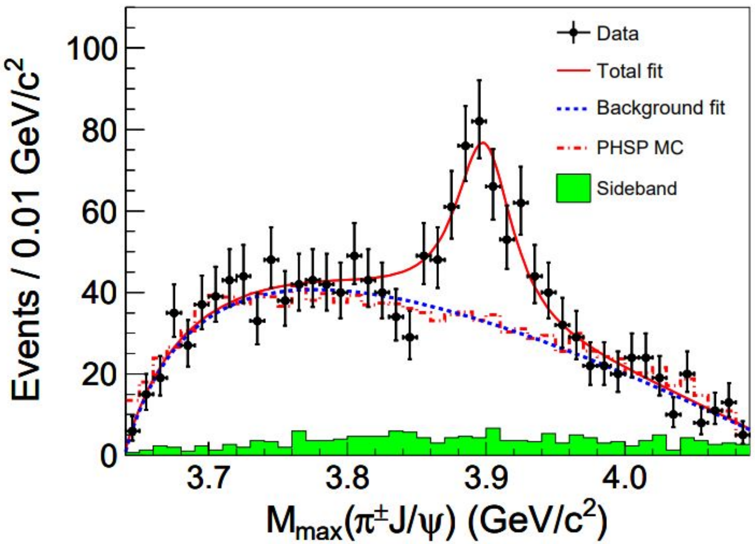
Multi-quark resonances, hadronic molecules, hadrocharmonia, **kinematic effect**, hybrid

**For reviews of XYZs see e.g.:**
**A. Hosaka et al. [arXiv:1603.09229]**
**N. Brambilla et al. [arXiv:1907.07583]**
**F-K. Guo et al. [arXiv:1912.07030]**



# Case of the Zc(3900)+

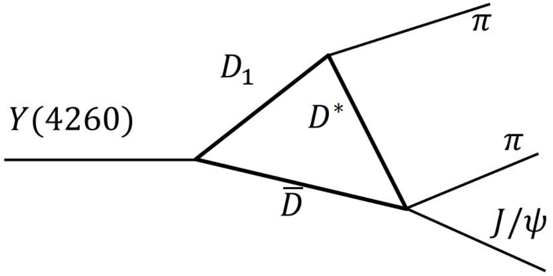
BESIII [Phys. Rev. Lett. 110, 252001 (2013)]




Charmonium-like state seen in π J/ψ and D*D*bar and various production modes.

***but always with extra final state particles***

Charged nature unambiguously points to exotic nature but precise structure still unknown.




Triangle rescattering with final state pions unlikely to explain away Z-like signal but must still be accounted for in amplitude analysis and parameter extraction.

Guo, Liu, Sakai [arXiv:1912.07030]
Szczepaniak [arXiv:1501.01691]

[arXiv:hep-ex/0003020]

# Exclusive photoproduction

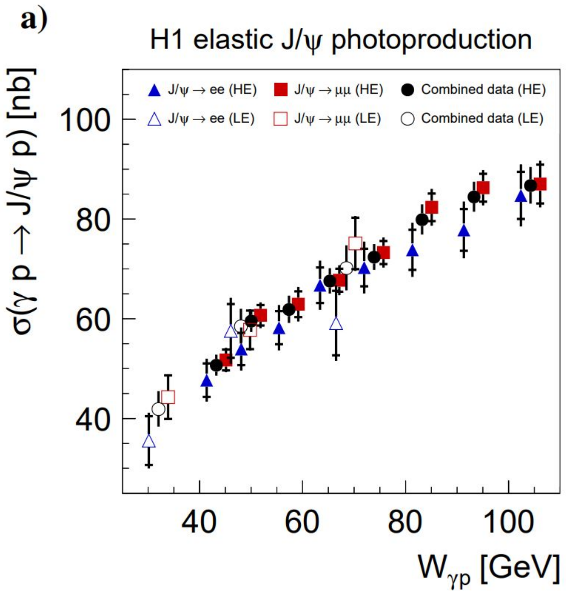
None of the XYZ’s have been observed in photon-induced reactions

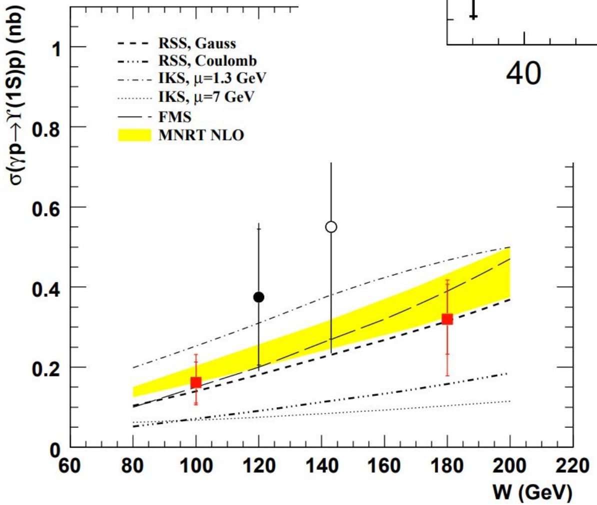
Current dedicated photoproduction facilities (e.g. GlueX@JLab)  too low in energy reach.

Ideal laboratory for spectroscopy

- Constrained kinematics ⇒ precise determination of production mechanism
- Direct production ⇒ eliminates contribution from triangle rescattering and FSI
- Phenomenology well understood
- Heavy quarkonium photoproduction studies at *ep* colliders demonstrated at HERA

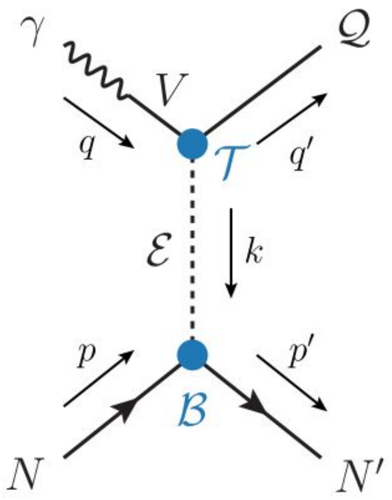
**Higher luminosity and energy at EIC allow study of exotic hadrons!**




[arXiv:0903.4205]

# Exclusive photoproduction




**JPAC [arXiv:2008.01001]**

**See also e.g.**
Galata **[arXiv:1102.2070]**
Lin, Liu, & Xu **[ arXiv:1308.6345]**
Wang et al. **[arXiv:2009.05789]**

**Recipe for an amplitude:**

1. Identify relevant exchanges
2. Photon couplings fixed by observed decay widths and VMD
3. Bottom couplings from other reactions

Necessary distinction between production near-threshold and high-energy

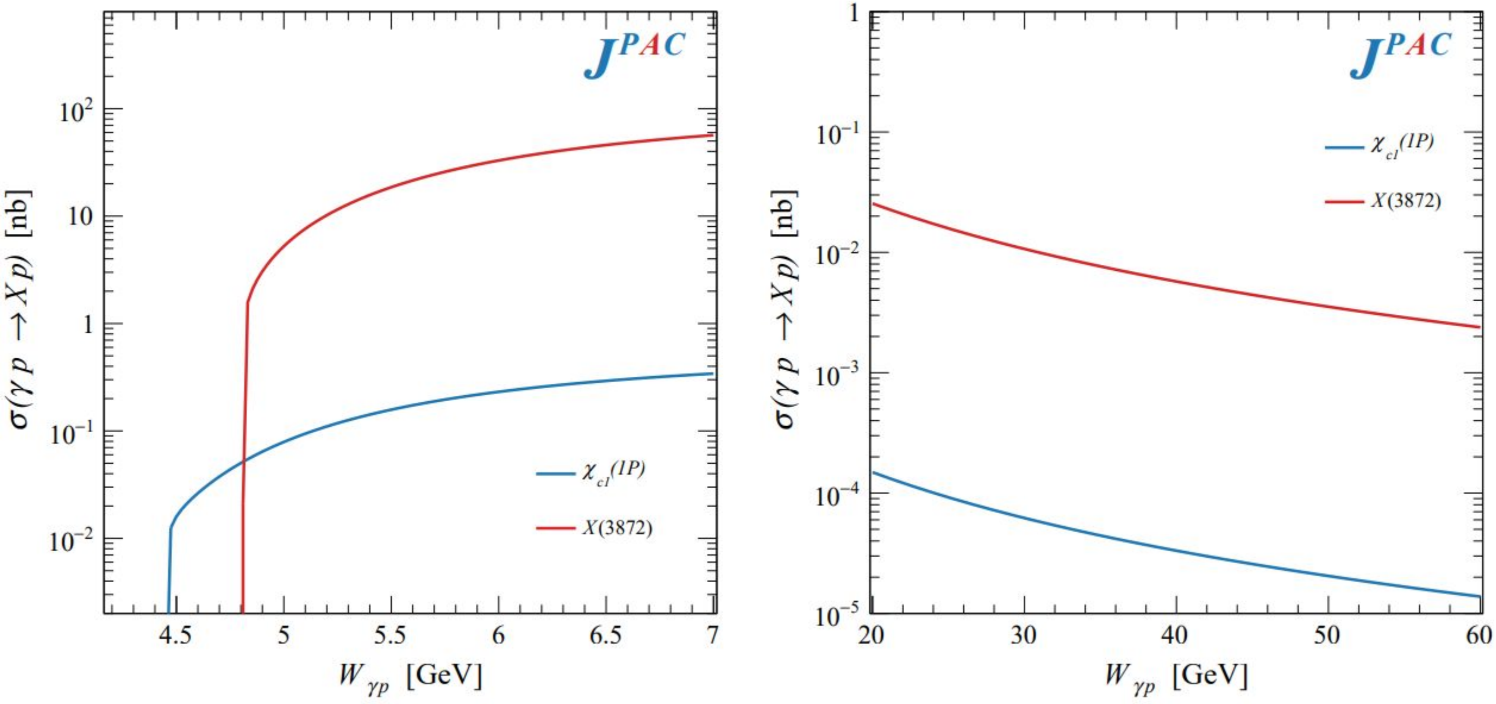
- In near threshold production lowest spin exchanges dominate
- At high-energies Regge physics kicks in

Production cross-sections by meson exchanges fall at high energies as a consequence of unitarity (Reggeization).

**Lower γp invariant mass ⇒ higher cross-section for X and Z**

# X(3872)

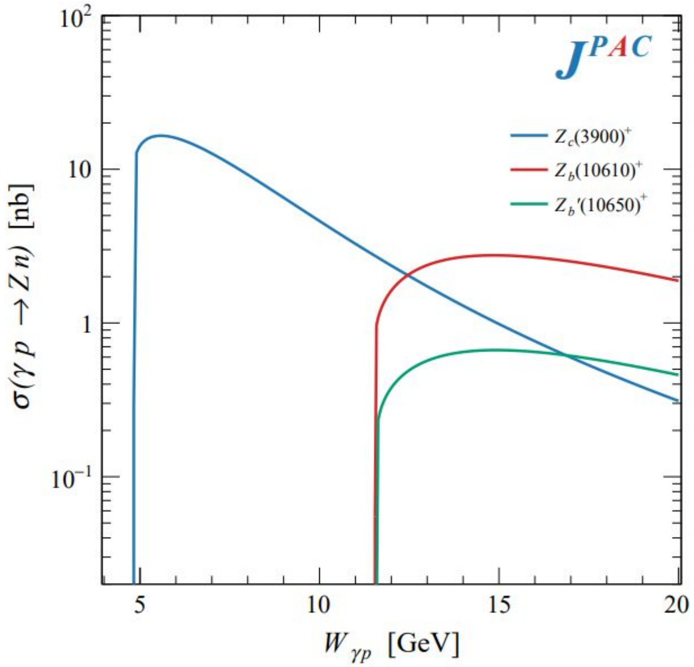
Effect very dramatic for vector exchanges, X(3872) production
(note: interpolation between high and low energy not really straightforward)

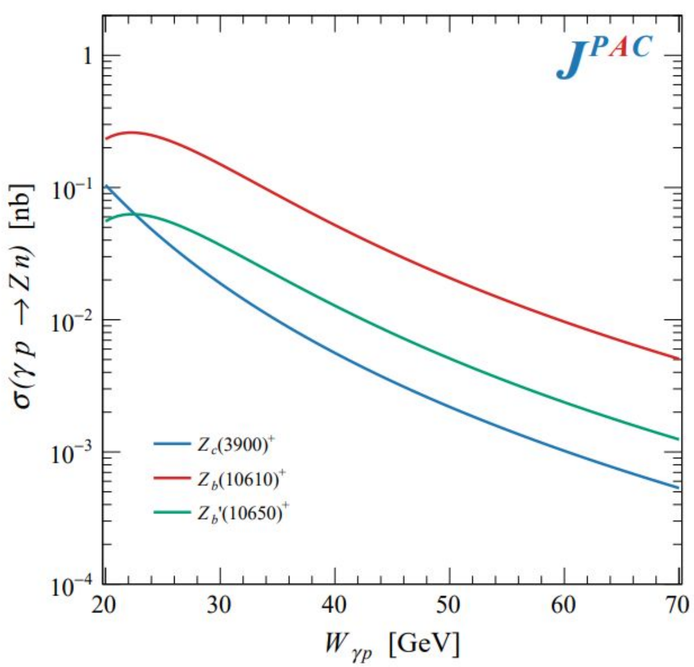


# Zc(3900)+

Spin-0, pion exchange ⇒ cross-sections for Z states fall less dramatically from threshold production.

***Spectroscopy of Z's possible with high-luminosity at low CM energies!***

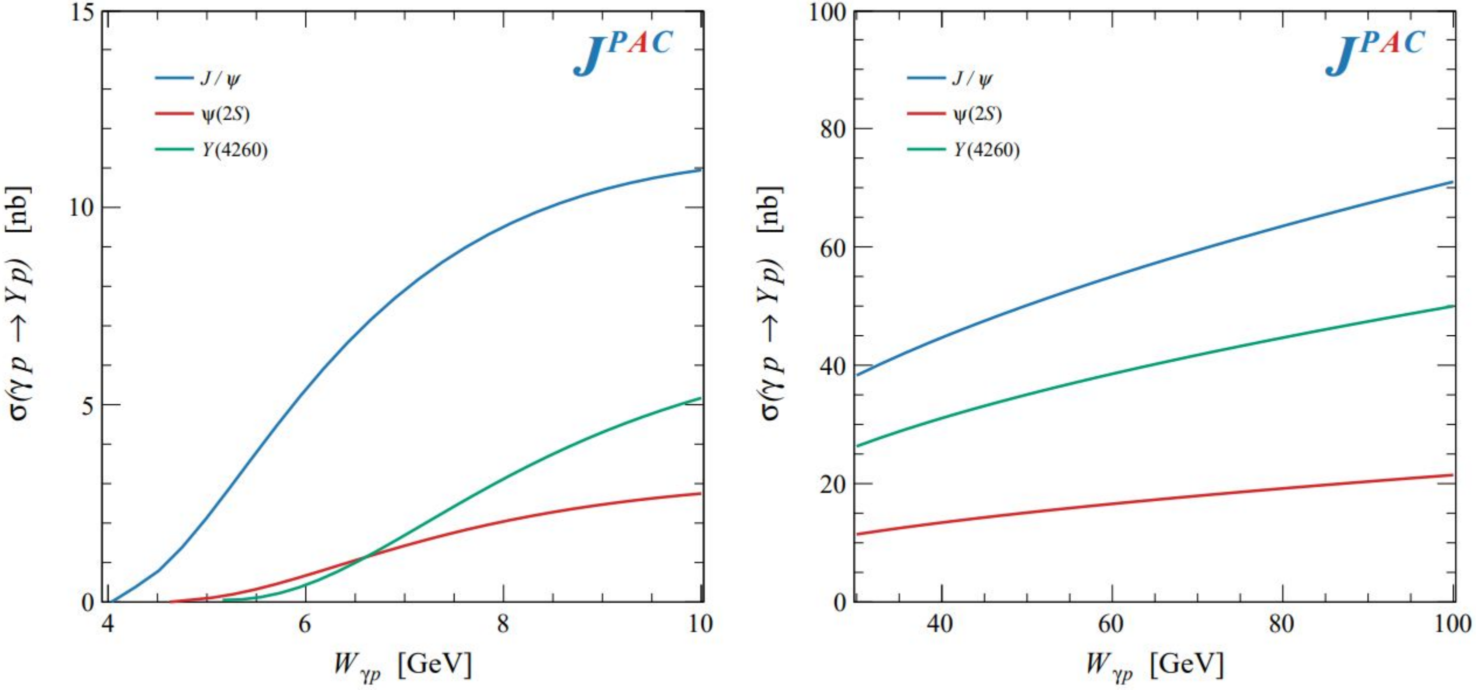


# Vector charmonia and Y(4260)

Unlike X and Z, vector states produced via diffractive Pomeron exchange.

**Diffractive cross-section rise with energy, Y states instead benefit from high CM.**



# jpacPhoto

Code implementations of all amplitudes mentioned here (and more) freely available for download and use at **github.com/dwinney/jpacPhoto**

- Probability distribution ( $\Sigma_\lambda |A|^2$ )
- Differential cross section ( $d\sigma / dt$ )
- Integrated total cross section ( $\sigma$ )
- Polarization asymmetries ( $A_{LL}$ and $K_{LL}$ )
- Spin density matrix elements ( $\rho^\alpha_{\lambda,\lambda'}$ )
- Integrated beam asymmetry ( $\Sigma_{4\pi}$ )
- Beam asymmetry in the y-direction ( $\Sigma_y$ )
- Parity asymmetry ( $P_\sigma$ )

Available amplitudes, so far, include:

- Baryon resonance (s-channel)
- Pomeron exchange (t-channel)
- (fixed-spin and reggeized) Charged pseudo-scalar meson exchange (t-channel)
- (fixed-spin and reggeized) Vector meson exchange (t-channel)
- Primakoff effect off nuclear target (t-channel)
- (fixed-spin) Dirac fermion exchange (u-channel)
- (fixed-spin) Rarita-Schwinger fermion exchange (u-channel)

Can incorporate production and subsequent decays in MC generators, **see Derek's talk up next!**

# Summary

The EIC offers a unique opportunity to study exotics in photoproduction to complement measurements at existing facilities.

In particular production of Zc and Zb states hugely benefits from a high-luminosity, low energy program (e.g. at IR2). Production cross-sections comparable to existing e+e- machines.

# Thank you!

# Backup Slides

## 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:

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

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

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

# 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

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

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

$$\alpha_\rho(t) = 1 + 0.9\,(t - m^2_\rho) \qquad \alpha_\pi(t) = 0.7\,(t - m^2_\pi)\ .$$

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