Studying the $P_c(4450)$ resonance in $J/\psi$ photoproduction off protons

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Pentaquark-like structure

Discovery in 2015 of exotic resonances in $J/\psi\; p$ channel:

LHCb collaboration, PRL 115 (2015) 072001

Narrow 39 MeV, at 4.45 GeV
Broad 205 MeV, at 4.38 GeV
Pentaquark-like structure

Discovery in 2015 of exotic resonances in $J/\psi$ $p$ channel:

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Narrow 39 MeV, at 4.45 GeV
Broad 205 MeV, at 4.38 GeV

- Favored spin-parity assignment for $P_c(4450)$: $3/2^−$ or $5/2^+$
- Excellent candidate for $J/\psi$ photoproduction off protons
  - Wang et al., PRD 92 (2015), 034022; Karliner and Rosner, PLB 752 (2016), 329
- Probing this approved for JLab Hall C with A rating
  - Meziani et al., arXiv:1609.00676
Advantages of study in $J/\psi$ photoproduction

- The structure appears close to threshold: low background
Advantages of study in $J/\psi$ photoproduction

- The structure appears close to threshold: **low background**
- Sneak preview:

![Graph showing $d\sigma/dt$ vs $E_\gamma$ with 1σ band and mean value data points.]

- Photoproduction constrains the nature of the structure
Nature of the structures

- Triangle singularities (rescattering effects): **not a resonance**
  - Mikhasenko, arXiv:1507.06552
  - Liu et al., PLB 757 (2016) 231
  - Guo et al., EPJA 52 (2016) 318
  - Guo et al., PRD 92 (2015) 071502
  - ...

- Quark degrees of freedom
  - Anisovich et al., arXiv:1507.07652
  - Lebed, PLB 749 (2015) 454
  - Maiani et al., PLB 749 (2015) 289
  - ...

- Meson-baryon molecules or bound states
  - He, PLB 753 (2016) 547
  - Eides et al., PRD 93 (2016) 054039
  - Meißner and Oller, PLB 751 (2015) 59
  - Roca et al., PRD 92 (2015) 094003
  - Chen et al., PRL 115 (2015) 172001
  - ...

\[ P_c(4450) \] in \( J/\psi \) photoproduction would exclude scenarios of kinematical effects!
Reaction model

\[ \gamma \rightarrow J/\psi \]

\[ p \rightarrow p \]
Reaction model

\[
\frac{d\sigma}{d \cos \theta} \sim \sum_{\lambda_\gamma, \lambda_p, \lambda_\psi, \lambda_{p'}} |\langle \lambda_\psi \lambda_{p'} | T_r | \lambda_\gamma \lambda_p \rangle|^2
\]

- Resonant amplitude — Breit-Wigner ansatz
- Non-resonant contribution — Pomeron exchange
Breit-Wigner s-channel contribution: hadronic couplings

\[ \langle \lambda_\psi \lambda_{p'} | T_r | \lambda_\gamma \lambda_p \rangle = \frac{\langle \lambda_r | T_{em}^\dagger | \lambda_\gamma \lambda_p \rangle \langle \lambda_\psi \lambda_{p'} | T_{dec} | \lambda_r \rangle}{M_r^2 - W^2 - i\Gamma_r M_r} \]

- Three independent (parity) helicity amplitudes \( \sim g_{\lambda_{p'}, \lambda_\psi} \):
  - \( \lambda_\psi = \pm 1, 0, \lambda_p = \pm \frac{1}{2} \) \( \rightarrow \) in total 6 helicity amplitudes
  - Assumption: \( g_{\lambda_{p'}, \lambda_\psi} = g \)
  - \( g \) extracted from hadronic decay width

\[ \Gamma_{\psi p} = B_{\psi p} \Gamma_r = B_{\psi p} 39 \text{ MeV} \]
Breit-Wigner s-channel contribution: photocouplings

\[ \langle \lambda_{\psi} \lambda_{p'} | T_r | \lambda_{\gamma} \lambda_p \rangle = \frac{\langle \lambda_r | T_{em}^{\dagger} | \lambda_{\gamma} \lambda_p \rangle \langle \lambda_{\psi} \lambda_{p'} | T_{dec} | \lambda_r \rangle}{M_r^2 - W^2 - i\Gamma_r M_r} \]

- Photocouplings \( A_{1/2}, A_{3/2} \) estimated with VMD:
  - Karliner and Rosner, PLB 752 (2016) 329
  - \( J/\psi \) exchange dominates radiative decays
  - Electromagnetic width \( \Gamma_{\gamma} \) related to hadronic width:

\[ \Gamma_{\gamma} = \Gamma_{\psi p} \left( \frac{e f_{\psi}}{M_{\psi}} \right)^2 \left( \frac{p_i}{p_f} \right)^{2\ell+1} \times \frac{4}{6} \Rightarrow A_{1/2}, A_{3/2} \] fixed by \( \mathcal{B}_{\psi p} \)
Pomeron t-channel exchange

\[ p p \xrightarrow[\gamma]{\text{IP}} p' \gamma J/\psi \]

- Background described by Pomeron exchange

\[ iA \left( \frac{s - s_t}{\text{GeV}^2} \right)^{\alpha_0 + \alpha't} e^{b_0(t - t_{\text{min}})} \delta \lambda_p \lambda_{p'} \delta \lambda_\psi \lambda_\gamma \]

- \( A, b_0, s_t, \alpha_0, \alpha' \) fitted to world \( J/\psi \) photoproduction data from threshold up to 300 GeV

- **Simultaneous** fit with branching ratio \( B_{\psi p} \)
Background fit to high-energy data...

Chekanov et al. [ZEUS], EPJC 24 (2002) 345
Aktas et al. [H1], EPJC 46 (2006) 585
...simultaneously to low-energy data

Spin-3/2 vs. spin-5/2

Camerini et al., PRL 35 (1975) 483

Two points closest to threshold: unpublished SLAC data
(only forward direction!) Ritson, AIPCP 30 (1976) 75; Anderson, SLAC-PUB-1741 (1976)

Relevant to constrain pentaquark peak and branching ratio!
First results: no smearing due to experimental resolution
Different smearing scenarios

\[ \sigma_s = 60 \text{ MeV}, J_r = 3/2 \]

\[ \sigma_s = 120 \text{ MeV}, J_r = 3/2 \]

\[ \sigma_s = 60 \text{ MeV}, J_r = 5/2 \]

\[ \sigma_s = 120 \text{ MeV}, J_r = 5/2 \]
Branching ratio and photocouplings

- Branching ratio $P_c(4450) \to J/\psi p$ not yet known
  
  We gave a first prediction for its upper limit!

| $\sigma_s$ (MeV) | 0  | 60 | 120 |
|------------------|----|----|-----|
| Spin-3/2 case    | $\leq 29\%$ | $\leq 30\%$ | $\leq 23\%$ |
| Spin-5/2 case    | $\leq 17\%$ | $\leq 12\%$ | $\leq 8\%$ |

- Status: data at peak scarce and only for forward direction
- At JLab the **angular distributions** at the $P_c(4450)$ energy are to be studied
- Excellent opportunity to fix the **photocouplings**!
Angular dependence of the differential XS

\[
\frac{d\sigma}{dt} \, [\text{nb GeV}^{-2}] = 0 \text{ MeV}, J_r = 3/2
\]

\[
A_{1/2} = A_{3/2}
A_{3/2} = 0
A_{1/2} = 0
\]

\[
\alpha_s = 0 \text{ MeV}, J_r = 3/2
\]

\[
\alpha_s = 60 \text{ MeV}, J_r = 3/2
\]

\[
\alpha_s = 120 \text{ MeV}, J_r = 3/2
\]

\[
\alpha_s = 0 \text{ MeV}, J_r = 5/2
\]

\[
\alpha_s = 60 \text{ MeV}, J_r = 5/2
\]

\[
\alpha_s = 120 \text{ MeV}, J_r = 5/2
\]

Relax VMD condition on \( A_{1/2} \) and \( A_{3/2} \):

**Angular behavior** and choice of **photocouplings** strongly related!
Our work: mean value
Our work: 1σ band
Two-gluon exchange
S. J. Brodsky et al., PLB 498 (2001) 23
Summary

▶ The narrow resonance **might have escaped detection**: we estimate the upper limit of the **branching ratio**

▶ $P_c(4450)$ in $J/\psi$ **photoproduction** to **confirm** resonance: **JLab Hall C** experiment

▶ Strong correlation **angular distributions ↔ photocouplings**: helps fixing them **experimentally**!

▶ Code and **interactive** website (own parameter choices) available at **www.indiana.edu/~jpac/**

Outlook

▶ Extension to $J/\psi$ **electro**production (approved: JLab Hall A)

▶ To obtain **SDMs**: upgrade CLAS12 to **muon detection**
Additional material
Comparing with previous work

\[ E_\gamma = E_r = 10.1 \text{ GeV} \]
\[ \beta_{\psi p} = 10\% \]
\[ J = 3/2 \]
\[ \text{no background} \]

For \( \sigma(\gamma \ p \rightarrow \ J/\psi \ p) \approx 14 \text{ nb} \)

Karliner and Rosner, PLB 752 (2016) 329
Integrated cross section in the different best-fit scenarios

\[ \sigma_{\text{tot}} \text{ [nb]} \]

\[ E_{\gamma} \text{ [GeV]} \]

- \( J_r = \frac{5}{2}, \sigma_s = 0 \text{ MeV} \)
- \( \frac{5}{2}, 60 \text{ MeV} \)
- \( \frac{5}{2}, 120 \text{ MeV} \)
- \( \frac{3}{2}, 0 \text{ MeV} \)
- \( \frac{3}{2}, 60 \text{ MeV} \)
- \( \frac{3}{2}, 120 \text{ MeV} \)
## Couplings and widths for the spin-3/2 case

| $J^P_r$ | $3/2^-$ |
|---------|---------|
| $\sigma_s$ (MeV) | 0 | 60 | 120 |
| $B_{\psi p}$ | \leq 29% | \leq 30% | \leq 23% |
| $g$ (GeV) | \leq 2.1 | \leq 2.2 | \leq 1.9 |
| $\Gamma_\gamma$ (keV) | \leq 14.4 | \leq 14.9 | \leq 11.0 |
| $A_{1/2,3/2}$ (GeV$^{-1/2}$) | \leq 0.007 | \leq 0.007 | \leq 0.006 |
| $\frac{d\sigma}{dt}|_{E_{\gamma}=E_r,t=t_{\text{min}}}$ (nb GeV$^{-2}$) | \leq 21.8 | \leq 7.2 | \leq 3.1 |
| $\sigma_{\text{tot}}|_{E_{\gamma}=E_r}$ (nb) | \leq 120 | \leq 38 | \leq 14 |
### Couplings and widths for the spin-5/2 case

| $J^P_r$ | 5/2$^+$ |
|--------|--------|
| $\sigma_s$ (MeV) | 0 | 60 | 120 |
| $B_{\psi p}$ | $\leq 17\%$ | $\leq 12\%$ | $\leq 8\%$ |
| $g$ (GeV) | $\leq 2.0$ | $\leq 1.5$ | $\leq 1.4$ |
| $\Gamma_\gamma$ (keV) | $\leq 56.9$ | $\leq 33.5$ | $\leq 26.8$ |
| $A_{1/2,3/2}$ (GeV$^{-1/2}$) | $\leq 0.017$ | $\leq 0.013$ | $\leq 0.012$ |
| $\frac{d\sigma}{dt} \big|_{E_\gamma=E_r, t=t_{\text{min}}}$ (nb GeV$^{-2}$) | $\leq 95.8$ | $\leq 11.3$ | $\leq 3.9$ |
| $\sigma_{\text{tot}} \big|_{E_\gamma=E_r}$ (nb) | $\leq 396$ | $\leq 44$ | $\leq 14$ |
Branching ratio and fit results

Branching ratio $P_c(4450) \rightarrow J/\psi p$ not yet known

We gave the first prediction for its upper limit!

| $\sigma_s$ (MeV) | 0         | 60        | 120       |
|------------------|-----------|-----------|-----------|
| $A$              | $0.156^{+0.029}_{-0.020}$ | $0.157^{+0.039}_{-0.021}$ | $0.157^{+0.037}_{-0.022}$ |
| $\alpha_0$      | $1.151^{+0.018}_{-0.020}$ | $1.150^{+0.018}_{-0.026}$ | $1.150^{+0.015}_{-0.023}$ |
| $\alpha'$ (GeV$^{-2}$) | $0.112^{+0.033}_{-0.054}$ | $0.111^{+0.037}_{-0.064}$ | $0.111^{+0.038}_{-0.054}$ |
| $s_t$ (GeV$^2$)  | $16.8^{+1.7}_{-0.9}$      | $16.9^{+2.0}_{-1.6}$     | $16.9^{+2.0}_{-1.1}$     |
| $b_0$ (GeV$^{-2}$) | $1.01^{+0.47}_{-0.29}$   | $1.02^{+0.61}_{-0.32}$   | $1.03^{+0.49}_{-0.31}$   |
| $B_{\psi p}$ (95% CL) | $\leq 29\%$       | $\leq 30\%$       | $\leq 23\%$       |

Spin-3/2 case
Branching ratio and fit results

Branching ratio $P_c(4450) \rightarrow J/\psi p$ not yet known

We gave the first prediction for its upper limit!

| $\sigma_s$ (MeV) | 0            | 60           | 120          |
|-----------------|--------------|--------------|--------------|
| $A$             | $0.152^{+0.032}_{-0.024}$ | $0.150^{+0.043}_{-0.034}$ | $0.150^{+0.044}_{-0.041}$ |
| $\alpha_0$      | $1.154^{+0.020}_{-0.020}$ | $1.156^{+0.027}_{-0.028}$ | $1.156^{+0.033}_{-0.028}$ |
| $\alpha'$ (GeV$^{-2}$) | $0.120^{+0.064}_{-0.052}$ | $0.125^{+0.076}_{-0.089}$ | $0.126^{+0.077}_{-0.105}$ |
| $s_t$ (GeV$^2$)  | $16.6^{+1.6}_{-1.1}$       | $16.6^{+2.2}_{-1.5}$       | $16.6^{+2.1}_{-2.0}$       |
| $b_0$ (GeV$^{-2}$) | $0.95^{+0.51}_{-0.51}$       | $0.90^{+0.85}_{-0.65}$       | $0.90^{+1.00}_{-0.69}$       |
| $B_{\psi p}$ (95% CL) | $\leq 17\%$       | $\leq 12\%$       | $\leq 8\%$       |

Spin-5/2 case
The meson sector: \( XYZ \)

- Many unexpected structures decaying into \( c\bar{c} + \) light
  \( \rightarrow \) Hardly reconciled with quarkonium interpretation
  See talk by A. Pilloni

- It is not possible to explore \( c\bar{c}q\bar{q} \) mesons at JLab
  But: \( s\bar{s}q\bar{q} \) yes. \( Y(2175), \ldots \)
Resonances beyond the 3-constituent quark models

- After observing a new state: study the $Q^2$ dependence of the electrocouplings and the hadronic decays
- Complex interplay:
  - 3 constituent quarks ↔ meson-baryon cloud $(q\bar{q})(qqq)$
- Strongly dependent on $N^*$ quantum numbers
- New direction: $(q\bar{q})(qqq)$ quark core