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

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Tuesday 22nd August, 2017

PRD 94 (2016) 034002
1606.08912 [hep-ph]

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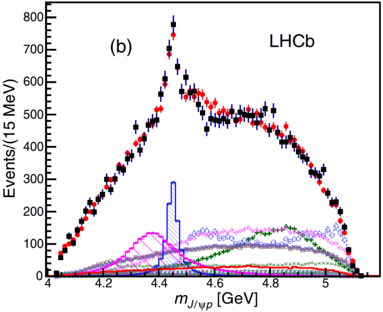
Pentaquark-like structure



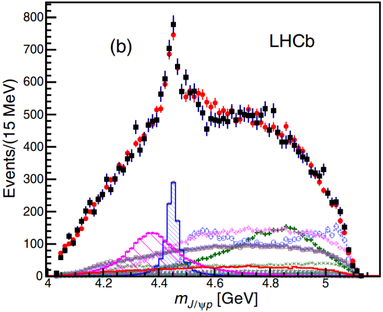
Discovery in 2015 of exotic resonances in $J/\psi\ p$ channel:

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:

LHCb collaboration, PRL 115 (2015) 072001

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/ψ **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**

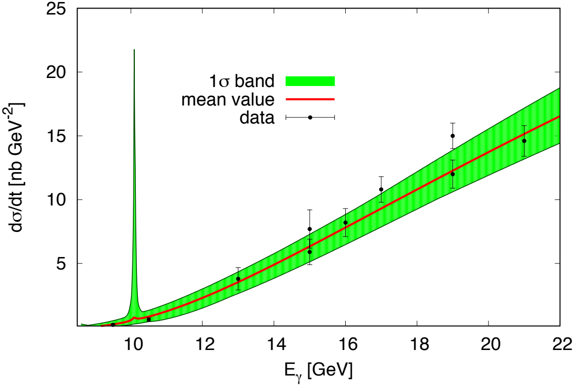
  Meziani et al., arXiv:1609.00676

Advantages of study in J/ψ photoproduction

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

Advantages of study in J/ψ photoproduction

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



- 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

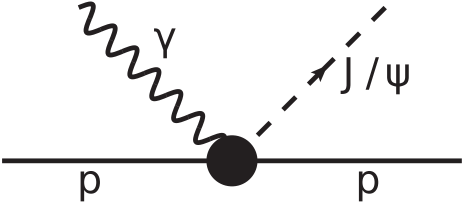
Anisovich et al., arXiv:1507.07652
Lebed, PLB 749 (2015) 454
Maiani et al., PLB 749 (2015) 289
...

- Meson-baryon molecules or bound states

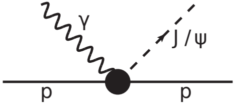
He, PLB 753 (2016) 547
Eides et al., PRD 93 (2016) 054039
Meißner and Oller, PLB 751 (2015) 59
Roca et al., PRD 92 (2015) 094003
Chen et al., PRL 115 (2015) 172001
...

$P_c(4450)$ in J/ψ photoproduction would
exclude scenarios of kinematical effects!

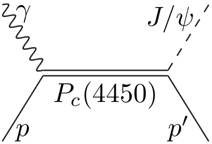
Reaction model

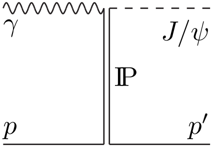


Reaction model



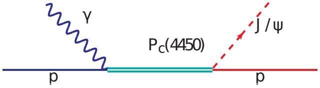
$$\frac{d\sigma}{d\cos\theta} \sim \sum_{\lambda_\gamma,\lambda_p,\lambda_\psi,\lambda_{p'}} \left| \langle \lambda_\psi \lambda_{p'} | \, T_r \, | \lambda_\gamma \lambda_p \rangle \right|^2$$





- Resonant amplitude — Breit-Wigner ansatz
- Non-resonant contribution — Pomeron exchange

Breit-Wigner s-channel contribution: hadronic couplings

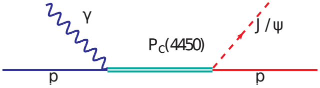


$$\langle \lambda_\psi \lambda_{p'} | \, T_r \, | \lambda_\gamma \lambda_p \rangle = \frac{\langle \lambda_r | \, T^\dagger_{\text{em}} \, | \lambda_\gamma \lambda_p \rangle \, \langle \lambda_\psi \lambda_{p'} | \, T_{\text{dec}} \, | \lambda_r \rangle}{M_r^2 - W^2 - \mathrm{i}\Gamma_r M_r}$$

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

$$\Gamma_{\psi p} = \mathcal{B}_{\psi p} \Gamma_r = \mathcal{B}_{\psi p} \, 39 \ \mathrm{MeV}$$

Breit-Wigner s-channel contribution: photocouplings



$$\langle \lambda_\psi \lambda_{p'} | \, T_r \, | \lambda_\gamma \lambda_p \rangle = \frac{\langle \lambda_r | \, T^\dagger_{\mathrm{em}} \, | \lambda_\gamma \lambda_p \rangle \, \langle \lambda_\psi \lambda_{p'} | \, T_{\mathrm{dec}} \, | \lambda_r \rangle}{M_r^2 - W^2 - \mathrm{i}\Gamma_r M_r}$$

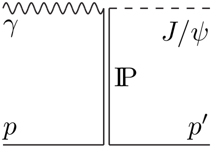
- Photocouplings $A_{1/2}, A_{3/2}$ estimated with VMD:

  Karliner and Rosner, PLB 752 (2016) 329

  - J/ψ exchange dominates radiative decays
  - Electromagnetic width Γ_γ related to hadronic width:

$$\Gamma_\gamma = \Gamma_{\psi p} \left(\frac{e \, f_\psi}{M_\psi} \right)^2 \left(\frac{p_i}{p_f} \right)^{2\ell+1} \times \frac{4}{6} \Longrightarrow A_{1/2}, \, A_{3/2} \text{ fixed by } \mathcal{B}_{\psi p}$$

Pomeron t-channel exchange



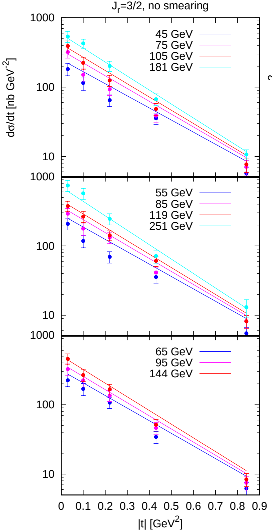
- Background described by Pomeron exchange

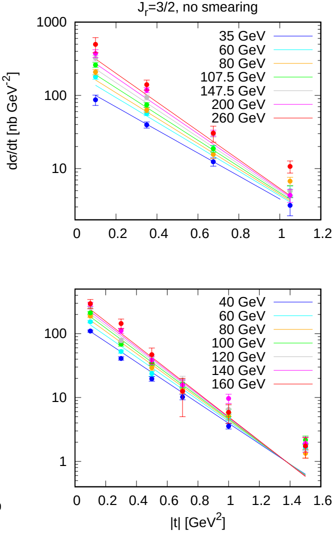
$$\mathrm{i}A \left(\frac{s - s_t}{\mathrm{GeV}^2}\right)^{\alpha_0 + \alpha' t} e^{b_0(t - t_{\min})} \delta_{\lambda_p \lambda_{p'}} \delta_{\lambda_\psi \lambda_\gamma}$$

- A, b_0, s_t, α_0, α' fitted to world J/ψ photoproduction data from threshold up to 300 GeV

- **Simultaneous** fit with branching ratio $\mathcal{B}_{\psi p}$

Background fit to high-energy data. . .



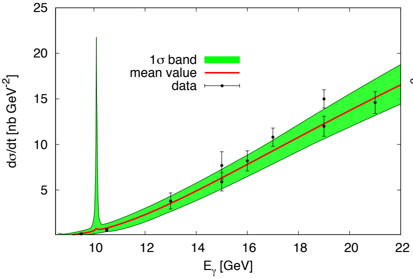


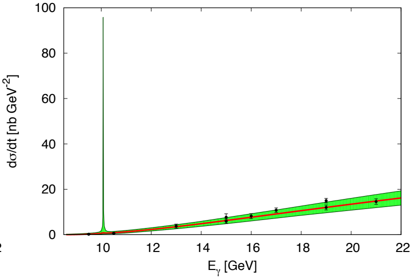
Chekanov et al. [ZEUS], EPJC 24 (2002) 345

Aktas et al. [H1], EPJC 46 (2006) 585

. . . simultaneously to low-energy data

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

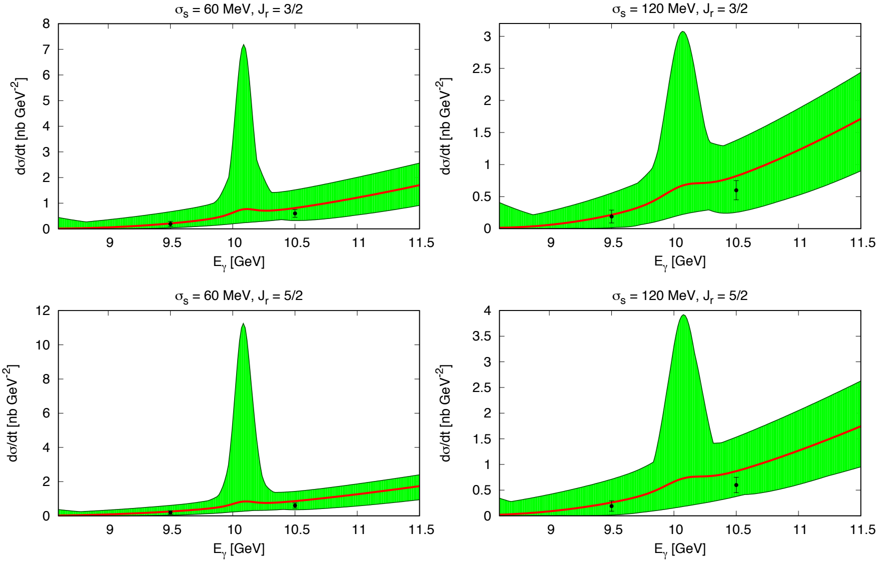




Camerini et al., PRL 35 (1975) 483

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



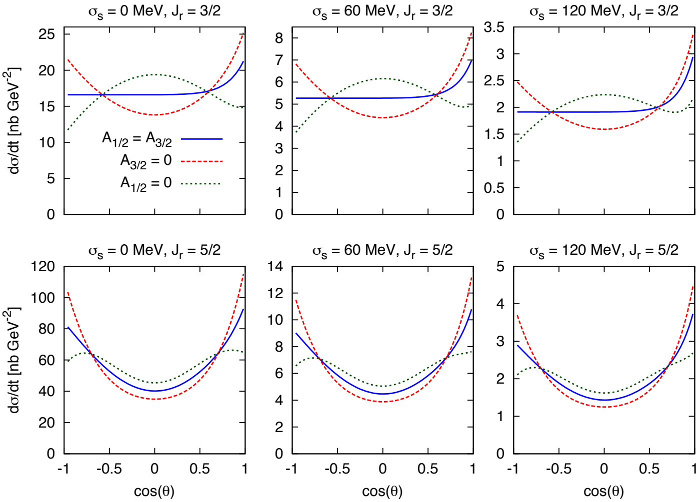
Branching ratio and photocouplings

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

σ_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**!

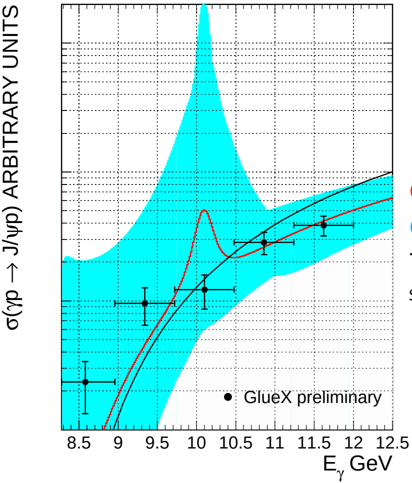
Angular dependence of the differential XS



Relax VMD condition on $A_{1/2}$ and $A_{3/2}$:

Angular behavior and choice of **photocouplings** strongly related!

Total cross section



Our work: mean value

Our work: 1σ band

Two-gluon exchange

S. J. Brodsky et al., PLB 498 (2001) 23

Summary

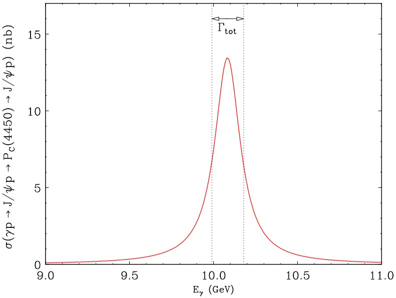
- The narrow resonance **might have escaped detection**: we estimate the upper limit of the **branching ratio**
- $P_c(4450)$ in J/ψ **photoproduction** to **confirm** resonance: **JLab Hall C** experiment
- Strong correlation **angular distributions** $\leftrightarrow$ **photocouplings**: helps fixing them **experimentally**!
- Code and **interactive** website (own parameter choices) available at **www.indiana.edu/∼jpac/**

Outlook

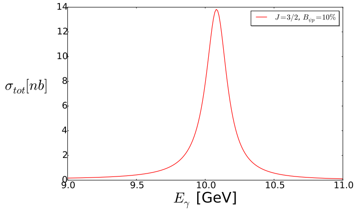
- Extension to J/ψ **electro**production (approved: JLab Hall A)
- To obtain **SDMs**: upgrade CLAS12 to **muon detection**

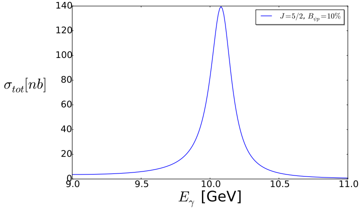
Additional material

Comparing with previous work



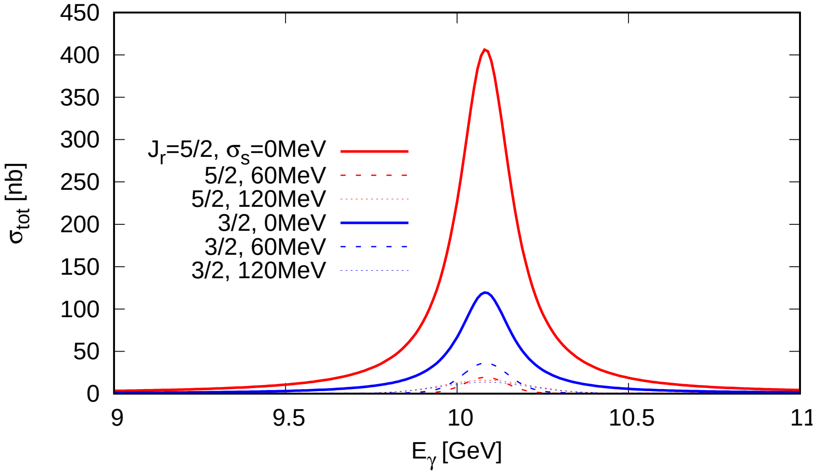
Karliner and Rosner, PLB 752 (2016) 329





For $\begin{cases} E_\gamma = E_r = 10.1 \text{ GeV} \\ \mathcal{B}_{\psi p} = 10\% \\ J = 3/2 \\ \text{no background} \end{cases}$ we reproduce $\sigma(\gamma\ p \to J/\psi\ p) \approx 14 \text{ nb}$

Integrated cross section in the different best-fit scenarios



Couplings and widths for the spin-3/2 case

J_r^P	$3/2^-$		
σ_s (MeV)	0	60	120
$\mathcal{B}_{\psi p}$	$\leq 29\%$	$\leq 30\%$	$\leq 23\%$
g (GeV)	≤ 2.1	≤ 2.2	≤ 1.9
Γ_γ (keV)	≤ 14.4	≤ 14.9	≤ 11.0
$A_{1/2,3/2}$ ($\mathrm{GeV}^{-1/2}$)	≤ 0.007	≤ 0.007	≤ 0.006
$\frac{\mathrm{d}\sigma}{\mathrm{d}t}\big\vert_{E_\gamma=E_r, t=t_{\mathrm{min}}}$ (nb GeV^{-2})	≤ 21.8	≤ 7.2	≤ 3.1
$\sigma_{\mathrm{tot}}\big\vert_{E_\gamma=E_r}$ (nb)	≤ 120	≤ 38	≤ 14

Couplings and widths for the spin-5/2 case

J_r^P	$5/2^+$		
σ_s (MeV)	0	60	120
$\mathcal{B}_{\psi p}$	$\leq 17\%$	$\leq 12\%$	$\leq 8\%$
g (GeV)	≤ 2.0	≤ 1.5	≤ 1.4
Γ_γ (keV)	≤ 56.9	≤ 33.5	≤ 26.8
$A_{1/2,3/2}$ ($\mathrm{GeV}^{-1/2}$)	≤ 0.017	≤ 0.013	≤ 0.012
$\frac{\mathrm{d}\sigma}{\mathrm{d}t}\big\vert_{E_\gamma=E_r,t=t_{\min}}$ (nb GeV^{-2})	≤ 95.8	≤ 11.3	≤ 3.9
$\sigma_{\text{tot}}\big\vert_{E_\gamma=E_r}$ (nb)	≤ 396	≤ 44	≤ 14

Branching ratio and fit results

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

We gave the first prediction for its upper limit!

σ_s (MeV)	0	60	120
A	$0.156^{+0.029}_{-0.020}$	$0.157^{+0.039}_{-0.021}$	$0.157^{+0.037}_{-0.022}$
α_0	$1.151^{+0.018}_{-0.020}$	$1.150^{+0.018}_{-0.026}$	$1.150^{+0.015}_{-0.023}$
α' (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})	$1.01^{+0.47}_{-0.29}$	$1.02^{+0.61}_{-0.32}$	$1.03^{+0.49}_{-0.31}$
$\mathcal{B}_{\psi p}$ (95% CL)	$\leq$ **29** %	$\leq$ **30** %	$\leq$ **23** %

Spin-3/2 case

Branching ratio and fit results

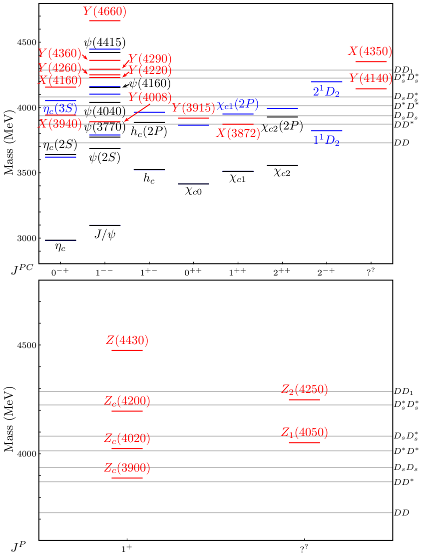
Branching ratio $P_c(4450) \to J/\psi p$ not yet known

We gave the first prediction for its upper limit!

σ_s (MeV)	0	60	120
A	$0.152^{+0.032}_{-0.024}$	$0.150^{+0.043}_{-0.034}$	$0.150^{+0.044}_{-0.041}$
α_0	$1.154^{+0.020}_{-0.020}$	$1.156^{+0.027}_{-0.028}$	$1.156^{+0.033}_{-0.028}$
α' (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})	$0.95^{+0.51}_{-0.51}$	$0.90^{+0.85}_{-0.65}$	$0.90^{+1.00}_{-0.69}$
$\mathcal{B}_{\psi p}$ (95% CL)	$\leq$ **17** %	$\leq$ **12** %	$\leq$ **8** %

Spin-5/2 case

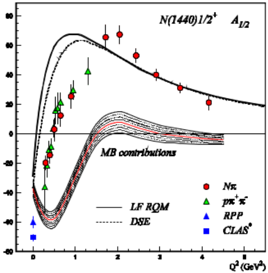
The meson sector: *XYZ*

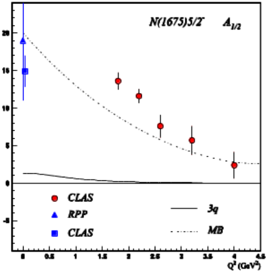


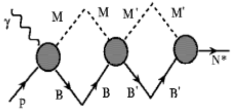
- Many unexpected structures decaying into $c\bar{c}$ + light $\Longrightarrow$ Hardly reconciled with quarkonium interpretation
  See talk by A. Pilloni

- 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 $\leftrightarrow$ **meson-baryon cloud** $(q\bar{q})(qqq)$
- Strongly dependent on N* quantum numbers
- **New direction:** $(q\bar{q})(qqq)$ quark **core**