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

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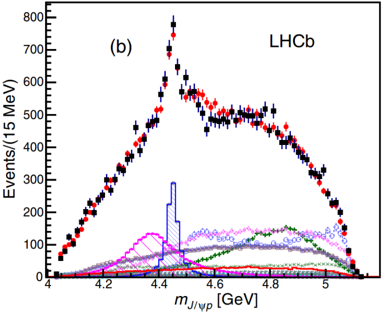
Pentaquark-like structure



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

- Favored spin-parity assignment for narrow structure $P_c(4450)$: $3/2^-$ or $5/2^+$
- Proposed as an excellent candidate for J/ψ **photoproduction** off a proton target

  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

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

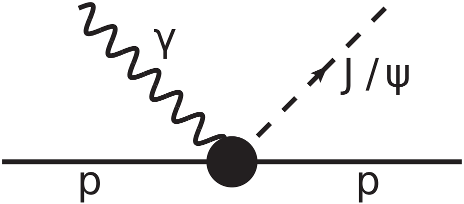
Anisovich et al., arXiv:1507.07652
Lebed, PLB 749 (2015) 454
Maiani et al., PLB 749 (2015) 289
...

- Meson-baryon molecules or bound states

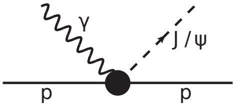
He, PLB 753 (2016) 547
Eides et al., PRD 93 (2016) 054039
Meißner and Oller, PLB 751 (2015) 59
Roca et al., PRD 92 (2015) 094003
Chen et al., PRL 115 (2015) 172001
...

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

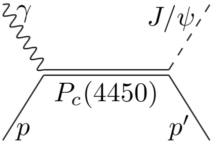
Reaction model

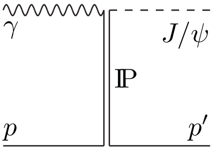


Reaction model



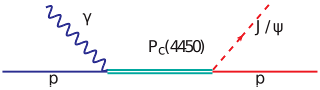
$$\frac{d\sigma}{d\cos\theta} \sim \sum_{\lambda_\gamma,\lambda_p,\lambda_\psi,\lambda_{p'}} \left| \langle \lambda_\psi \lambda_{p'} | \, T_r \, | \lambda_\gamma \lambda_p \rangle \right|^2$$





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

Breit-Wigner s-channel contribution: hadronic couplings

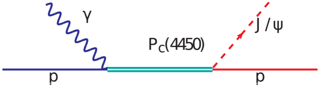


$$\langle \lambda_\psi \lambda_{p'} | \, T_r \, | \lambda_\gamma \lambda_p \rangle = \frac{\langle \lambda_r | \, T^\dagger_{\text{em}} \, | \lambda_\gamma \lambda_p \rangle \, \langle \lambda_\psi \lambda_{p'} | \, T_{\text{dec}} \, | \lambda_r \rangle}{M_r^2 - W^2 - \mathrm{i}\Gamma_r M_r}$$

- 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



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

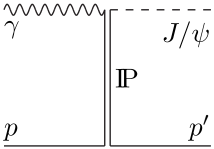
- Photocouplings $A_{1/2}, A_{3/2}$ estimated with VMD:

  Karliner and Rosner, PLB 752 (2016) 329

  - J/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



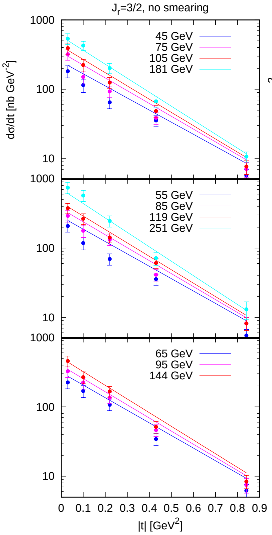
- Background described by Pomeron exchange

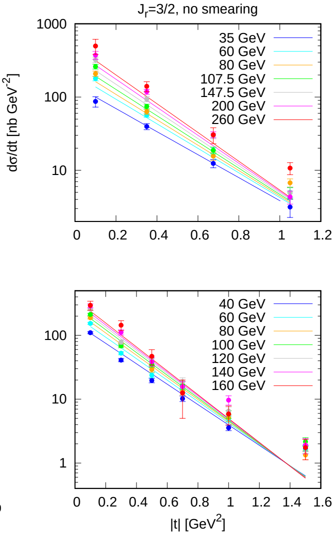
$$iA \left(\frac{s - s_t}{\mathrm{GeV}^2}\right)^{\alpha_0 + \alpha' t} e^{b_0(t - t_{\min})} \delta_{\lambda_p \lambda_{p'}} \delta_{\lambda_\psi \lambda_\gamma}$$

- 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. . .



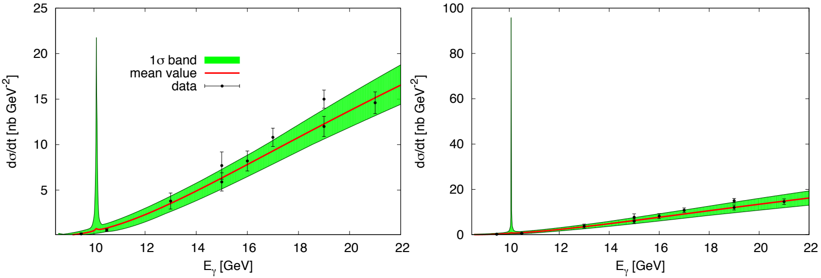


Chekanov et al. [ZEUS], EPJC 24 (2002) 345

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

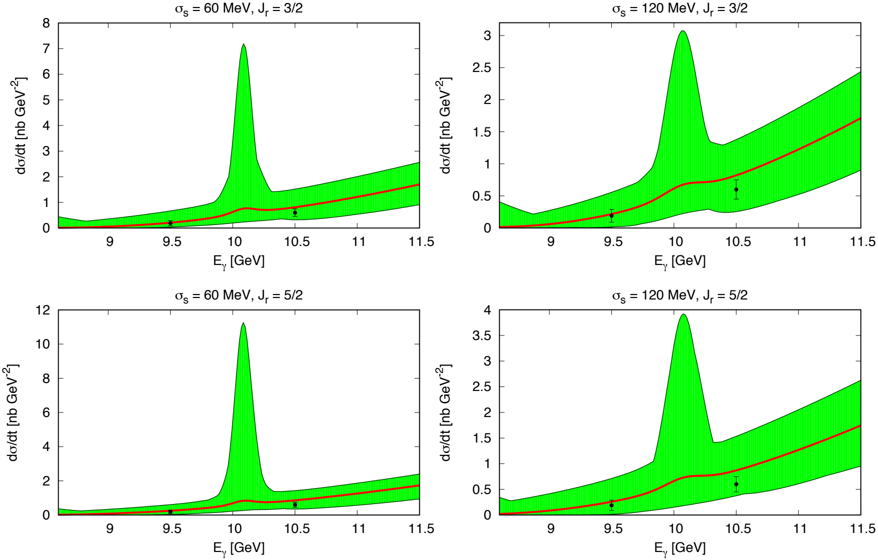
Two points closest to threshold: unpublished SLAC data

Ritson, AIPCP 30 (1976) 75; Anderson, SLAC-PUB-1741 (1976)

Relevant for the pentaquark peak!

First results: no smearing due to experimental resolution

Different smearing scenarios



Branching ratio

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** %

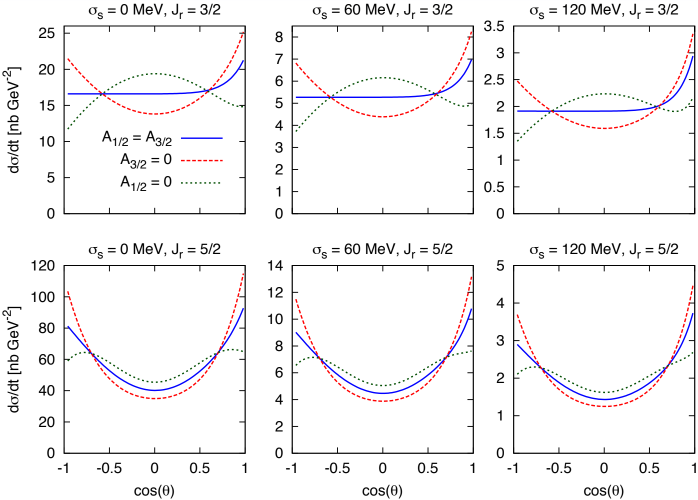
Studying angular distributions experimentally

- Data close to threshold:
  scarce and only for **forward angles**

- $\gamma\ p \to p\ J/\psi$ experiment:
  approved at JLab

- Study the **angular distribution** at the $P_c(4450)$ energy:
  excellent opportunity to fix the **photocouplings**!

Angular dependence of the differential cross section



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

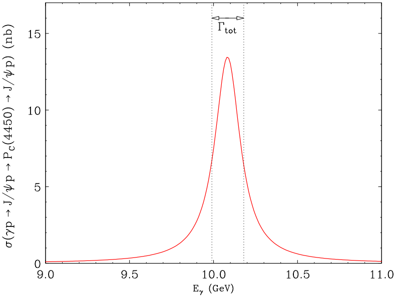
Angular behavior and choice of **photocouplings** strongly related!

Summary

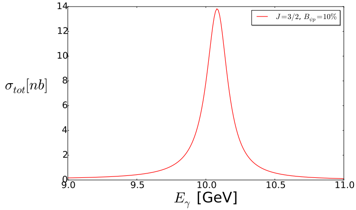
- The narrow resonance could have escaped detection until now
- $P_c(4450)$ in J/ψ **photoproduction** to **confirm** resonance: **JLab Hall C** experiment
- We estimate the upper limit of the **branching ratio**
- Strong correlation **angular distributions** $\leftrightarrow$ **photocouplings**: helps fixing them **experimentally**!

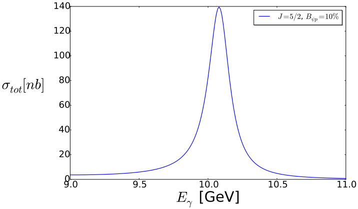
Additional material

Comparing with previous work



Karliner and Rosner, PLB 752 (2016) 329

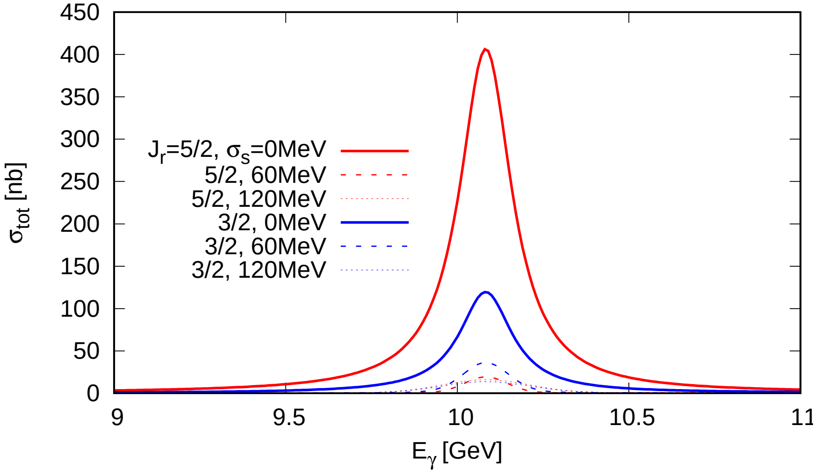




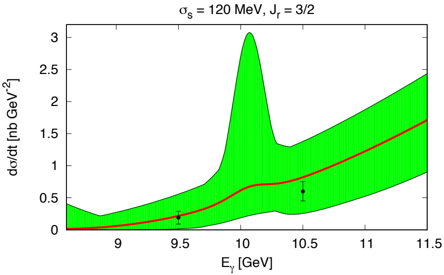
For
$$\begin{cases} E_\gamma = E_r = 10.1 \text{ GeV} \\ \mathcal{B}_{\psi p} = 10\% \\ J = 3/2 \\ \text{no background} \end{cases}$$

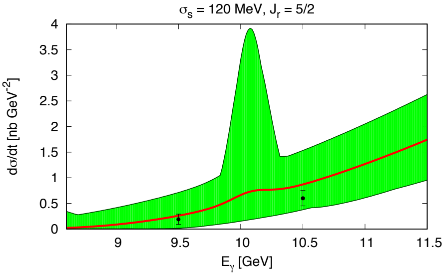
we reproduce $\sigma(\gamma\ p \to J/\psi\ p) \approx 14$ nb

Integrated cross section in the different best-fit scenarios



Different smearing and spin 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
$A_{1/2,3/2}$ (GeV$^{-1/2}$)	≤ 0.007	≤ 0.007	≤ 0.006
$\frac{d\sigma}{dt}\big\|_{E_\gamma=E_r,t=t_{\min}}$ (nb GeV^{-2})	≤ 21.8	≤ 7.2	≤ 3.1
$\sigma_{\text{tot}}\big\|_{E_\gamma=E_r}$ (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
$A_{1/2,3/2}$ (GeV$^{-1/2}$)	≤ 0.017	≤ 0.013	≤ 0.012
$\frac{d\sigma}{dt}\|_{E_\gamma=E_r,t=t_{\min}}$ (nb GeV^{-2})	≤ 95.8	≤ 11.3	≤ 3.9
$\sigma_{\text{tot}}\|_{E_\gamma=E_r}$ (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

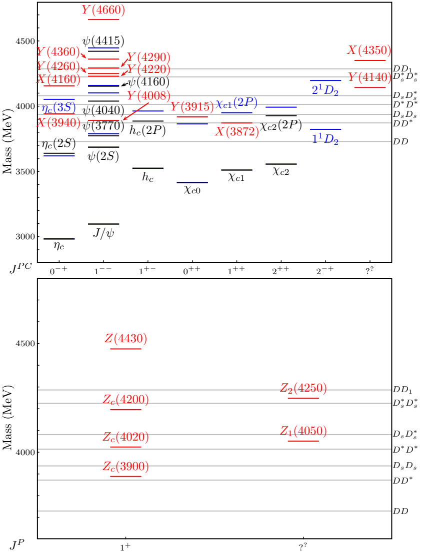
Branching ratio $P_c(4450) \to J/\psi p$ not yet known

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

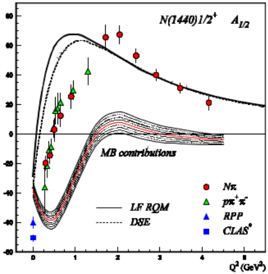


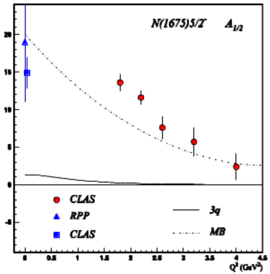
- Many unexpected structures decaying into $c\bar{c}$ + light
  $\Longrightarrow$ Hardly reconciled with quarkonium interpretation
  See talk by A. Pilloni

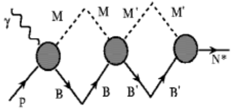
- It is not possible to explore $c\bar{c}q\bar{q}$ mesons at JLab
  But: $s\bar{s}q\bar{q}$ yes. $Y(2175)$,...

- Another bridge: assess $c\bar{c}qqq$ baryons, **pentaquarks**

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**