A Search for the LHCb Charmed "Pentaquark" using Photoproduction of J/Ψ at Threshold in Hall C at Jefferson Lab

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(A new experiment proposal to JLab-PAC44)

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Abstract

We propose to measure the photoproduction cross section of J/Ψ near threshold in search of the recently observed LHCb hidden-charm resonances $P_c(4380)$ and $P_c(4450)$ consistent with "pentaquarks." The observation of these resonances in photoproduction is important to differentiate the true resonance nature of the LHCb states from kinematics enhancements. The bremsstrahlung photon beam produced with an 11 GeV electron beam at CEBAF enables us to cover the energy range of J/Ψ production from the threshold photoproduction energy of 8.2 GeV to an energy beyond the presumed $P_c(4450)$ resonance production. The proposed experiment will be carried out in Hall C using a 50 μA incident electron beam current striking a 9% copper radiator that will produce a bremsstrahlung photon beam passing through a 15 cm liquid hydrogen target and producing J/Ψ's, either through a diffractive process in the t-channel or a resonant process through the s- and u-channel. The decay e^+e^- pairs of the J/Ψ's will be detected in coincidence using the two high momentum spectrometers of Hall C, namely the existing HMS and the newly built SHMS. The SHMS will be set at an angle of 13° with positive polarity to detect positrons while the HMS will be set at 34.5° in order to detect the corresponding electrons of these pairs. These settings were optimized to distinguish the resonance s- and u-channel production from its diffractive t-channel production of the J/Ψ. Compared to the t-channel production of the J/Ψ, the s- and u-channel production of the charmed 5-quark resonance appears to dominate the t distribution at large t. Furthermore, the momentum and angular resolution of the spectrometers allow the reconstruction of the photon energy with a resolution sufficient to observe a clear resonant enhancement in the total cross section as shown in the projected results. This setup is also optimized to minimize the absolute rate of leptons in both spectrometers and thus the rate of accidental coincidences between the two spectrometers. We request a total of 10 days of beam time with 9 days to carry the bulk of the proposed experiment and 2 days to acquire the needed t-channel elastic J/Ψ production data for a calibration measurement.

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1 Introduction and motivation

Photoproduction of J/Ψ on a nucleon very close to threshold is an important subject in the field of non-perturbative QCD in its own right and is already planned to be investigated at Jefferson Lab as the 12 GeV upgrade of CEBAF is completed [1, 2]. Oddly enough the potential of discovery of hidden charm baryon resonances via photoproduction was discussed in 2014 [3] inspired in part by the SoLID-J/Ψ approved proposal at Jefferson Lab [2]. However, CERN's recent experimental discovery [4] has spurred a new excitement and a sense of urgency to carry on measurements of photoproduction at threshold in a timely manner.

Less than a year ago, on July 14, 2015, a press release from the CERN press office announced the observation of exotic pentaquark particles [4] just a day after the manuscript describing the discovery was posted on the arXiv.org [5] website by the collaboration. A month later, on August 12, 2015 the announcement was followed by the publication of the manuscript describing the discovery in Physical Review Letters [6]. This announcement was received with both excitement and a healthy dose of skepticism due to the early saga of "pentaquarks," in the beginning of the new millennium, which proved inconclusive. Unlike these earlier announced pentaquarks, which consisted of four light quarks and one strange quark, the resonant state observed by the LHCb includes two heavy quarks, namely charm and anti-charm quarks and three light quarks and thus must be different in nature.

Subsequent to the announcement a series of theoretical papers [7, 8, 9, 10] appeared in the literature with possible interpretations of the observed resonance. A range of explanations was invoked, from a possible true pentaquark resonant state to a kinematic enhancement like those observed in other experiments close to kinematic thresholds [11] including a bound state of charmonium($2S$) and the proton [10] and a molecule composed of Σ_c and $\bar{D}^*$ [12, 13]. But without further experimental measurements it is not clear whether the formed exotic resonance can be unambiguously identified as a resonance. Some authors suggested that effects of final state interactions are responsible for the LHCb observed rate enhancements [14]. While the interest of the theory community has produced more than 200 citations up to date, LHCb is the only experiment that has observed these states. The hadronic physics community is eager to see these possible resonant states confirmed in more than one experiment and proceed with a detailed investigation of the quantum numbers of such states.

In summary, to resolve the true nature of the $P_c^+(4380)$ and $P_c^+(4450)$ states it is proposed to study these pentaquark candidates in direct photoproduction of J/Ψ on the proton and provide not only further evidence of their existence but also investigate their spin and parity, as noted in several papers among them [7, 8]. This proposal is more specifically about a direct search of the higher mass narrow width $P_c^+(4450)$ and follows Wang et al. [7] using the different spins and parity described in the paper but with the less optimistic assumptions about the coupling to the resonant states during our complete simulations, namely a 5% coupling.

We believe that its confirmation at Jefferson Lab will have a high impact on the broader physics community.

1.1 Present data status

The photoproduction of J/Ψ has been measured in many experiments at high invariant mass of the photon-nucleon system at HERA and LHCb more recently [15, 16, 17]. The total elastic

J/Ψ production at high photon-nucleon invariant mass $W_{\gamma p}$ is well described by the t-channel exchange of a colorless object between the photon and the proton [18], in this case two-gluon exchange. The differential cross section in the proton momentum transfer variable t is usually described by $d\sigma/dt \propto e^{bt}$ with a value of b that depends on $W_{\gamma p}$. As $W_{\gamma p}$ decreases towards the threshold region of J/Ψ production, the mechanism is described by a Pomeron exchange or two-gluon exchange [19] or perhaps a more complicated multi-gluon exchange carrying the non-perturbative information of the gluonic fields in the nucleon. The new LHCb resonance happens to be in this threshold region of invariant mass, a region that has been poorly explored in modern times. It is worth pointing out that the few measurements of this region occurred in the 1970s at Cornell and SLAC and in the 80s at Fermilab. In those experiments, issues of unambiguously defining the elastic process of J/Ψ production were hampered in some cases by the use of nuclear targets, detector resolution and the detection of one lepton only in the case of the J/Ψ pair decay.

In Hall C at Jefferson Lab, a photoproduction experiment (E03-008) was performed in the *subthreshold* regime, but unfortunately no signal was observed after one week of beam scattering off a ^{12}C target [20]. The experiment used a bremsstrahlung beam produced in a copper radiator by the 6 GeV incident electron beam at CEBAF. The pair of spectrometers (HMS and SOS) of Hall C were used to detect the pair of leptons resulting from the decay of the J/Ψ.This experiment allowed an upper limit to be set on the cross section which was found to be consistent with the quasi-free production. More recently a proposal [21] for the 12 GeV upgrade of Hall C was considered by the PAC and conditionally approved. The authors proposed again the use of bremsstrahlung photon beam created in a radiator to look at the photoproduction at threshold in a series of nuclei. The physics goal was to measure the photoproduction cross section in order to investigate the A-dependence of the propagation of the J/Ψ in the nuclear medium as well as extract the $J/\Psi - N$ interaction. In the latter proposal, the J/Ψ decay pair was to be detected by the HMS and SHMS similar to what is proposed here, however the optimization of the spectrometer settings was related to enhancing the rate of pairs detected from J/Ψ decays in primarily diffractive J/Ψ production off nuclei, no resonant production was considered. In summary, the near threshold region of elastic J/Ψ production has yet to be fully explored in the context of understanding the non-perturbative gluonic J/Ψ-nucleon interaction. At Jefferson Lab there are approved proposals to measure this region using the CLAS12 detector in Hall B [1] and the SoLID detector in Hall A [2]. In this proposal our focus is to confirm the observation of LHCb through a resonant production of the $P_c(4450)$ in the s- and u-channel.

2 The Proposed measurement in Hall C at Jefferson Lab

We propose to measure the elastic J/Ψ photoproduction cross section as a function of t and photon energy E_γ in the near threshold region in Hall C. A bremsstrahlung photon beam will be created using a 9% copper radiator in front of a liquid hydrogen target as described in reference [30]. Both high momentum spectrometers of Hall C along with their associated detectors will be used to detect the di-lepton pair decay, namely e^+e^-. The photon beam mixed with the primary electron beam will strike a 15 cm liquid hydrogen target. The electron-positron decay pair will be detected in coincidence between the high momentum spectrometer (HMS) set for electron detection and the super-high momentum spectrometer (SHMS) set for positron

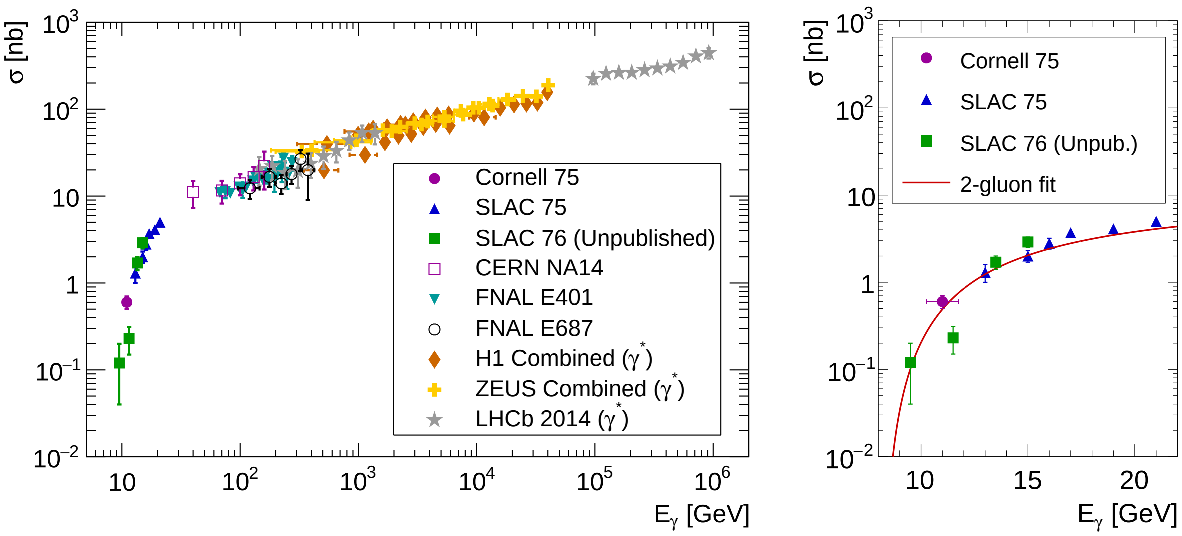

Figure 1: Compilation of world data for the electro- and photo-production of elastic J/Ψ is shown in the left panel. Legend in the figure with γ^* refer to electro-production data where we used an effective photon energy definition for the virtual photon. The right panel zooms in on the region of interest near the J/Ψ production threshold. The red curve on the right figure is the result of a 2-gluon fit. Cornell data form [22], SLAC data from [23, 24], CERN NA14 data from [25], FNAL data from [26, 27], H1 data from [28, 16], ZEUS data from [29] and LHCb data from [17].

detection. The proposed measurement is designed to search for the highest mass narrow exotic resonant state discovered at LHCb, namely the $P_c(4450)$. The spectrometer settings are optimized to be most sensitive to the possible resonant production of $P_c(4450)$ in the s- and u-channel. The two spectrometers will detect the J/Ψ decay into e^+e^- from either the diffractive channel or resonant P_c channel production. However, we will take advantage of the different t-dependence of the two processes to optimize the spectrometers' angle and momentum settings to enhance the $P_c(4450)$ signal relative to that of the t-channel production.

2.1 The Experiment in Hall C

The layout of the proposed experiment is shown in Fig. 2 where the HMS is set at an angle of 34° to detect the electrons of the e^+e^- decay pairs while the SHMS is set at angle of 13° to detect the corresponding positrons. This configuration has been optimized to reduce the accidental coincidences between the two spectrometers as well as minimize the absolute background in each spectrometer. Part of the momentum acceptance of the spectrometer will allow for the detection of the Bethe-Heitler process in a kinematic region forbidden to the diffractive or resonant production of J/Ψ. The HMS is chosen to detect electrons because the inclusive inelastic electron scattering cross section drops rapidly with increasing scattering angle. On the other hand the SHMS would have a very large rate of inclusive electron scattering if it were to be used to detect electrons at the small angle setting of 13°. It is thus run in positive polarity

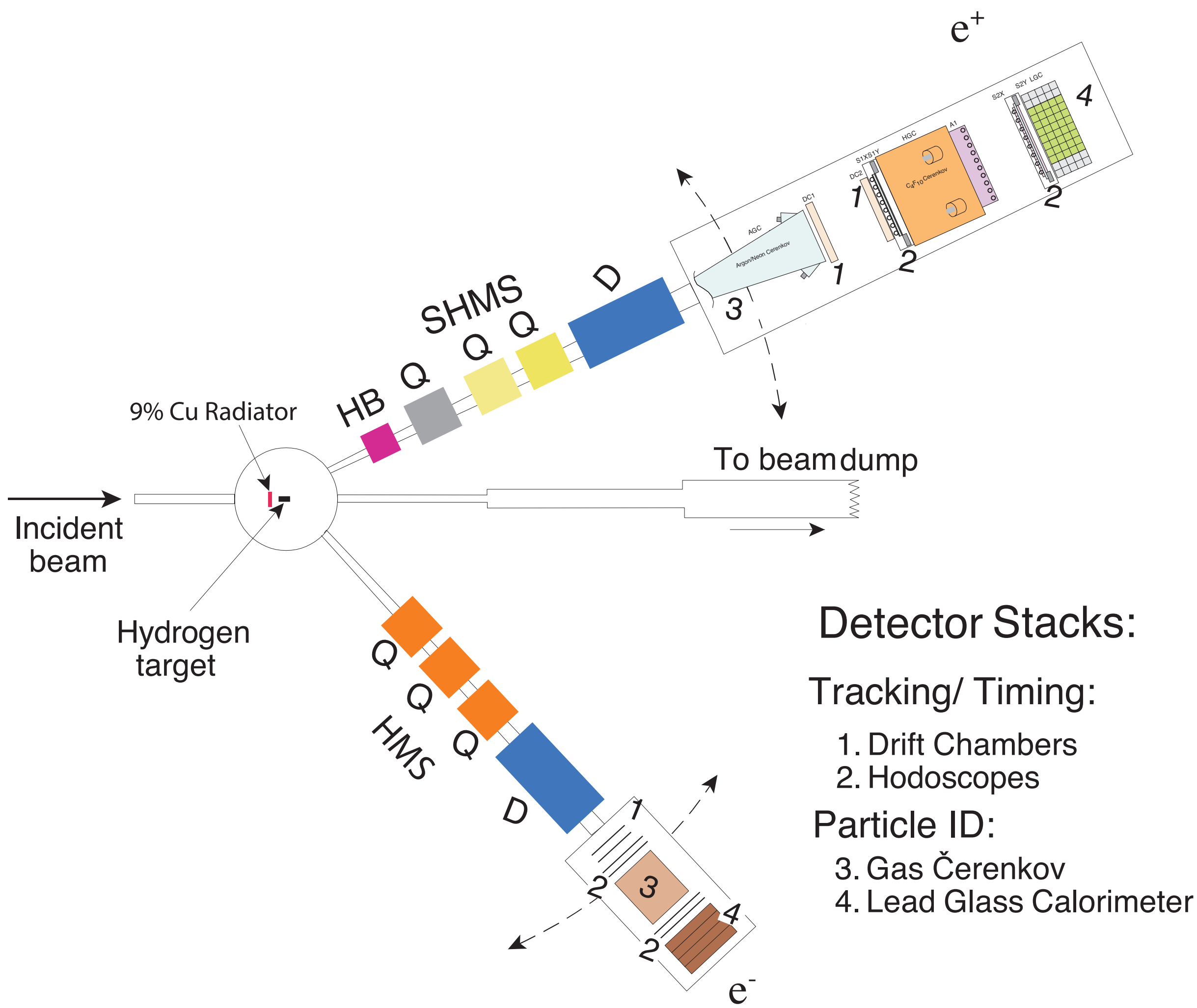

Figure 2: The experimental layout of the HMS (for e^- detection) and SHMS (for e^+ detection) and associated detectors combined with a liquid 15 cm hydrogen target and a 9% copper radiator. We will detect the J/Ψ decay e^+e^- pair in coincidence between the two spectrometers. From the scattering angle and momentum determination of the lepton pairs, we are able to reconstruct the invariant mass of the J/Ψ as well as its three-momentum. From this information the four-momentum transfer to the proton t is calculated and the real photon energy E_γ is determined.

to detect positrons but it will also accept positive pions and protons.

Each spectrometer has a similar set of standard detectors to identify electrons/positrons and reject charged pions and protons. In each case the momentum of the particles is provided through tracking by a set of drift chambers, and electron identification is ensured by a light gas Čerenkov counter and an electromagnetic calorimeter. The trigger in each spectrometer is defined by a coincidence between a set of 2 hodoscope scintillator planes along the path of the particles. These configurations offer an electron or positron detection efficiency greater than 98% and a pion rejection factor of about a thousand. The timing resolution online will be defined by the time coincidence between the hodoscopes in each spectrometer first and then a time coincidence between both spectrometers. We expect it to be on the range of nanoseconds, however improvements will be possible when the tracking information is corrected for offline.

Table 1: Kinematic setting of the HMS and SHMS spectrometers to measure in coincidence the decay-pair of the J/Ψ. The main spectrometer setting (1) is optimized to measure the $P_c(4450)$ with minimal background, while the additional setting (2) is chosen to allow for a precise determination of the t-channel background left of the $P_c(4450)$ resonance.

	HMS		SHMS		Acceptance	
	p	θ	p	θ	t-channel	$P_c(4450)$
setting	GeV/c		GeV/c		%	%
(1)	3.25	34.5°	4.5	13.0°	0.0004	0.003
(2)	4.75	20.0°	4.25	20.0°	0.01	0.003

We point out that if the electron beam energy is 10.7 GeV rather than 11 GeV with the same settings of the spectrometers will result in a more suppressed t channel production and should not affect the s and u channel $P_c(4450)$ production.

2.2 Kinematics

The kinematics were optimized using a full simulation of the experiment and focused on enhancing the resonant production of J/Ψ through the $P_c(4450)$ relative to the diffractive production. This is done by taking advantage of the t-dependence of the diffractive production since the latter is suppressed at large values of t while the resonant production in the s-channel of P_c is rather flat across the same t range. The spectrometer settings are chosen to take advantage of this difference in t-dependence. In Table 1 we list the spectrometers' momentum and angle settings converged upon and the resulting acceptance for a coincident detection of the di-lepton pair. Also shown is the additional spectrometer setting needed for a precise determination of the t-channel background left of the $P_c(4450)$ peak.

Shown in Fig. 4 left and right are the distributions of angle versus momentum of the decay pair of leptons, the full correlated phase space of the t-channel production of the pair is shown on the left figure while the similar phase space of the resonant P_c production is shown on the right.

It is important to take into account the different possibilities of spin of the exotic charmed resonance. In all cases we found that it is best to keep the kinematics that correspond to $\cos\theta$

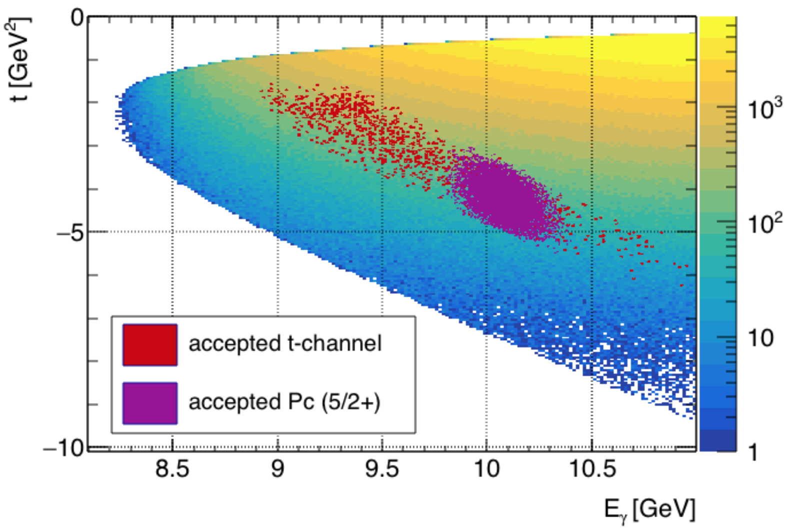

Figure 3: Full phase space of the t channel elastic J/Ψ production with the acceptance rate shown. The variable t versus incoming photon energy E_γ is plotted. The kinematic setting (# 1) for this experiment with the accepted t channel events (red) and the $P_c(4450)-5/2+$ (purple) resonant state events.

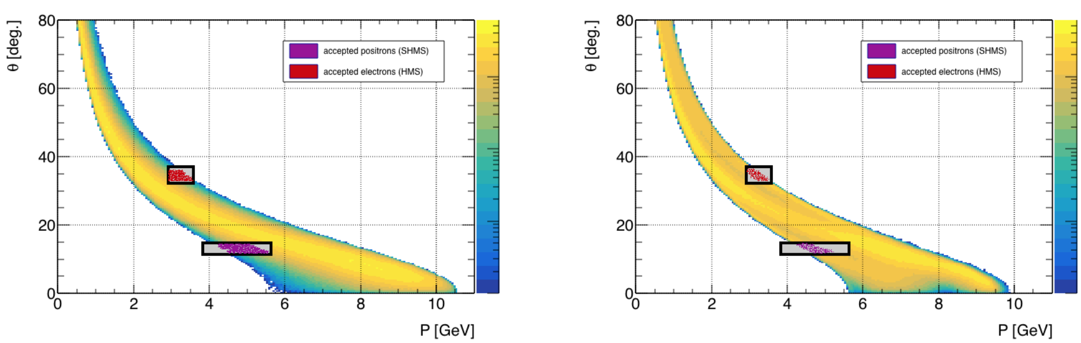

Figure 4: Results from the spectrometer optimization to select the high-t region where the t-channel production is highly suppressed compared to the P_c production rate. See also Fig. 5

between -0.4 and 0.2 as shown in Fig. 5, in other words close to the 90° range in the center of mass in order to maximize the P_c production rate relative to the t-channel production.

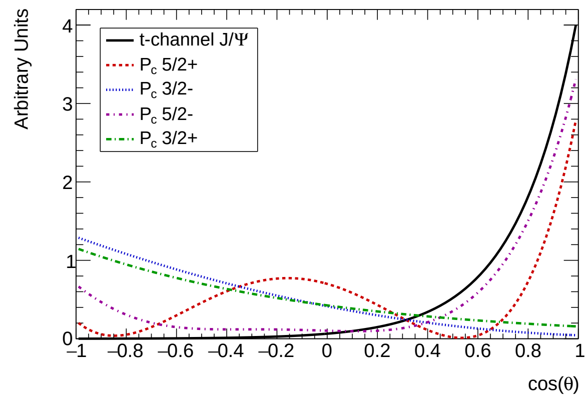

Figure 5: Angular distribution of the J/Ψ production for the t-channel, normalized to the same area for each curve in arbitrary units, in comparison with the J/Ψ production through the exotic P_c resonant state with various possible spin/parity assumptions. Note that, for the t-channel this is directly related to the t-dependence of the cross section.

3 Physics and accidental backgrounds

The typical process of elastic J/Ψ production is usually described by a Feynman diagram represented in Fig. 6 and is well understood at high energies using perturbation theory [31]. This process at threshold is usually described by a two-gluon exchange [19, 18] although at threshold the gluons could be an effective representation of an interaction that conserves color but is much more complicated. A full experimental physics program to explore the threshold region of J/Ψ production completely is planned by gathering large amount of data through electroproduction and photoproduction using CLAS12 and SoLID detectors in the coming years.

3.1 Production of e^+e^- through elastic J/Ψ production and decay

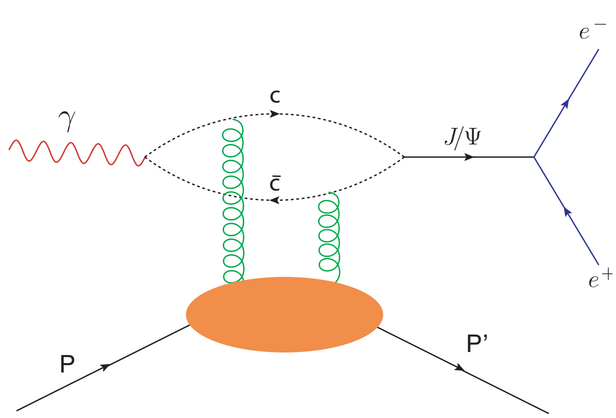

Figure 6: t-channel 2-gluon exchange elastic J/Ψ photoproduction mechanism.

In the proposed experiment we are not concerned with the elastic t-channel production of J/Ψ, which we consider to be a physics background, but are rather interested in confirming the possible resonance production of the J/Ψ through the decay of the newly discovered states at LHCb, namely $P_c(4450)$ and $P_c(4380)$. This production is typically described by an s- and u-channel production of these resonances according to the diagrams of Fig. 7. More specifically it is $P_c(4450)$ that we are focused on in this proposal. $P_c(4380)$ is broader with less coupling strength and thus requires a more challenging setup to be determined cleanly.

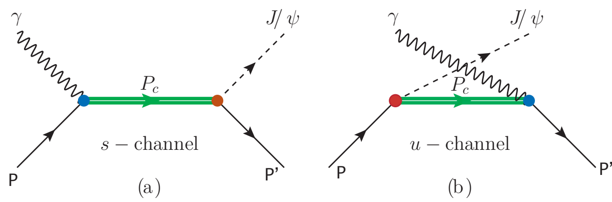

Figure 7: $s-$ (a) and $u-$ (b) channel resonant production of J/Ψ through P_c.

Therefore, in this experiment the challenge is to separate the two different processes, one that we consider to be a physics background (t-channel production of J/Ψ) and one that is our important signal (s- and u-channel resonant production through P_c).

3.2 Bethe-Heitler pair production

To evaluate the Bethe-Heitler background represented by the processes described in Fig. 8 we used the calculations of Pauk and Vanderhaeghen [32, 33] but with $M_{l^+l^-}$ evaluated within the acceptance of our spectrometer settings centered around the mass of $P_c(4450)$. We use the dipole electromagnetic form factor for the range of momentum transfers covering the proposed experiment. We find that this background is over 10 times smaller as shown in Fig. 9, nevertheless it can be calculated and subtracted.

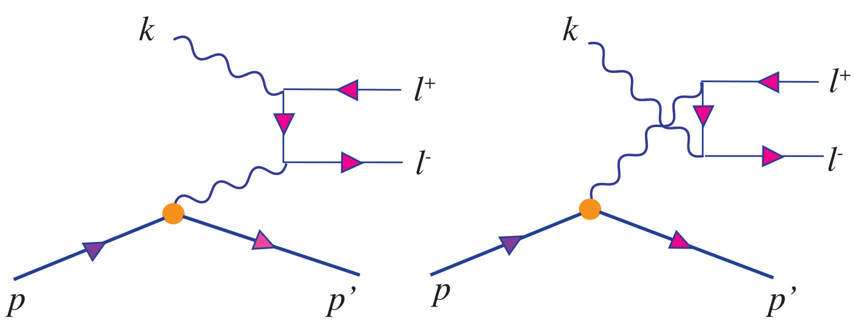

Figure 8: Bethe-Heitler (BH) mechanism producing a background process to the t-channel and P_c resonant production.

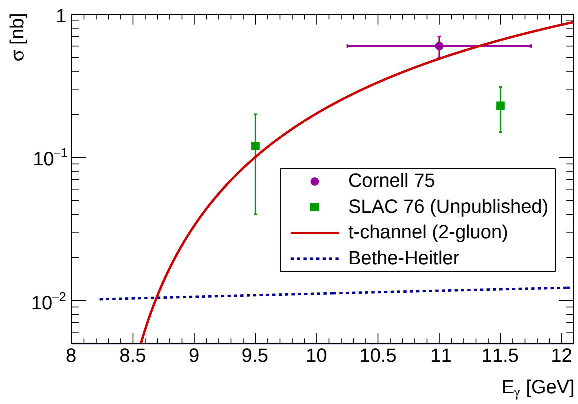

Figure 9: B-H rate relative to the elastic J/Ψ production in the t channel.

3.3 Accidental e^+e^- background

The electron rate in the HMS was estimated using the F1F209 program [34] and found to be about 30Hz. The positron rate in the SHMS was estimated using the EPC program combined with a positron background program calibrated on the JLab 6 GeV and SLAC inclusive measurements. The accidental e^+e^- coincidence rate between the HMS and the SHMS was found to be negligible.

4 Simulation of the experiment

We use a custom Monte-Carlo generator to obtain a realistic estimate of the J/Ψ photoproduction rates. This generator uses the bremsstrahlung spectrum for a 10% radiator, appropriate models for the t-channel and P_c resonant channel, and the HMS and SHMS spectrometer acceptance with realistic smearing effects. The the leptonic $J/\Psi \to e^+e^-$ decay is simulated using a $(1 + cos^2\theta_e)$ angular distribution in the J/Ψ helicity frame. More details about the simulation can be found below.

4.1 Model for the t-channel cross section

In order to calculate the cross section for the t-channel production, we fit the cross section ansatz for two gluon exchange from Brodksy et al. [19] (equation (3)) to the available world data. The result of this fit (in nb/GeV^2) is given by,

$$\frac{d\sigma}{dt} = Av\frac{(1-x)^2}{M^2_{J/\Psi}}(s - M_p^2)^2 \exp bt, \tag{1}$$

where x is given by a near-treshold definition of the fractional momentum carried by the valence quark, v is a kinematic factor, b the impact parameter and A an overal normalization constant that was determined by a fit to the world data,

$$x = \frac{2M_p^2 + M_{J/\Psi}^2}{s - M_p^2} \tag{2}$$

$$v = \frac{1}{16\pi(s - M_p^2)^2} \tag{3}$$

$$b = 1.13\,\mathrm{GeV}^{-2}, \tag{4}$$

$$A = 6.499 \times 10^3\,\mathrm{nb}. \tag{5}$$

Additionally, M_p and $M_{J/\Psi}$ are resp. the proton mass and J/Ψ mass in GeV. The curve from Eq. 1 is shown as a red line in Figures 1 and 10.

4.2 Model for the $P_c \to J/\Psi p$ cross section

We based our model of the $\gamma p \to P_c \to J/\Psi p$ cross section on the work by Wang et al. [7]. Note that this cross section depends quadratically on the coupling to the $J/\Psi p$ channel. We considered the (5/2+) and (5/2-) spin/parity assumptions for the narrow $P_c(4450)$ state, with the corresponding (3/2-) and (3/2+) assumption for the $P_c(4380)$ state. The angular distribution for the J/Ψ production for each of the spin-parity assumptions can be found in Fig. 5. The contributions of the (5/2+,3/2-) channels to the J/Ψ photoproduction cross section as a function of photon energy E_γ are shown in Fig. 10.

We optimized the spectrometer settings for a (5/2+) $P_c(4450)$ case with 5% coupling to the $J/\Psi p$ channel, as it agrees well with the existing photoproduction data. This setting, also has a good sensitivity to a (5/2-) $P_c(4450)$ as its production cross section is a full order of magnitude larger. To perform this optimization, a total of 3.4 million possible spectrometer settings were considered. We selected a setting that maximizes the acceptance for J/Ψ produced with a $\cos\theta$ between -0.4 and 0.2% in the center-of-mass frame, as shown in Fig.5. This corresponds to a setting that selects the high-t region, where there is a maximum sensitivity to the (5/2+) $P_c(4450)$ resonant production, while simultaneously the sensitivity to the t-channel J/Ψ production is highly suppressed. This setting is listed on the first line of Table 1.

4.3 Bremsstrahlung spectrum

The generator uses equation (24) from Tsai [35] to evaluate for the bremsstrahlung spectrum. For a 10% radiator, the photon beam has an integrated intensity of 2.3% of the primary electron beam.

4.4 Detector acceptance and resolution

The spectrometer acceptance and realistic smearing are simulated using the parameters listed in Table 2. An e^+e^- invariant mass spectrum that was generated using the optimized setting listed on the first line of Table 1 can be found in Figure 11. The reconstructed J/Ψ mass resolution is 12 MeV.

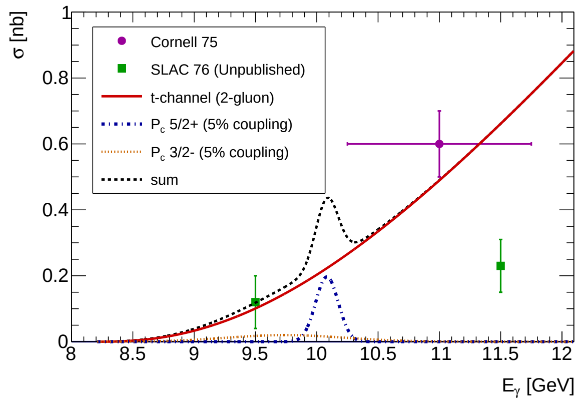

Figure 10: J/Ψ production cross section as a function of the photon energy. The P_c resonant production is shown for the (5/2+,3/2-) case assuming 5% coupling, compared with the available measurements in this region [22, 24].

5 Projected results

In this section we describe the results of our simulation and the expected results for 9 days of beam on target. As shown in Fig. 12 and Fig. 13 the results, while limited in statistics, clearly reveal the resonant structure of the pentaquark assuming a 5% coupling. In case of a larger coupling, the projected yields become much larger, as the cross section is proportional to the coupling squared [7].

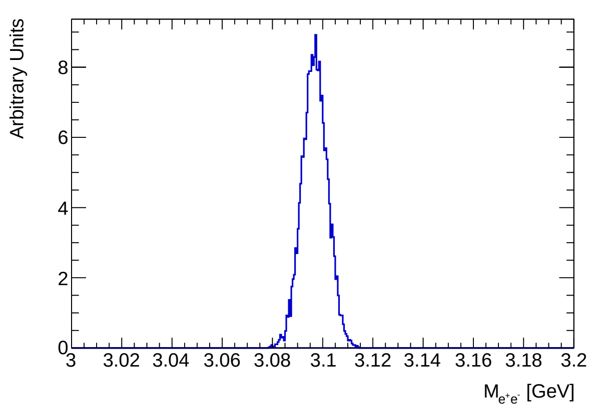

Figure 11: Invariant mass of the detected lepton pair with realistic smearing. The full width at half maximum of the spectrum is 12 MeV.

Table 2: Properties of the Hall C spectrometers.

	P GeV/c	$\Delta P/P$	$\sigma P/P$	$\theta^{\rm in}$	$\Delta\theta^{\rm in}$ mrad	$\Delta\theta^{\rm out}$ mrad	$\Delta\Omega$ msr	$\sigma\theta^{\rm in}$ mrad	$\sigma\theta^{\rm out}$ mrad
HMS	0.4-7.4	-10 +10%	0.1%	10.5°-90°	±24	±70	8	0.8	1.0
SHMS	2.5-11.	-15 +25%	0.1%	5.5°-25°	±20	±50	4	1.0	1.0

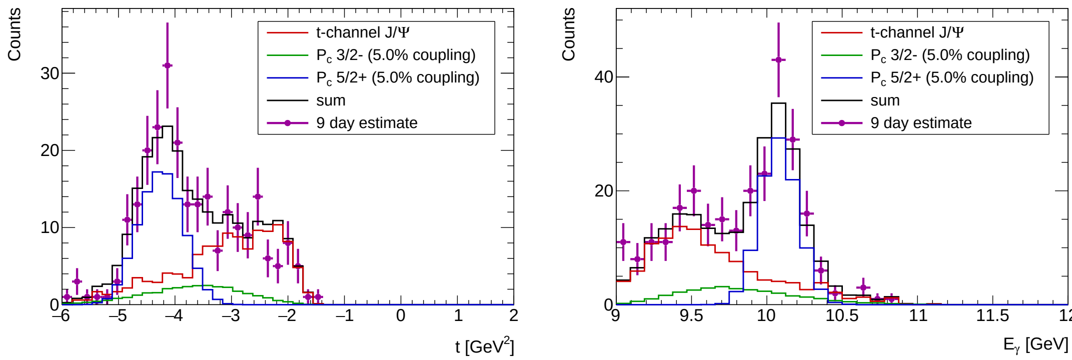

Figure 12: Expected results for the reconstructed t and E_γ spectrum for 9 days of beam on target, assuming the most probable (5/2+, 3/2-) P_c from [7] with 5% coupling. There is clear separation in both spectra between the P_c (5/2+) resonant channel, and the t-channel.

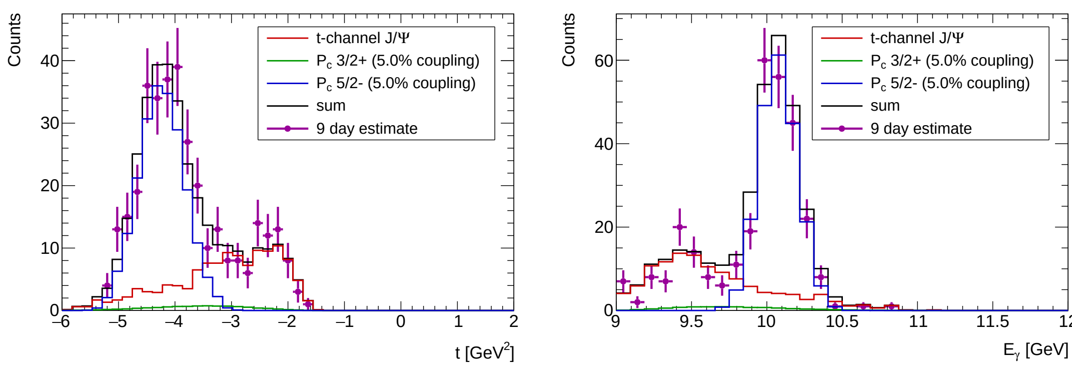

Figure 13: Expected results for the reconstructed t and E_γ spectrum for 9 days of beam on target, assuming the less probable (5/2-, 3/2+) P_c from [7] with 5% coupling. Due to the larger cross section for the 5/2-, the separation in both spectra is even better than for the 5/2+ assumption shown in Fig. 12.

The projected results from the calibration measurement of the t-channel background to the P_c for 1 day of beam on target can be found in Fig. 14. This calibration measurement will provide us with the required knowledge of the t-channel J/Ψ photoproduction near threshold, where currently no world data exist.

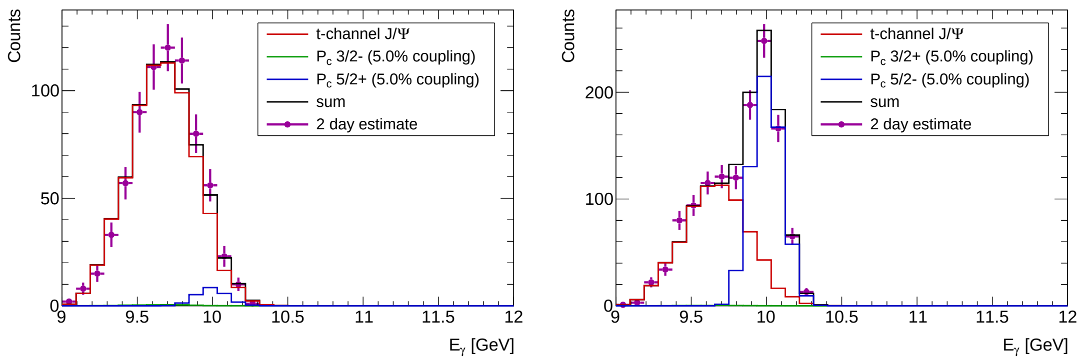

Figure 14: Expected results for the reconstructed E_γ spectrum for the calibration measurement with 1 day of beam on target. The left panel shows the (5/2+, 3/2-) case , and the right panel shows the (5/2-, 3/2+) case, both with 5% coupling.

6 Run plan and beam request

We propose to carry the measurement of elastic photoproduction of J/Ψ in the threshold region with the aim to confirm the LHCb $P_c(4450)$ discovery. The experiment uses the standard equipment of the upgraded Hall C standard apparatus at Jefferson Lab. We request 11 days of beam time where 9 days will be used to collect the data at one fixed setting, namely setting (# 1 in Table 1)) of the spectrometers and provide for the projected results described in the section 5. Accidental coincidences between the two spectrometers will be measured at the same setting and the same time in the momentum acceptance of the spectrometers outside the true physics events. Two days of data taking will focus on measuring the shape of the t distribution with high statistics by using setting (# 2, in Table 1) to maximize the combined acceptance for this process.

We request 11 days to perform this high-impact measurement.

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