
Near threshold J/ψ photo-production

S. Stepanyan (JLAB)

SoLID collaboration meeting

June 29 - 30, 2017, JLAB



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Jefferson Lab
Thomas Jefferson National Accelerator Facility

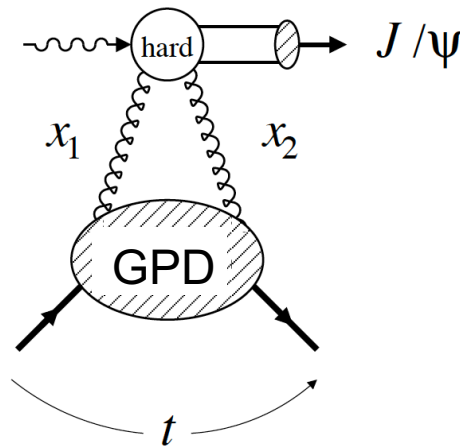


- Why J/ψ photoproduction near threshold
- J/ψ -N interactions
 - Proton mass
 - J/ψ -nucleon s-wave scattering length
- LHCb (J/ψ p) pentaquarks
- JLAB12 – a new energy regime
- Expectations from JLAB experiments
- Summary

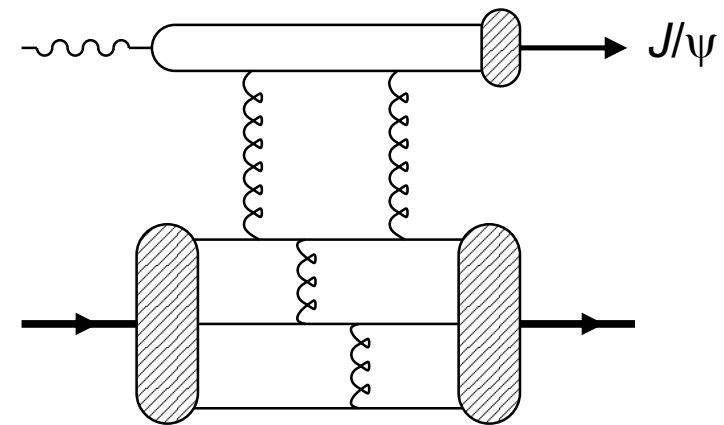


Why study J/ψ photoproduction?

- Allows effectively to study J/ψ -N scattering
- Probes gluon field of the target

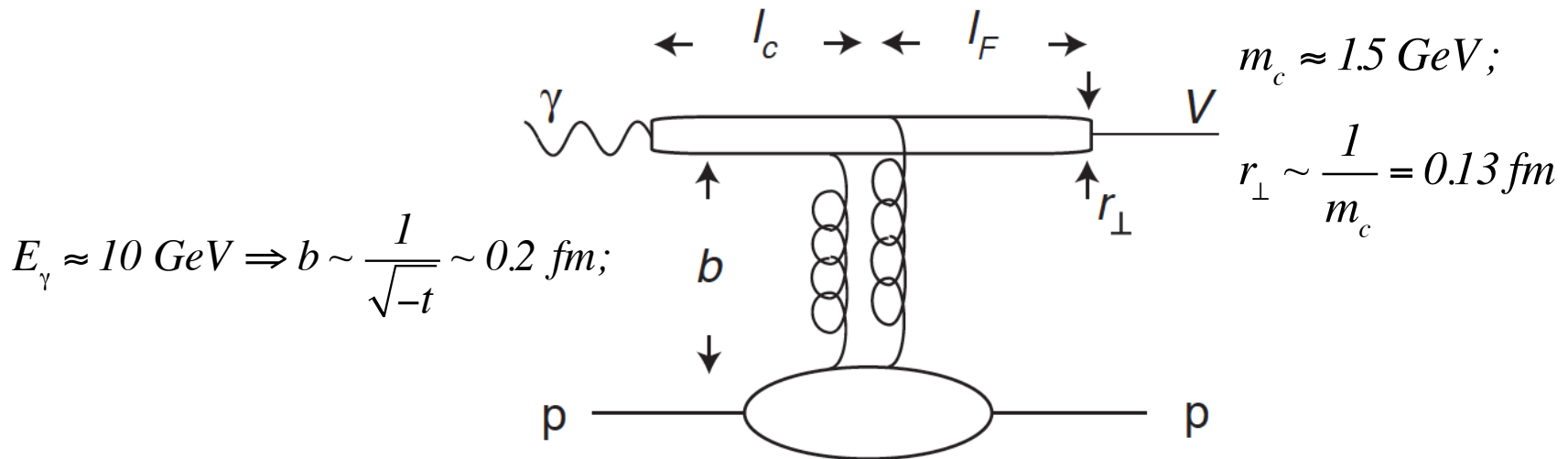


At high energies (HERA, FNAL) probes gluon GPDs. Considerable amount of data at $W > 10$ GeV, in good agreement with 2-gluon exchange mechanism



Near threshold (large momentum transferred) probes gluonic form factor. No data below $E_\gamma = 11$ GeV, enhancement near threshold is expected due to multi-gluon exchange

VDM picture of the production



$$E_\gamma \approx 10 \text{ GeV} \Rightarrow l_c = \frac{2E_\gamma}{4m_c^2} \approx 0.4 \text{ fm}; \quad l_F \approx \frac{2E_{J/\psi}}{2m_c(m_{\psi'} - m_{J/\psi})} \sim 1 - 2 \text{ fm};$$

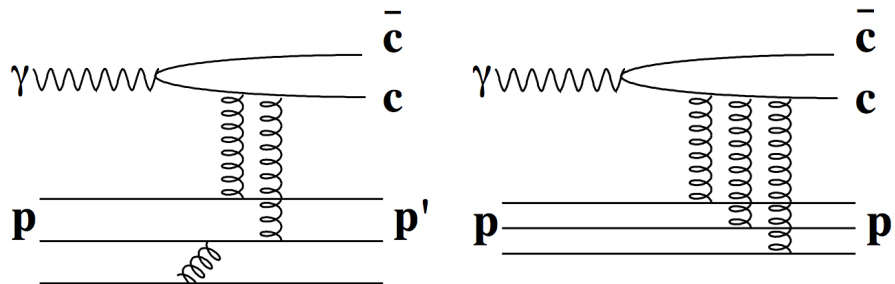
Favorable kinematics for studying

- production mechanism near threshold
- nucleons' local gluon field distribution, $b, r \ll 1 \text{ fm}$
- $J/\psi N$ scattering, l_c and $l_F \sim \text{fm}$



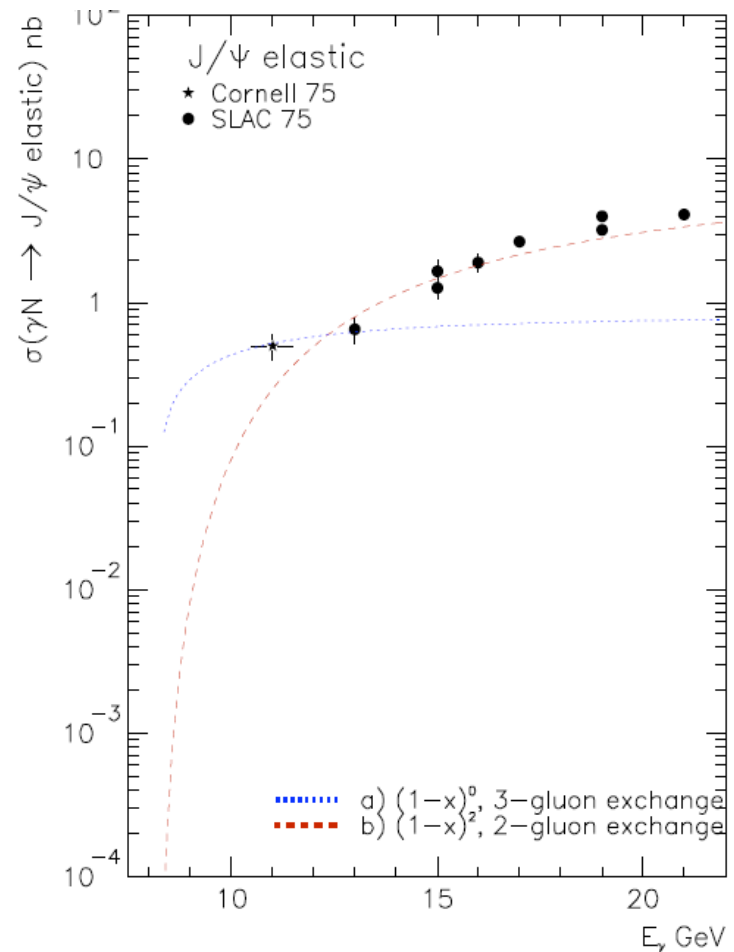
J/ψ photoproduction near threshold

- The lowest published energy point is at $E_\gamma = 11$ GeV
- Production mechanisms, 2-gluon or 3-gluon exchange, has been around for quite some time
- Need precision data to sort-out cross section trend towards the threshold



$$\frac{d\sigma}{dt} = \mathcal{N}_{2g} v \frac{(1-x)^2}{R^2 \mathcal{M}^2} F_{2g}^2(t) (s - m_p^2)^2$$

$$\frac{d\sigma}{dt} = \mathcal{N}_{3g} v \frac{(1-x)^0}{R^4 \mathcal{M}^4} F_{3g}^2(t) (s - m_p^2)^2$$



S.J. Brodsky, E. Chudakov, P. Hoyer, and J-M. Laget, Phys.Lett. B498, 23-28 (2001)

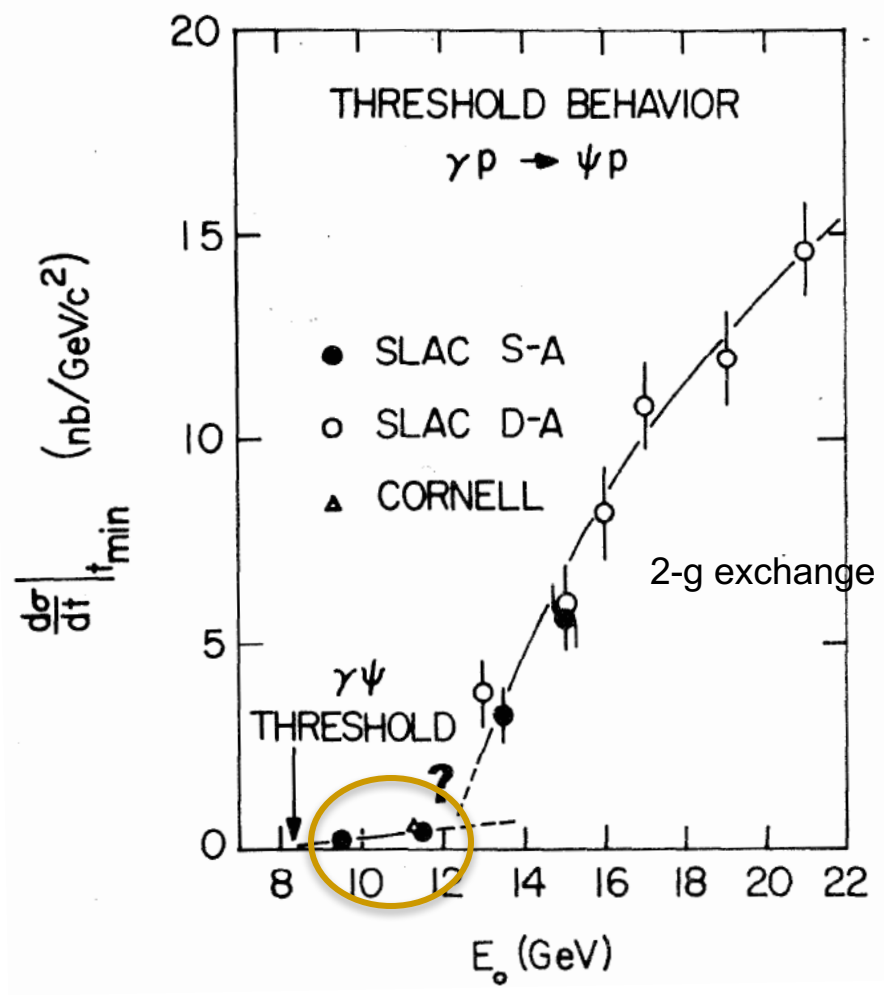
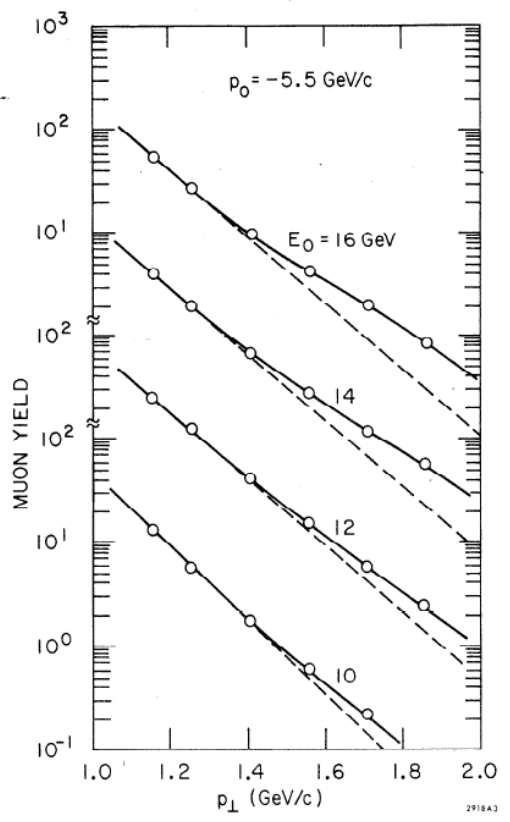


SLAC single arm measurements

Flattening of cross section near the threshold –
can it be due to a resonance?

S. Brodsky, SLAC-PUB-14985

R.L. Anderson, SLAC-PUB-1741



S. Stepanyan



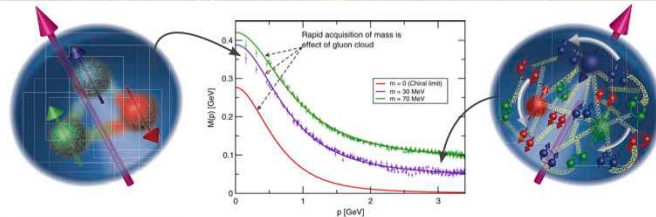
J/ψ -nucleon interaction

- VDM relates J/ψ -photoproduction to J/ψ -N scattering
- There are no $c\bar{c}$ in the nucleon, light-quark exchange between the J/ψ and nucleon cannot occur, OZI suppressed.
- The J/ψ -N scattering goes via multi-gluon exchange, small size object probes gluon distribution of the nucleon
- Close to the threshold real part of the J/ψ -N amplitude dominates providing a unique setting to short distance QCD:
 - trace anomaly of QCD energy-momentum tensor
 - QCD van der Waals interaction. If attraction is strong, this may produce J/ψ -nucleus bound state. So far no evidence for bound state



Charmonium photoproduction and the proton mass

Hot topic - JLAB experiments will have significant contribution



$$M_p = 2m_u^{\text{eff}} + m_d^{\text{eff}}$$

Speakers

Stan Brodsky (SLAC)
Xiandong Ji (Maryland)
Dima Khazeev (Stony Brook & BNL)
Keh-Fei Liu (University of Kentucky)
David Richards (JLab)
Craig Roberts (ANL)
Martin Savage (University of Washington)
Stepan Stepanyan (JLab)
George Sterman (Stony Brook)

Moderator

Alfred Mueller (Columbia)

Local Organizers

Zein-Eddine Meziani (Temple U.)
Jianwei Qiu (Brookhaven National Lab)

$$H_{\text{QCD}} = H_q + H_m + H_g + H_a$$

$$\text{Quark kinetic and potential energy } H_q = \int d^3x \psi^\dagger (-i\mathbf{D} \cdot \boldsymbol{\alpha}) \psi$$

$$\text{Quark masses } H_m = \int d^3x \bar{\psi} m \psi$$

$$\text{Gluon kinetic and potential energy } H_g = \int d^3x \frac{1}{2} (\mathbf{E}^2 + \mathbf{B}^2)$$

$$\text{Trace anomaly } H_a = \int d^3x \frac{9\alpha_s}{16\pi} (\mathbf{E}^2 - \mathbf{B}^2)$$

Workshop Topics

- Hadron Mass Calculation: Lattice QCD and Other Methods
- Hadron Mass Decomposition



Main Topics
Hadron mass decomposition in terms of constituents: Uniqueness of the decomposition, Quark mass, and quark and gluon energy contribution, Anomaly contribution, ...
Hadron mass calculations: Lattice QCD (total & individual mass components), Approximated analytical methods, Phenomenological model approaches, ...
Experimental access to hadron mass components: Exclusive heavy quarkonium production at threshold, nuclear gluonometry through polarized nuclear structure function, ...

Confirmed speakers and participants
Alexandru Constantia (Cyprus University), Brodsky Stan (SLAC), Burkardt Matthias (New Mexico State University), Chen Jian-Ping (Jefferson Lab), Chudakov Eugene (Jefferson Lab), Cloët Ilan (Argonne National Lab), de Teramond Guy (University Costa Rica), Deshpande Abhay (Stony Brook University), Eichmann Germar (Gießen University), Fudil Kwiatkowski (Argonne National Lab), Hoelling Christian (University of Wuppertal), Lin Xueyuan (Michigan State University), Liu Keh-Fei (University of Kentucky), Lorek Cédric (École Polytechnique, Palaiseau), Mülner Peter (Vrije University of Amsterdam), Papavasiliou Ioannis (Valencia University), Pascaut Vladimir (Johannes Gutenberg University of Mainz), Richards David (Jefferson Lab), Roberts Craig (Argonne National Lab), Silber Karl (University of New Hampshire), Maiti Anindita (University of Toronto & INFN), Bob Jaffe (Massachusetts Institute of Technology), Dima Khazeev (Stony Brook University), Xiangdong Ji (University of Maryland).

Organizers
Zein-Eddine Meziani (Temple University)
Barbara Pascaut (University of Padua)
Jianwei Qiu (Jefferson Lab)
Marc Vanderhaeghen (Université de Maine)

Director of the ECT*: Professor Jochem Wambach (ECT*)

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For local organization please contact: Giannaria Ziglio - ECT* Secretariat - Villa Tambosi - Strada delle Tabarelle 286 - 38123 Villazano (Trento) - Italy
Tel.: (+39-0461) 314721 Fax: (+39-0461) 314750, E-mail: ect@ectstar.eu or visit <http://www.ectstar.eu>



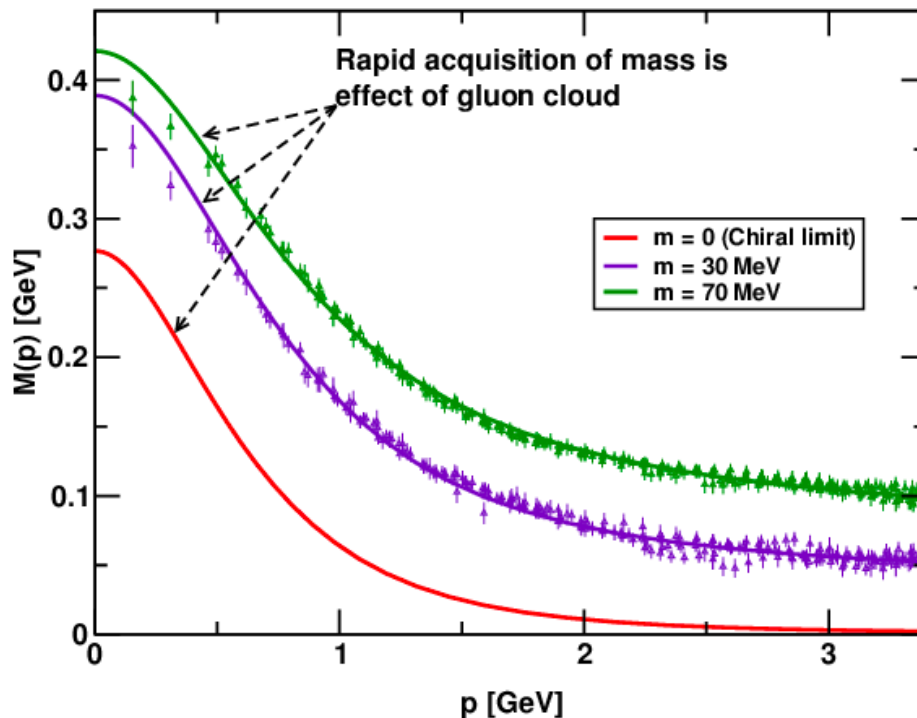
S. Stepanyan



Proton mass and J/ψ -nucleon interaction

- Current quark mass accounts only for $\sim 1\%$ of proton's mass
- The mass of the nucleon is due to quantum fluctuations, the gluons, and the kinetic energy of quarks
- Understanding the proton mass structure will shed light on dynamical chiral symmetry breaking and confinement

M. S. Bhagwat et al., Phys. Rev. C 68, 015203 (2003)



Advances in:

- Lattice QCD
- Bound State QCD: Dyson-Schwinger
- Ads/CFT: Holographic QCD



Proton mass decomposition

X. Ji, PRL (1995)

$$M_p = \frac{\langle P | \int d^3x T^{00} | P \rangle}{\langle P | P \rangle} \equiv \langle T^{00} \rangle \quad T^{\mu\nu}, \text{ QCD energy-momentum tensor}$$

four gauge invariant parts

$$\underbrace{\bar{T}_q^{\mu\nu}, \bar{T}_g^{\mu\nu}, \hat{T}_m^{\mu\nu}, \text{ and } \tilde{\hat{T}}_a^{\mu\nu}}_{\text{traceless}}$$

traceless

Corresponding breakdown for the hamiltonian

$$H_{QCD} = H_q + H_g + H_m + H_a$$

energy terms from PDFs

$$H_q = \int d^3\vec{x} \bar{\psi} (-i\mathbf{D} \cdot \boldsymbol{\alpha}) \psi$$

$$H_g = \int d^3\vec{x} \frac{1}{2} (\mathbf{E}^2 + \mathbf{B}^2)$$

u/d quark mass term from πN Σ -term and s-quark from ChPT, LQCD

$$H_m = \int d^3\vec{x} \bar{\psi} m \psi$$

trace anomaly from J/ψ -nucleon amplitude at the threshold

$$H_a = \int d^3\vec{x} \frac{9\alpha_s}{16\pi} (\mathbf{E}^2 - \mathbf{B}^2)$$



Proton mass decomposition

X. Ji, PRL (1995)

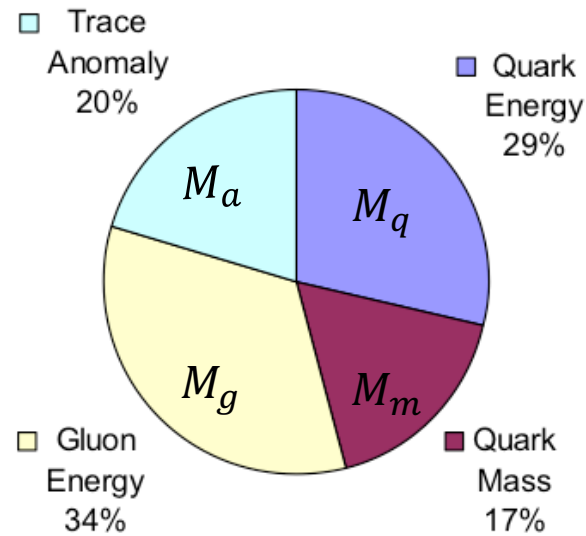
$$M_p = \frac{\langle P | \int d^3x T^{00} | P \rangle}{\langle P | P \rangle} \Big|_{\text{at rest}} = M_q + M_g + M_m + M_a$$

$$M_q = \frac{\langle P | H_q | P \rangle}{\langle P | P \rangle} \Big|_{\text{at rest}} = (a - b) \frac{3}{4} M_p$$

$$M_g = \frac{\langle P | H_g | P \rangle}{\langle P | P \rangle} \Big|_{\text{at rest}} = (1 - a) \frac{3}{4} M_p$$

$$M_m = \frac{\langle P | H_m | P \rangle}{\langle P | P \rangle} \Big|_{\text{at rest}} = b M_p$$

$$M_a = \frac{\langle P | H_a | P \rangle}{\langle P | P \rangle} \Big|_{\text{at rest}} = (1 - b) \frac{1}{4} M_p$$



mass type	H_i	M_i	$m_s \rightarrow 0(\text{MeV})$	$m_s \rightarrow \infty(\text{MeV})$
quark energy	$\bar{\psi}(-i\mathbf{D} \cdot \alpha)\psi$	$3(a - b)/4$	270	300
quark mass	$\bar{\psi}m\psi$	b	160	110
gluon energy	$\frac{1}{2}(\mathbf{E}^2 + \mathbf{B}^2)$	$3(1 - a)/4$	320	320
trace anomaly	$\frac{9\alpha_s}{16\pi}(\mathbf{E}^2 - \mathbf{B}^2)$	$(1 - b)/4$	190	210

Large uncertainty in quark mass and energy term from m_s , need *independent* determination of b



Quarkonium scattering and the trace anomaly

- The elastic photoproduction of a vector meson can be related to the vector-meson nucleon scattering

$$\frac{d\sigma_{\gamma N \rightarrow \psi N}}{dt} = \mathcal{K} \cdot \frac{3 \cdot \Gamma(V \rightarrow e^+ e^-)}{\alpha \cdot m_V} \cdot \frac{d\sigma_{\psi N \rightarrow \psi N}}{dt}$$

$$\frac{d\sigma_{\psi N \rightarrow \psi N}}{dt} \Big|_{t=0} = \frac{1}{64\pi} \cdot \frac{1}{m_\psi^2 (\lambda^2 - m_N^2)} |M_{\psi N}|^2$$

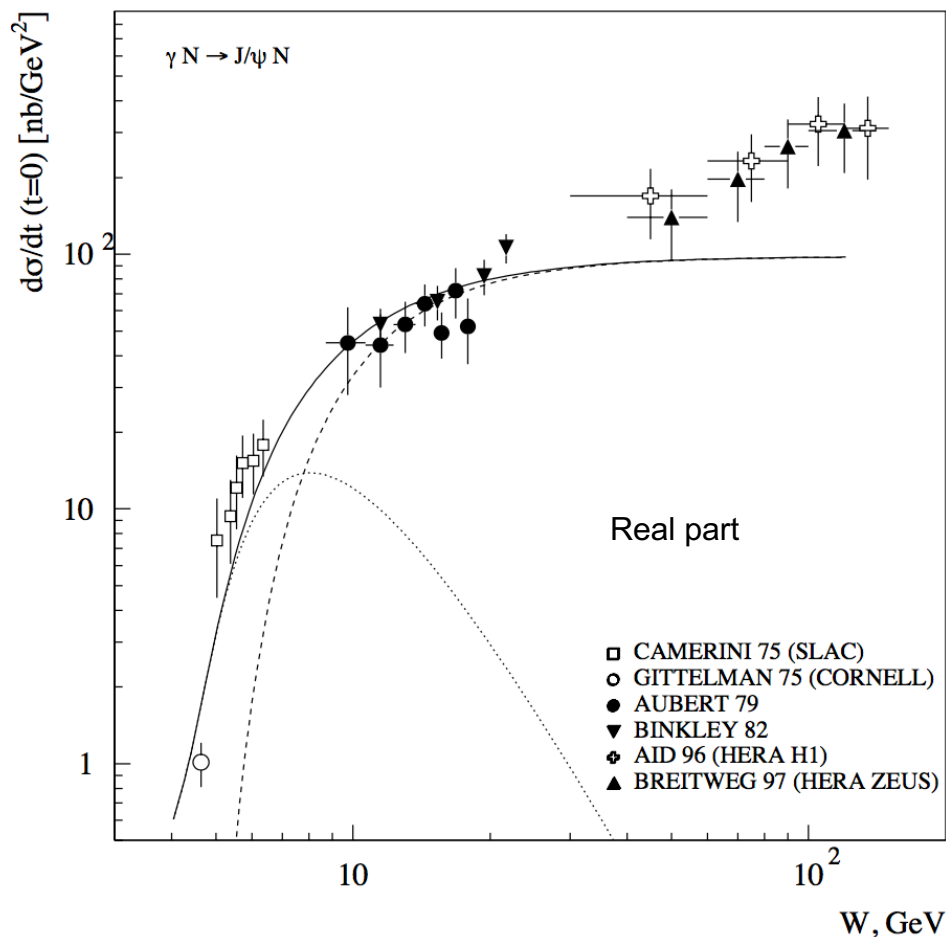
$$\sigma_{\psi N}^{tot} = \frac{\Im m M_{\psi N}}{2m_\psi \sqrt{\lambda^2 - m_N^2}}$$

- At threshold (low energy scattering) amplitude is proportional to the trace of the QCD energy momentum tensor (M.Luke, A.Manohar, M.Savage '92)
- Quarkonium-proton interaction at low energy probes the distribution of mass inside the proton.



Fit to the photoproduction data

$$\text{Re } M_{\psi N} = M_{\psi N}(0) + 2 \frac{\lambda^2}{\pi} \int_{\lambda_0}^{\infty} \frac{\Im m M_{\psi N}(\lambda')}{\lambda'^2 - \lambda^2} \frac{d\lambda'}{\lambda'}$$



- Dispersion relations are used to calculate the real part of the amplitude that dominates at the threshold
- J/ψ photoproduction near threshold will further constrain J/ψ -nucleon amplitude at the threshold

D. Kharzeev. Quarkonium interactions in QCD, 1995 nucl-th/9601029

D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999



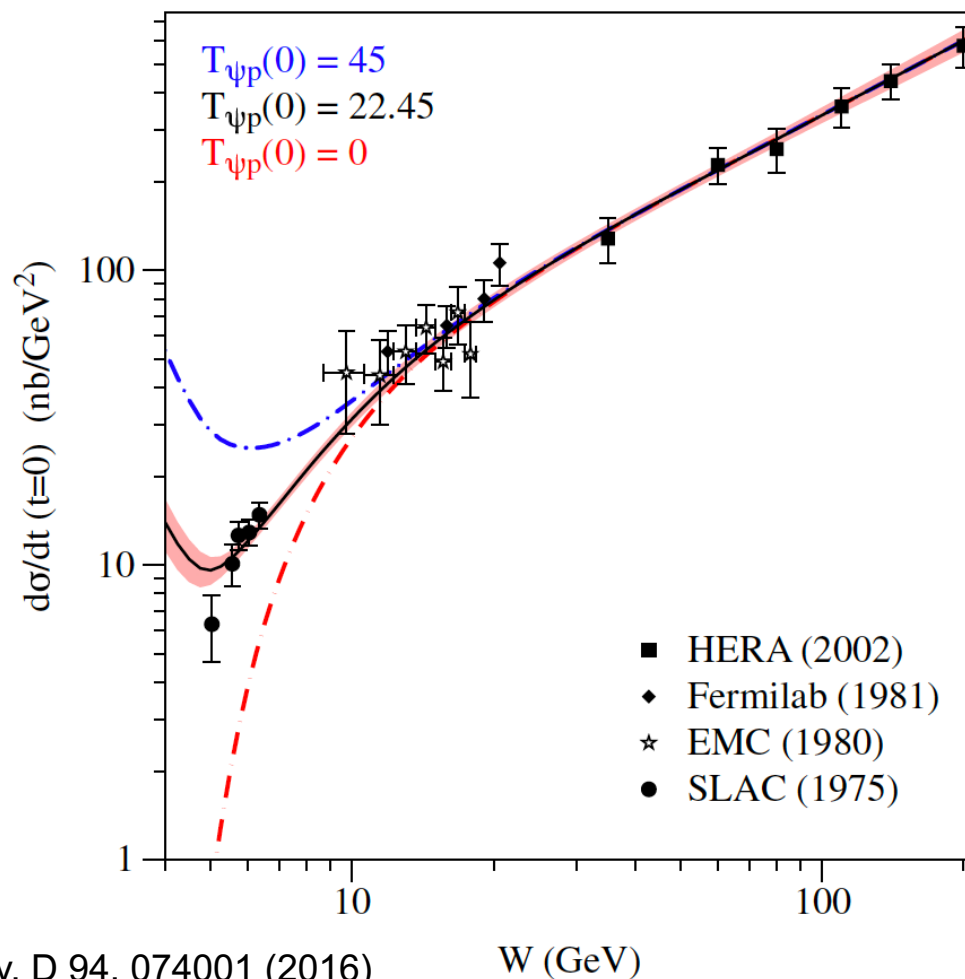
J/ψ -nucleon s-wave scattering length

- QCD van der Waals interactions characterized by s-wave scattering length, $a_{\psi p}$
- Current estimates for $a_{\psi p}$ ranging from 0.05 fm to 0.37 fm
- The largest value would lead to J/ψ binding energy in nuclear matter exceeding $B_{\psi} = 20$ MeV
- Recent LQCD calculations $B_{\psi} \leq 40$ MeV
- At the threshold:

$$\sigma_{\psi N}^{tot} \equiv 4\pi a_{\psi N}^2$$

Fit to the existing data favors:

$$a_{\psi p} = 0.05 \text{ fm} \quad B_{\psi} = 3 \text{ MeV}$$



O. Gryniuk and M. Vanderhaeghen, Phys. Rev. D 94, 074001 (2016)



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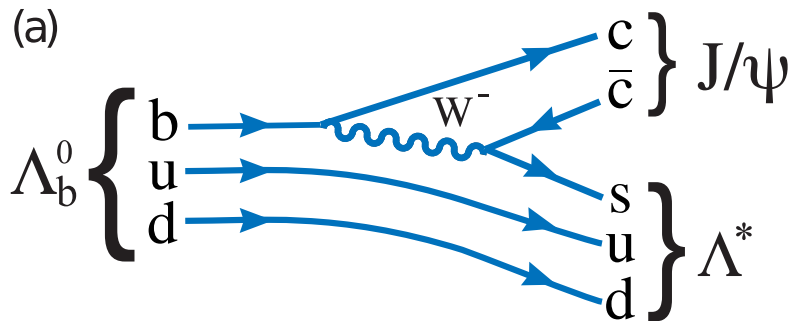


LHCb hidden charm pentaquarks

$\Lambda_b^0 \rightarrow K^- p J/\psi$ for precise measurement of the Λ_b^0 life time.

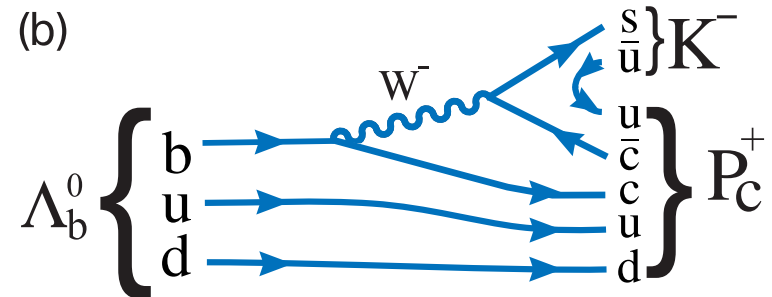
The dominant decay mode through Λ^*

$$\Lambda_b^0 \rightarrow \Lambda^* J/\psi$$



Small exotic contribution

$$\Lambda_b^0 \rightarrow K^- P_c^+$$



R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 115, 072001



$J/\psi p$ pentaquark states

Two exotic $cc\bar{c}uud$ 5-quark states, P_c^+ , were introduced to fit mass distributions

$$M_- = 4380 \pm 8 \pm 29 \text{ MeV}$$

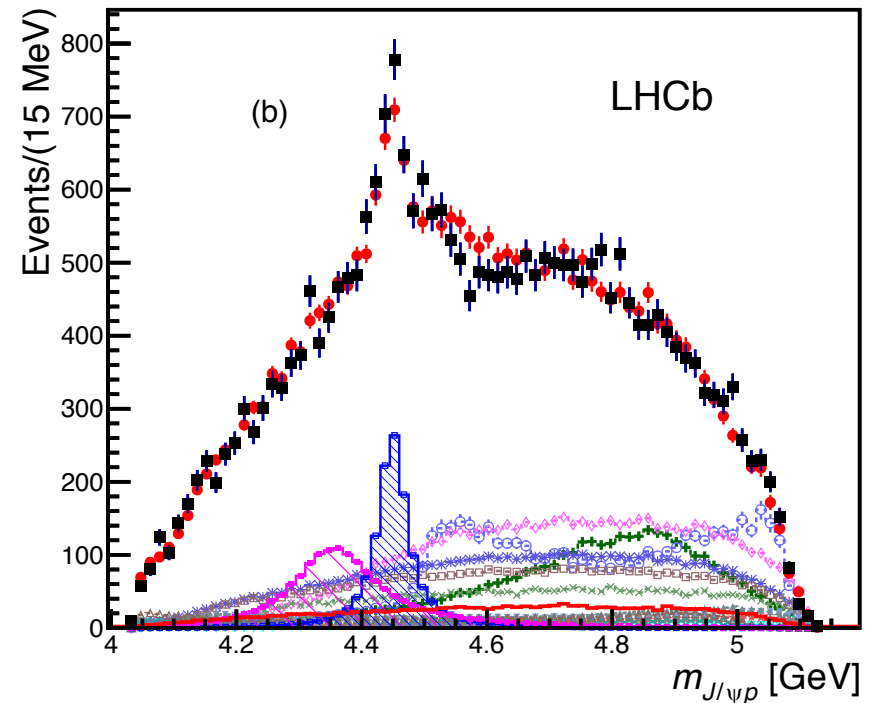
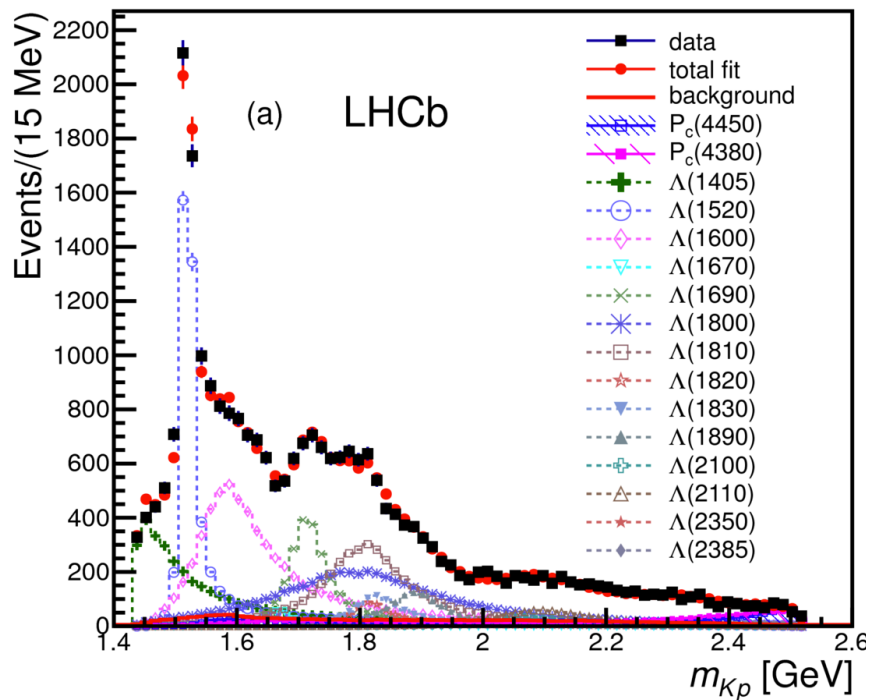
$$\Gamma_- = 205 \pm 18 \pm 86 \text{ MeV}$$

$$J^P = 3/2^-$$

$$M_+ = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$$

$$\Gamma_+ = 39 \pm 5 \pm 19 \text{ MeV}$$

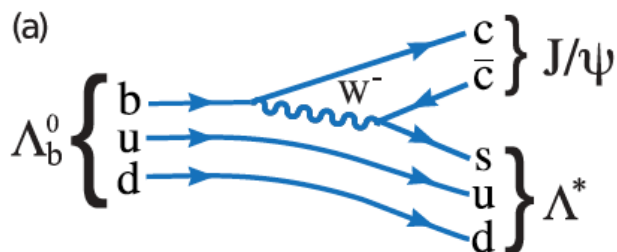
$$J^P = 5/2^+$$



R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 115, 072001



Amplitude analysis



Two models for fit - reduced and extended with different angular momentum between J/ψ and Λ^*

All known Λ^* states

State	J^P	M_0 (MeV)	Γ_0 (MeV)	limited L # Reduced	All possible L # Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$?	≈ 2585	200	0	6

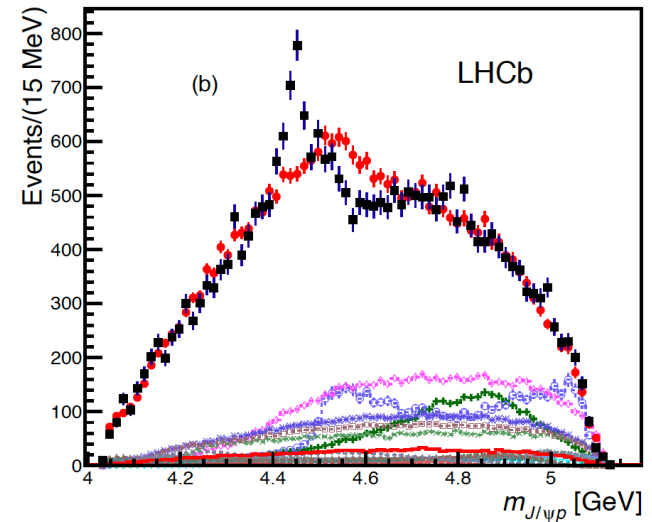
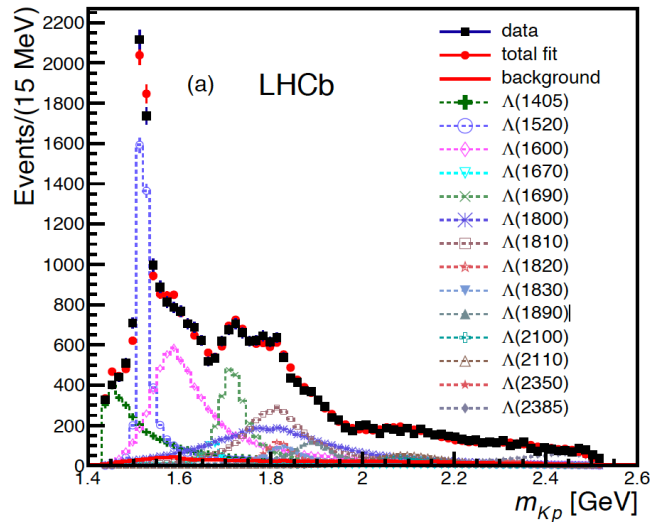
of fit parameters: 64

146

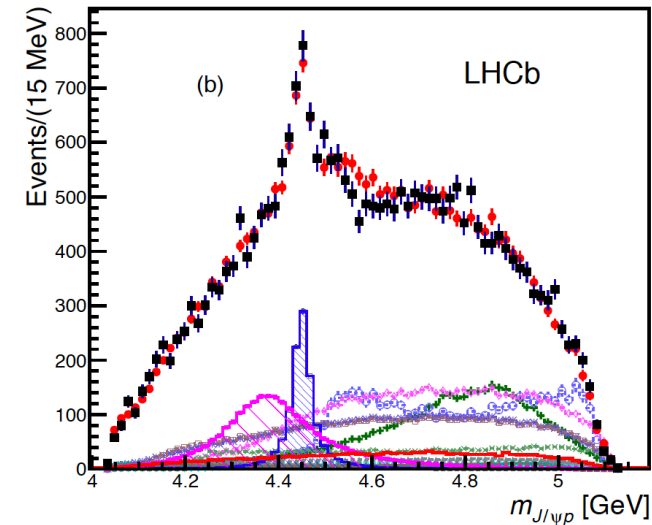
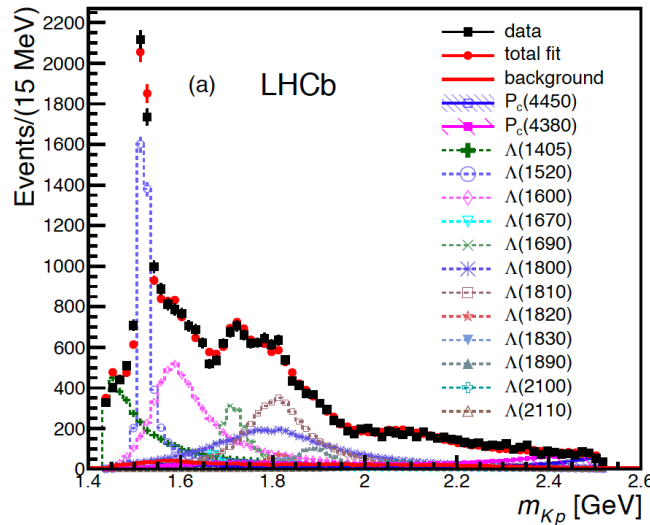


Fit to the mass spectra

No pentaquarks



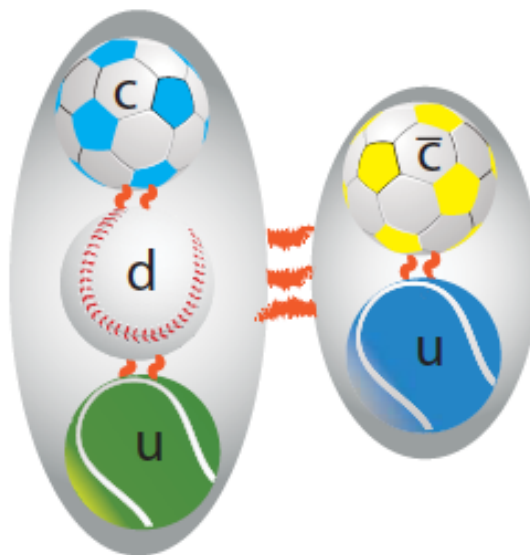
With pentaquarks



Interpretation of new states

Charmed Baryon and anti-charmed meson molecule:

- M. Karliner and J. L. Rosner, arXiv:1506.06386
- L. Roca, J. Nieves, and E. Oset, arXiv:1507.04249
- R. Chen, X. Liu, X.-Q. Li, and S.-L. Zhu, arXiv:1507.03704
- H-X. Chen, W. Chen, X. Liu, T.G. Steele, and S-L. Zhu, arXiv:1507.0317
- J. He, arXiv:1507.05200



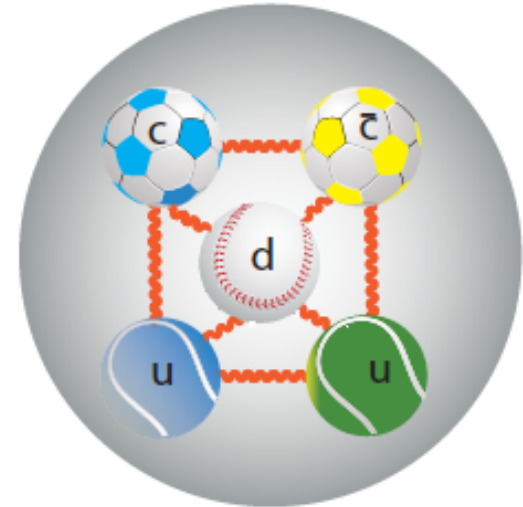
$$\bar{D}^* \Sigma_c - \bar{D}^* \Sigma_c^*$$

- U.-G. Meiner and J. A. Oller, arXiv:1507.07478. For $P(4550) - \chi_{c1} P$

Interpretation of new states (cont.)

Tightly correlated quarks/diquarks

- L. Maiani et al. Phys. Lett. B 749, 289 (2015)
- V. V. Anisovich et al., arXiv:1507.07652
- A. Mironov and A. Morozov, JETP Lett. 102, no. 5, 271 (2015)
- R. F. Lebed, Phys. Lett. B 749, 454 (2015)



or reflection

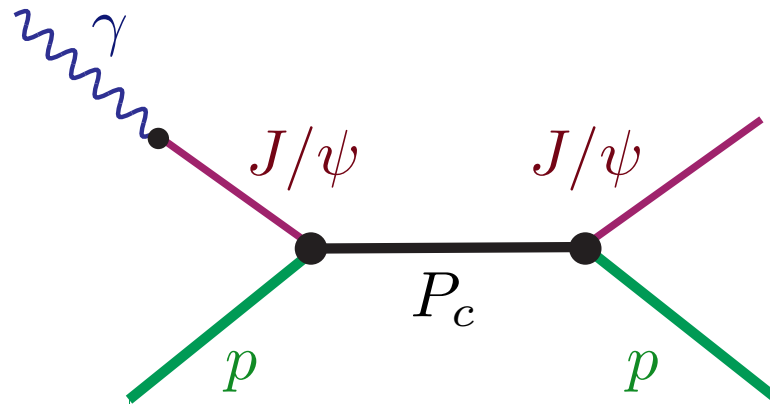
- F.-K. Guo, U.-G. Meiner, W. Wang, and Z. Yang, arXiv:1507.04950; $\chi_{c1}P$ rescattering
- M. Mikhasenko, arXiv:1507.06552. Possible reflection in the complicated decay chain
- X. H. Liu, Q. Wang and Q. Zhao, Phys. Lett. B 757, 231 (2016).

Need independent verification with a different production mechanism



Pentaquark in photo-production

- The production of pentaquarks proceeds as an s-channel resonance
- VDM can be used to relate initial and final states



$$\sigma(W) \approx \frac{2J+1}{4} \frac{4\pi}{k^2} \frac{\Gamma^2/4}{(W - M_c)^2 + \Gamma^2/4} Br(P_c \rightarrow \gamma + p) Br(P_c \rightarrow J/\psi + p)$$

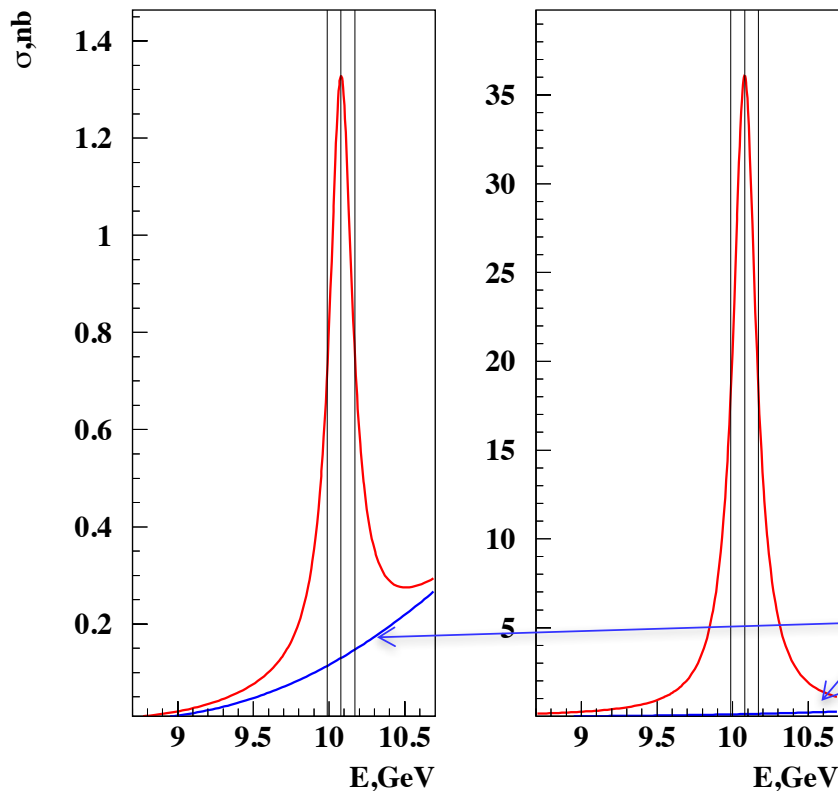
$$\Gamma(P_c \rightarrow \gamma + p) = \frac{3\Gamma_{ee}(J/\psi)}{\alpha M(J/\psi)} \sum_L f_L \left(\frac{k}{p}\right)^{2L+1} \Gamma_L(P_c \rightarrow J/\psi + p)$$

Q. Wang, X. H. Liu and Q. Zhao, arXiv:1508:00339.
 V. Kubarovsky and M.B. Voloshin, arXiv:1508.00888.
 M. Karliner and J.L. Rosner, arXiv:1508.01496.

Cross section estimates

$$1.5 \times 10^{-30} \text{ cm}^2 < \frac{\sigma_{max}[\gamma + p \rightarrow P_c(4380) \rightarrow J/\psi + p]}{Br^2[P_c(4380) \rightarrow J/\psi + p]} < 47 \times 10^{-30} \text{ cm}^2$$

$$1.2 \times 10^{-29} \text{ cm}^2 < \frac{\sigma_{max}[\gamma + p \rightarrow P_c(4450) \rightarrow J/\psi + p]}{Br^2[P_c(4450) \rightarrow J/\psi + p]} < 36 \times 10^{-29} \text{ cm}^2$$



Theoretical uncertainty is connected with the unknown partial wave decomposition of the pentaquark decay

$$Br(P_c(4450) \rightarrow p J/\psi) = 0.01$$

Prediction of 2-gluon exchange model for J/ψ elastic photoproduction. S.J. Brodsky, E. Chudakov, P. Hoyer, and J-M. Laget, Phys.Lett. B498, 23-28 (2001)

[V. Kubarovsky and M.B. Voloshin, arXiv:1508.00888.](https://arxiv.org/abs/1508.00888)



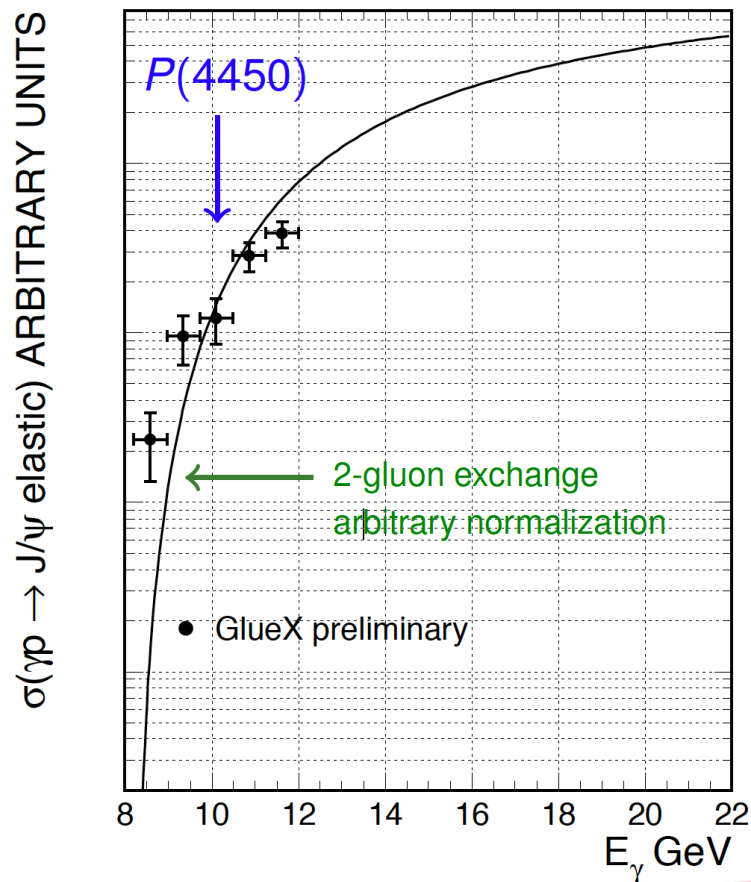
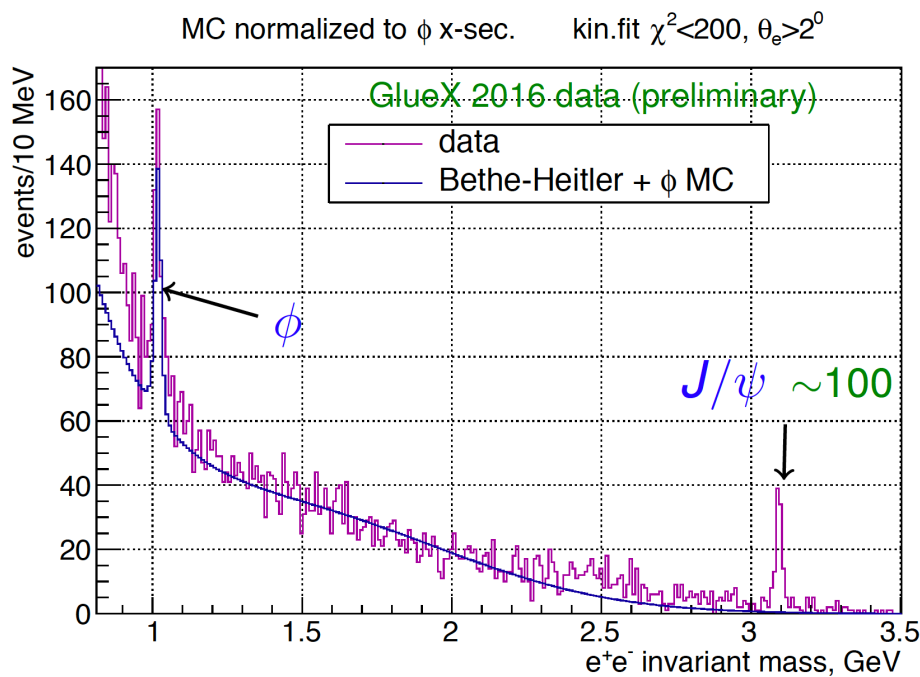
JLAB12 – a new energy regime

- The energy of upgraded JLAB machine, CEBAF, is well above J/ψ production threshold energy, 8.2 GeV, on a free nucleon
- With up to 12 GeV electron beam, the threshold region will be studied in great detail using high luminosity detectors in all Halls
- The same experiments are well positioned to search and study LHCb hidden charm pentaquarks
- Currently three experiments have been approved and one is running:
 - Gluex data analysis (no approved experiment)
 - E12-16-007 using spectrometers in Hall-C,
 - E12-12-006 using future SoLID detector in Hall-A, 50 days approved
 - **E12-12-001 on CLAS12 in Hall-B, 130 days approved and the new proposal PR12-17-001**
- A new proposal has been submitted to PAC45 for extended studies of the J/ψ and charmed pentaquark photoproduction



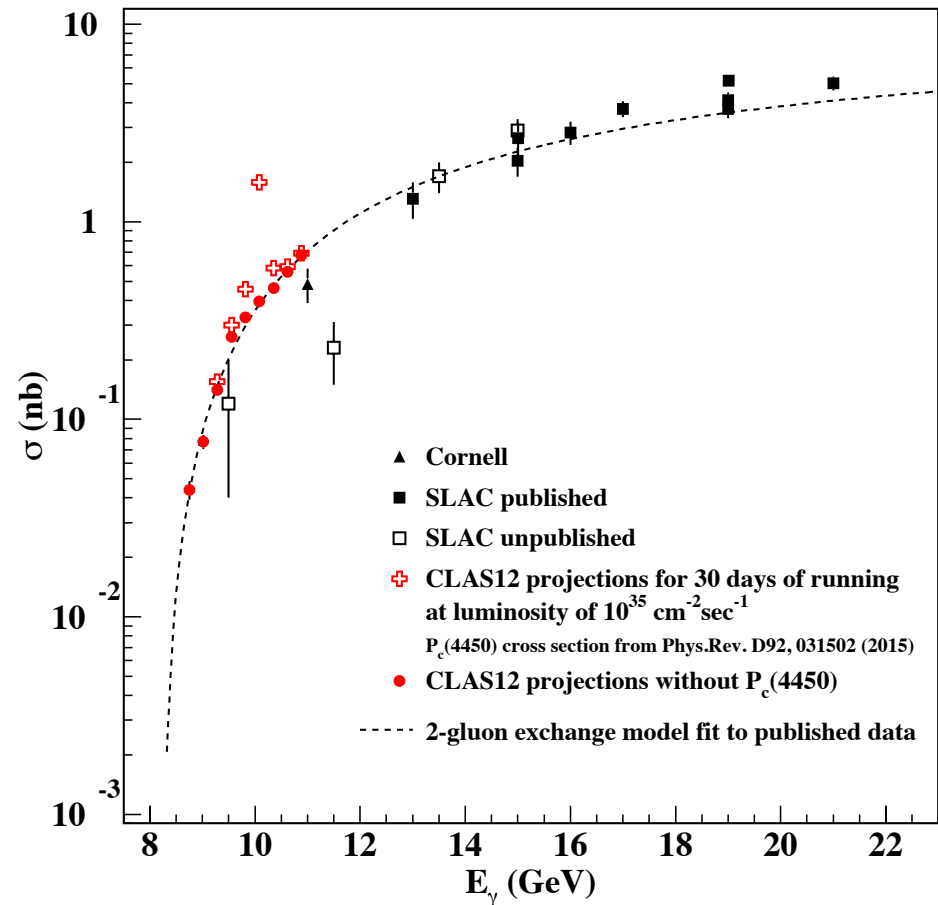
Hall-D Gluex results

- All 2016 data: exclusive events $p e^+ e^-$, the $e^+ e^-$ PID using the electromagnetic calorimeters BCAL and FCAL. Kinematic fit with the beam energy from the tagger
- Planned measurements, after adding the 2017 Spring data will limit the pentaquark yield (the mass resolution $6 \text{ MeV}/c^2$)



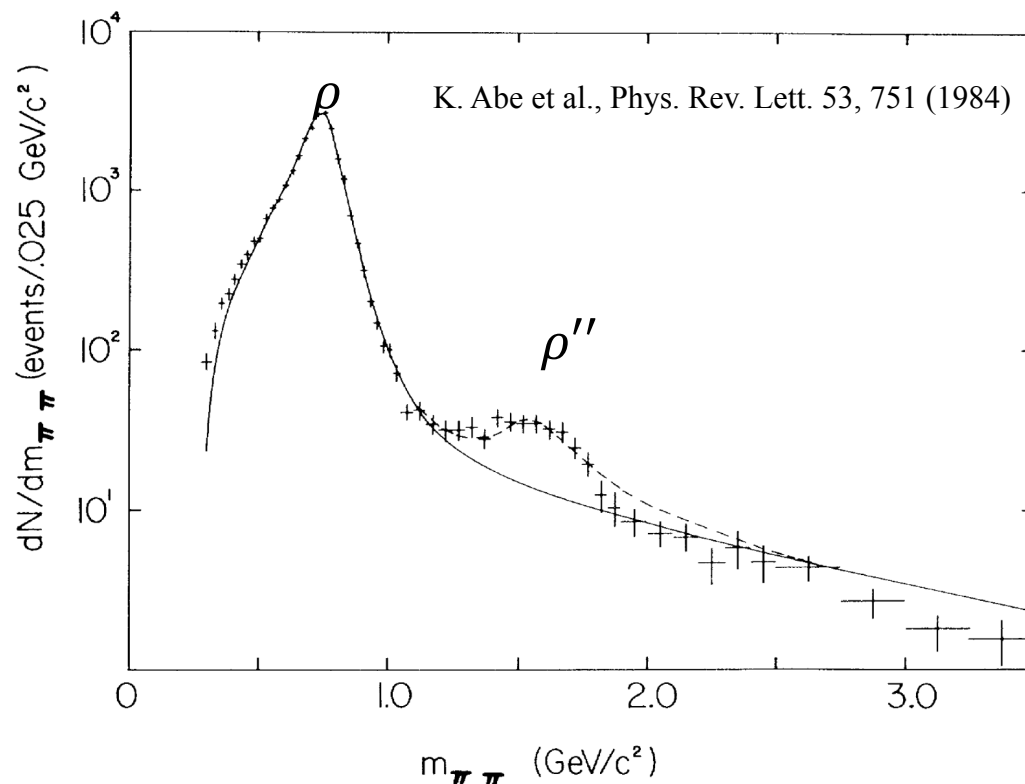
Expectations from JLAB experiments, $J/\psi \rightarrow e^+ e^-$

- From the two gluon exchange prediction for cross section, we expect total of 45 J/ψ detected per day in the whole energy range
- Expected total number of charmed pentaquarks 98 per day
- The Hall-C E12-16-007 with the same cross section formalism will detect 70 pentaquarks per day
- The Hall-A experiment E12-12-006 with future SoLID detector expects $\sim 42 J/\psi$ per day
- With current luminosity Hall-D Gluex experiments expects 5-10 J/ψ per day



Muon final state

- The main background to the exclusive muon pair final state is from $\gamma p \rightarrow p' \pi^+ \pi^-$
- In our energy range $\sigma_{tot}^{\pi\pi} \approx 15 \mu\text{b}$
- The fraction of pion pairs with $M_{\pi\pi} > 3 \text{ GeV}$ is $< 2 \cdot 10^{-4}$
- The effective cross section for pion pair photoproduction in the region of J/ψ is expected to be $< 5 \text{ nb}$



- With modest charged pion suppression, x3, achievable with calorimetry (e.g. MIP signature in EM calorimeters), the rate of pion pairs with the invariant mass $> 3 \text{ GeV}$ will then be the same order as J/ψ production



Summary

- The energy reach of upgraded JLAB machine crosses the threshold of charmonium production on the nucleon
- Together with new experimental facilities this provides an opportunity for detailed study of production of ground state charmonium
- Particular interest is the uncharted near threshold region, where different mechanisms for the production have been proposed. In this region, J/ψ production probes gluonic form-factors of the nucleon
- J/ψ photoproduction allows effectively study J/ψ -N interaction, where one will access unique information on the trace anomaly of QCD energy-momentum tensor
- JLAB experiments can search and study LHCb hidden charm pentaquark states in the pJ/ψ decay mode, $P_c(4380)$ and $P_c(4450)$
- Three experiments (in Halls A, B and C) for J/ψ photoproduction have already been approved
- First data from the Hall-D Gluex experiment has been already presented
- Future plans include J/ψ production on deuterium and heavier nuclear targets

