Near threshold J/ψ photo-production

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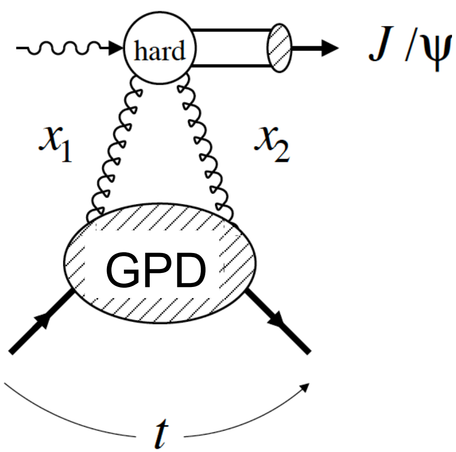
SoLID collaboration meeting

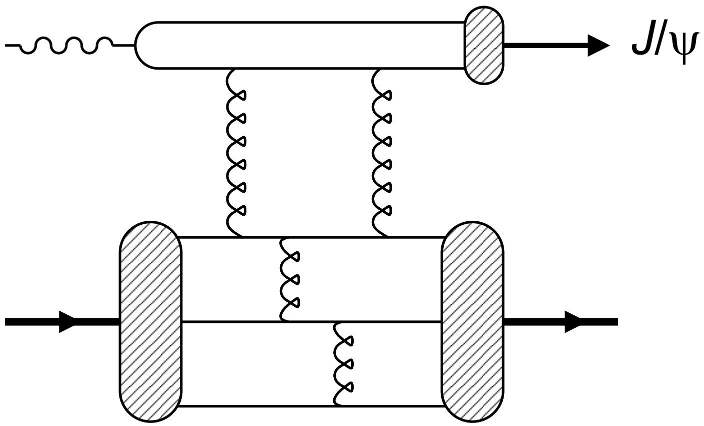
June 29 - 30, 2017, JLAB

- 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

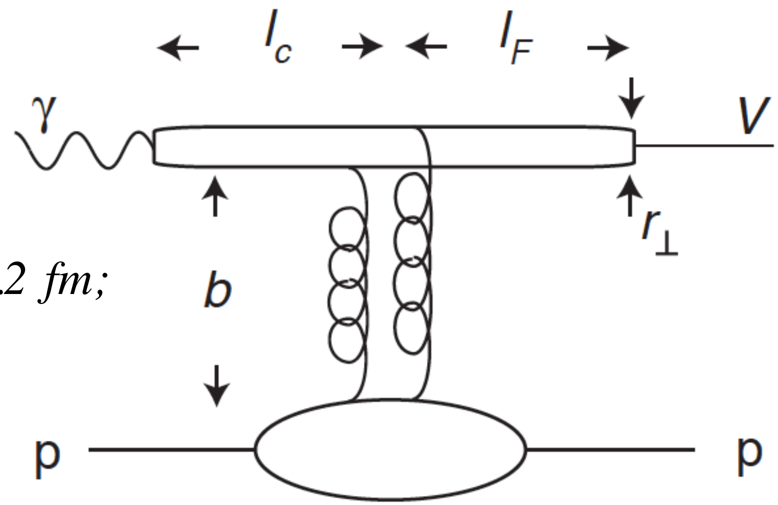




At high energies (HERA, FNAL) probes gluon GPDs. Considerable amount of data at W > 10 GeV, in good agreement with 2-gluon exchange mechanism

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



$$m_c \approx 1.5\ GeV;$$

$$r_\perp \sim \frac{1}{m_c} = 0.13\ fm$$

$$E_\gamma \approx 10\ GeV \Rightarrow b \sim \frac{1}{\sqrt{-t}} \sim 0.2\ fm;$$

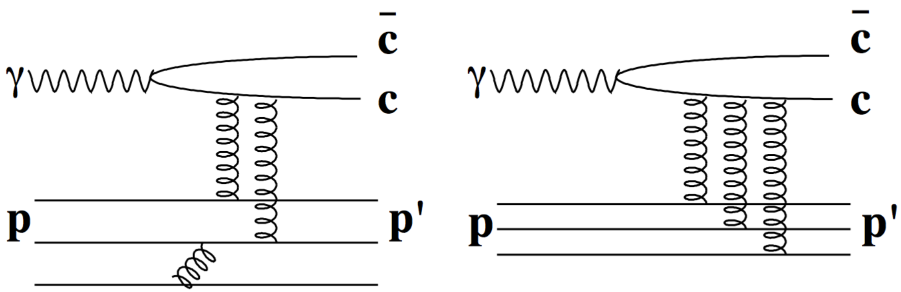
$$E_\gamma \approx 10\ GeV \Rightarrow l_c = \frac{2E_\gamma}{4m_c^2} \approx 0.4\ fm;\ l_F \approx \frac{2E_{J/\psi}}{2m_c\left(m_{\psi'} - m_{J/\psi}\right)} \sim 1-2\ fm;$$

Favorable kinematics for studying

- production mechanism near threshold
- nucleons' local gluon field distribution, *b, r* << 1 fm
- J/ψN scattering, l_c and l_F ~ fm

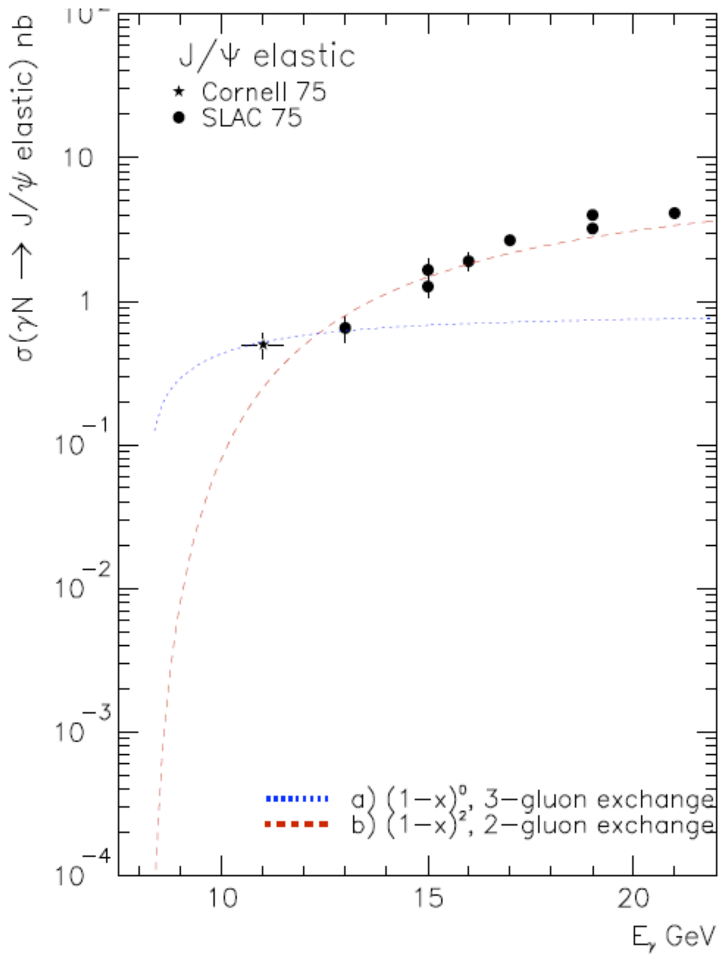
J/ψ photoproduction near threshold

- The lowest published energy point is at E_γ=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



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

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



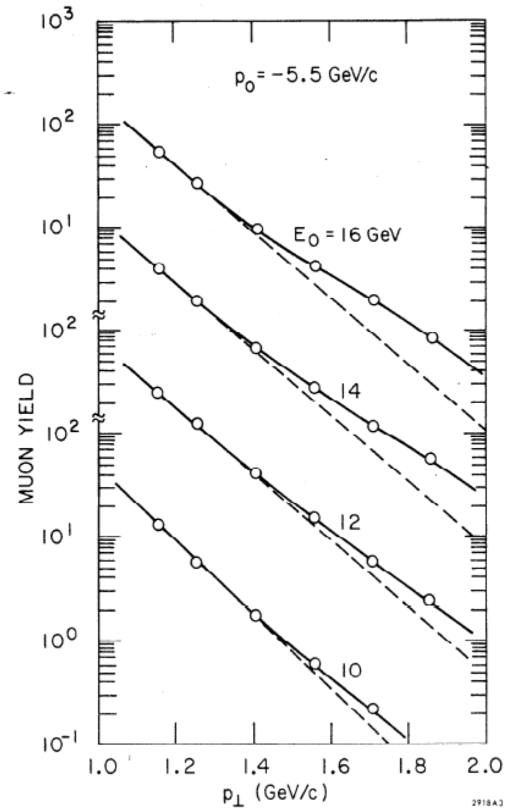
S.J. Brodsky, E. Chudakov, P. Hoyer, and J-M. Laget, Phys.Lett. B498, 23-28 (2001)

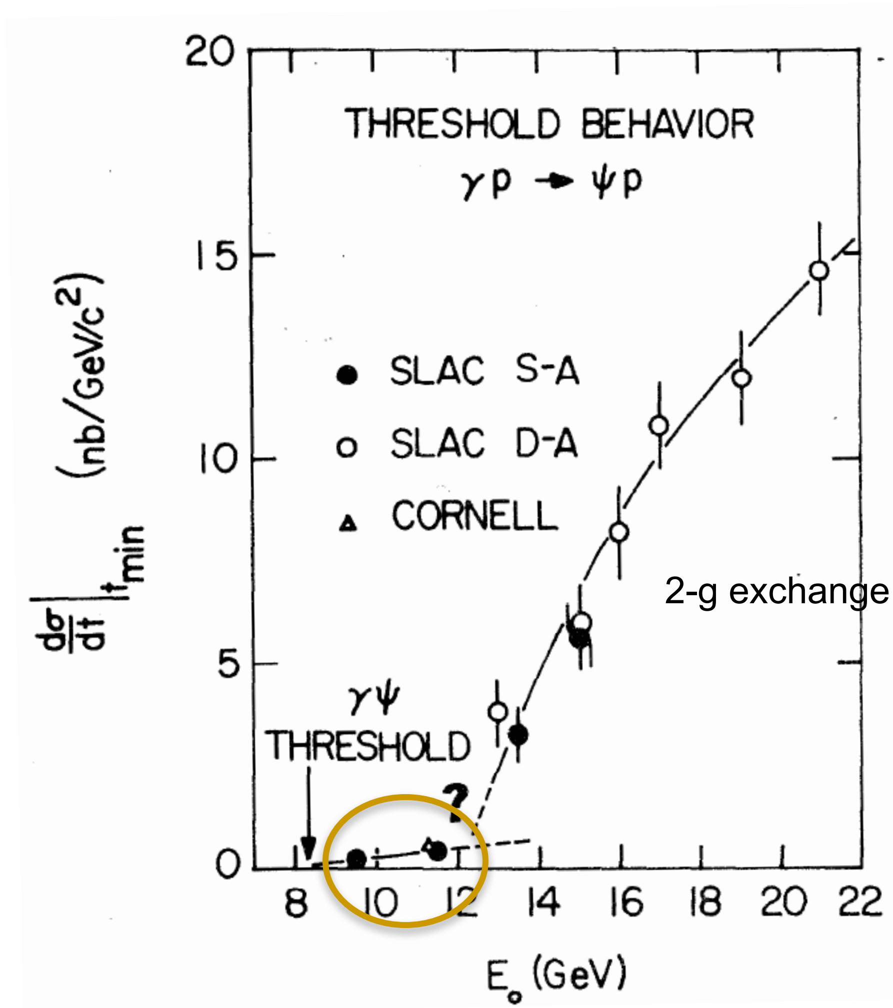
SLAC single arm measurements

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



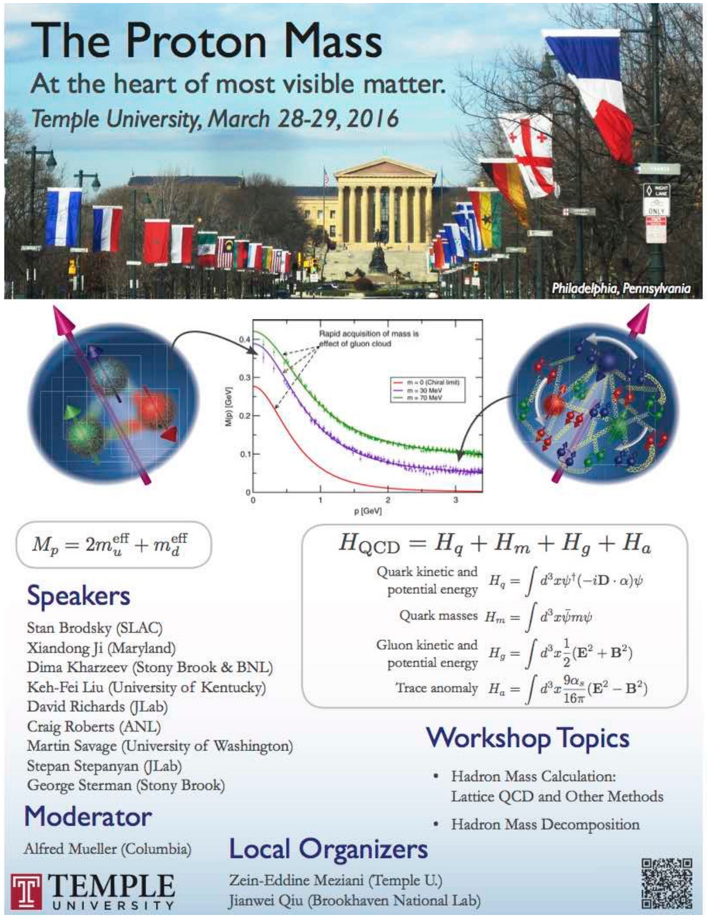


J/ψ-nucleon interaction

- 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

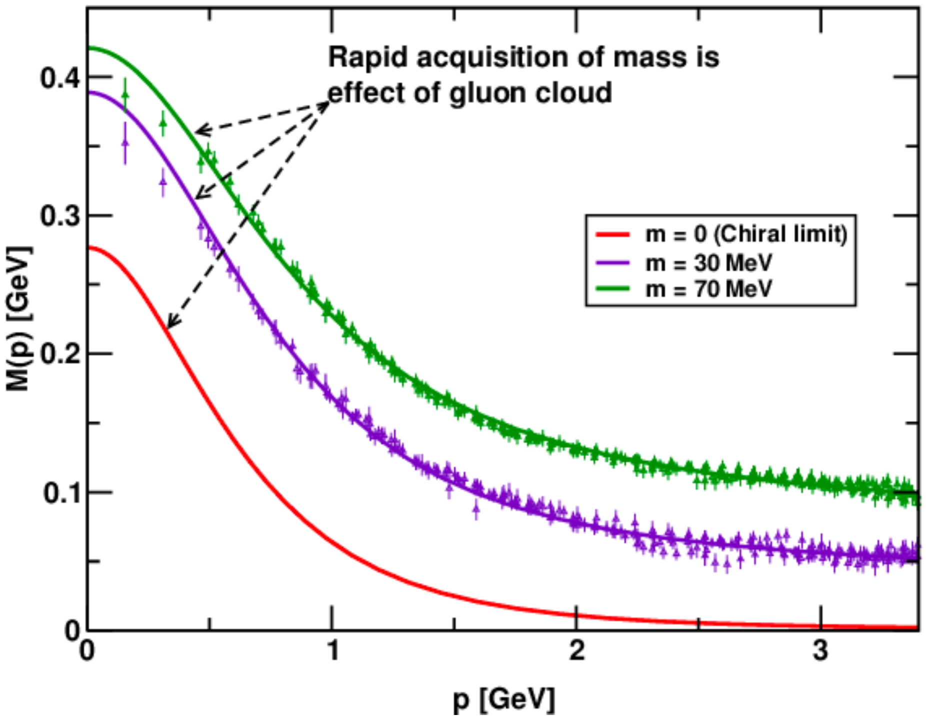
Hot topic - JLAB experiments will have significant contribution



Proton mass and J/ψ-nucleon interaction

- Current quark mass accounts only for ~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 shad 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)

$$M_p = \frac{\langle P|\int d^3x T^{00}|P\rangle}{\langle P|P\rangle} \equiv \langle T^{00}\rangle$$

$T^{\mu\nu}$, QCD energy-momentum tensor

four gauge invariant parts

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

energy terms from PDFs

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

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

Corresponding breakdown for the hamiltonian

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

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)

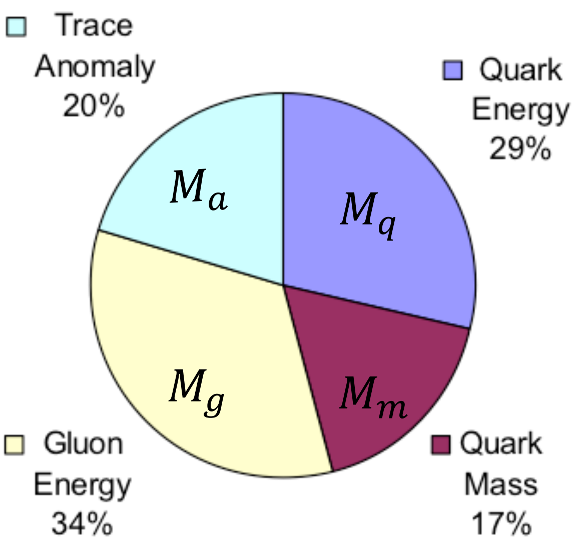
$$M_p = \frac{\langle P|\int d^3x T^{00}|P\rangle}{\langle P|P\rangle}\Big|_{at\ rest} = M_q + M_g + M_m + M_a$$

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

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

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

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



mass type	H_i	M_i	$m_s \to 0$(MeV)	$m_s \to \infty$(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

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

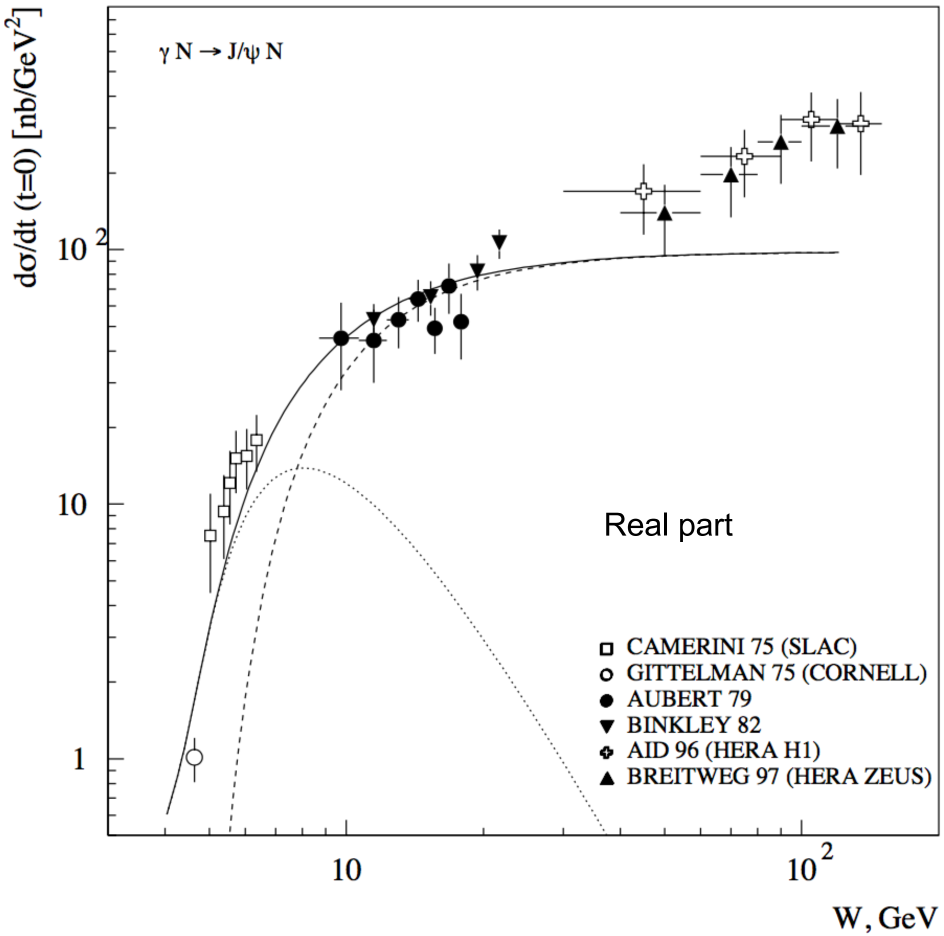
$$\frac{d\sigma_{\psi N\to\psi N}}{dt}\Big|_{t\,=\,0} = \frac{1}{64\pi} \cdot \frac{1}{m_\psi^2(\lambda^2 - m_N^2)} |M_{\psi N}|^2$$

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

- 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

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



- 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

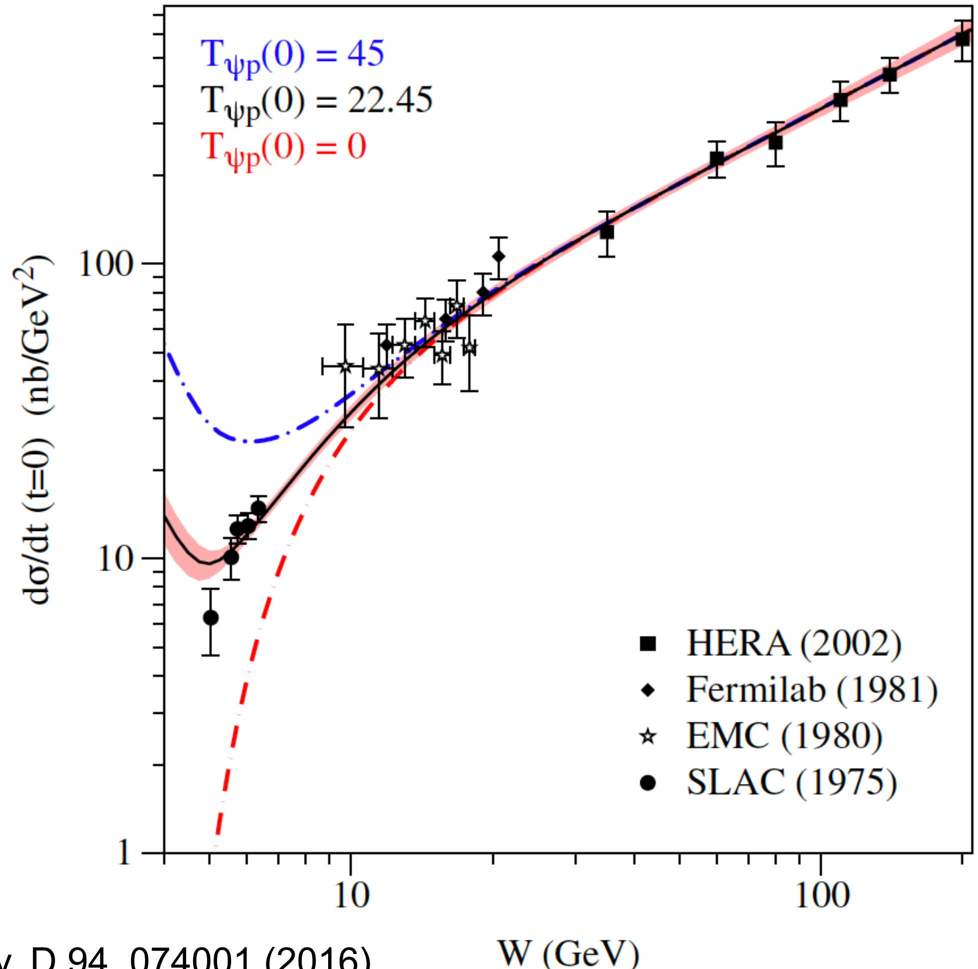
J/ψ-nucleon *s*-wave scattering length

- 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:

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



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

LHCb hidden charm pentaquarks

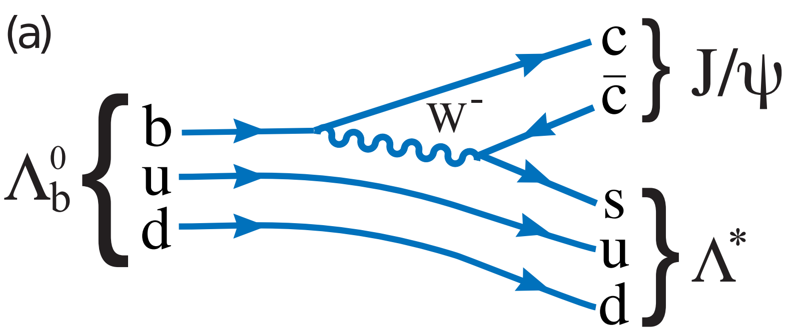
$\Lambda_b^0 \to K^- p\, J/\psi$ for precise measurement of the Λ_b^0 life time.

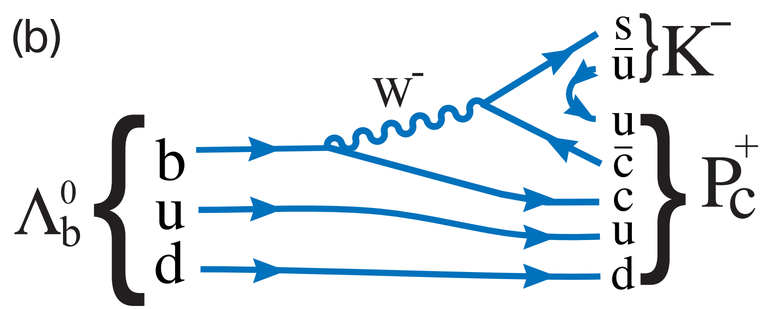
The dominant decay mode through Λ^*

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

Small exotic contribution

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



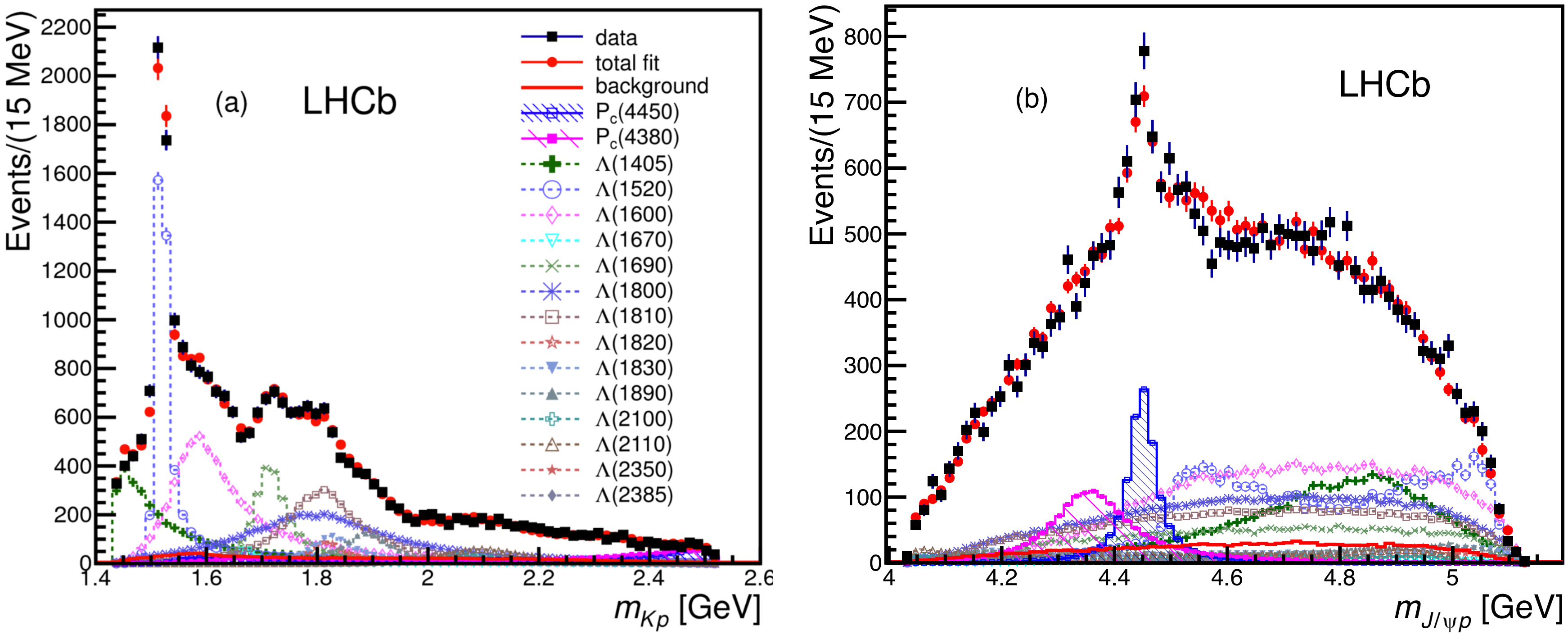


R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 115, 072001

$J/\psi p$ pentaquark states

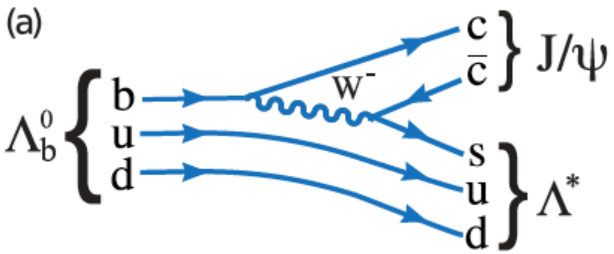
Two exotic $c\bar{c}uud$ 5-quark states, P_c^+, were introduce to fit mass distributions

M_-=4380±8±29 MeV	M_+=4449.8±1.7±2.5 MeV
Γ_-=205±18±86 MeV	Γ_+=39±5±19 MeV
$J^P=3/2^-$	$J^P= 5/2^+$



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

limited L — All possible L

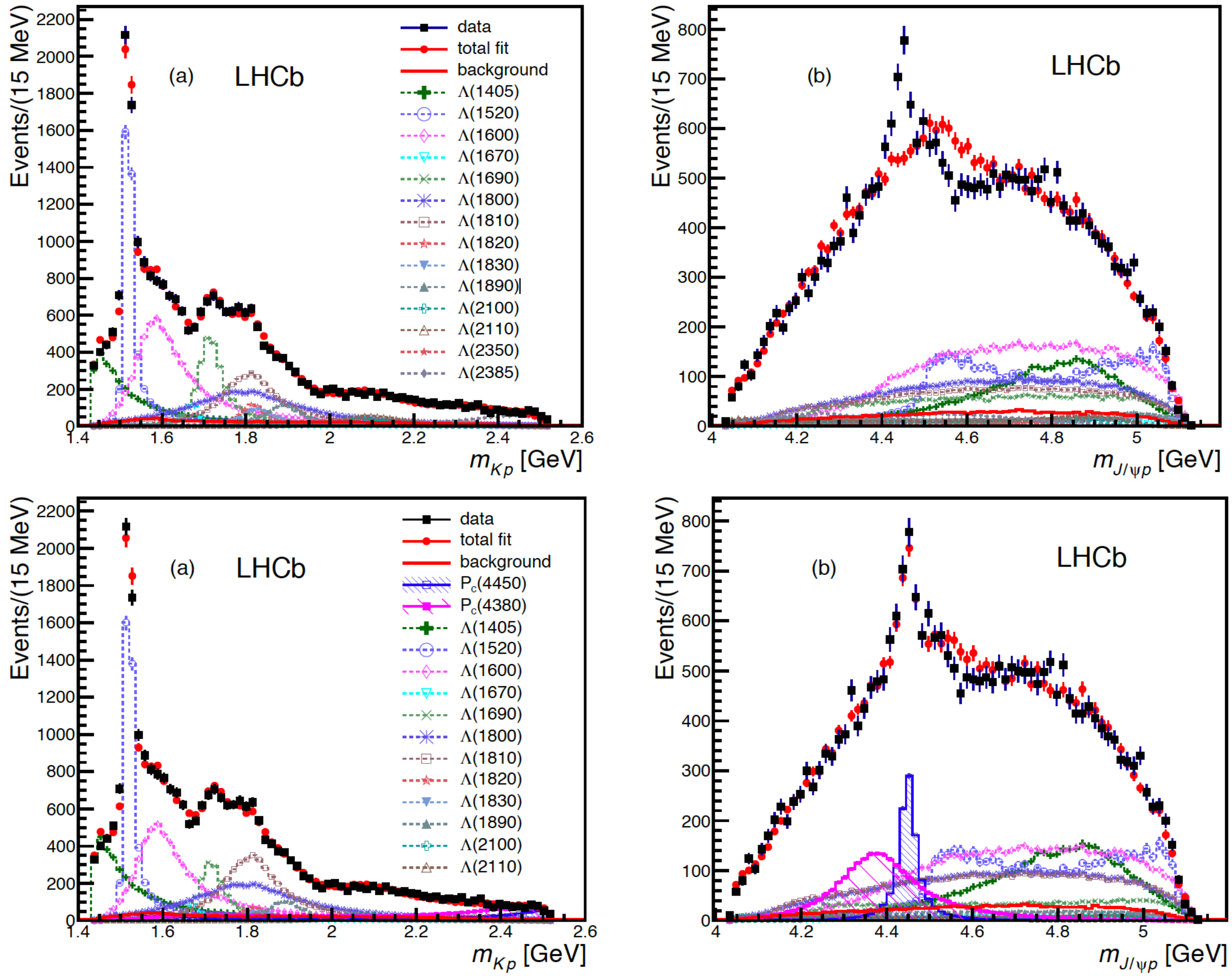
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	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

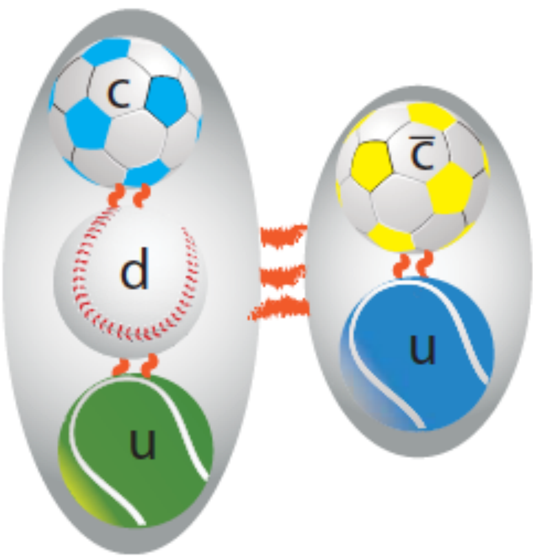
With pentaquarks



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

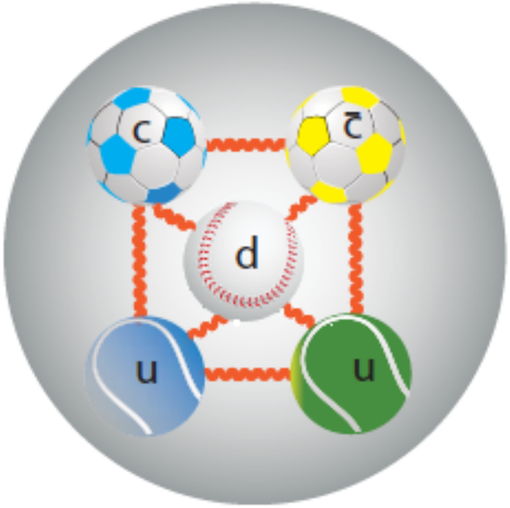


$$\bar{D}^*\Sigma_c - \bar{D}^*\Sigma_c^*$$

- 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. Anisovichet al., arXiv:1507.07652
- A. Mironov and A. Morozov, JETP Lett. 102, no. 5, 271 (2015)
- R. F. Lebed, Phys. LeN. B 749, 454 (2015)

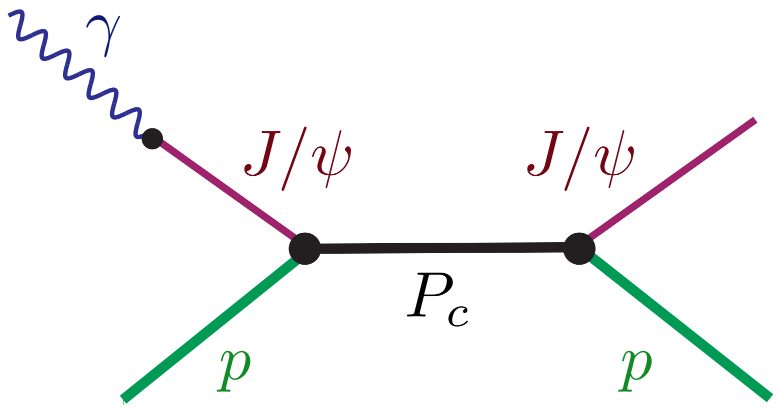
or reflection

- 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



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

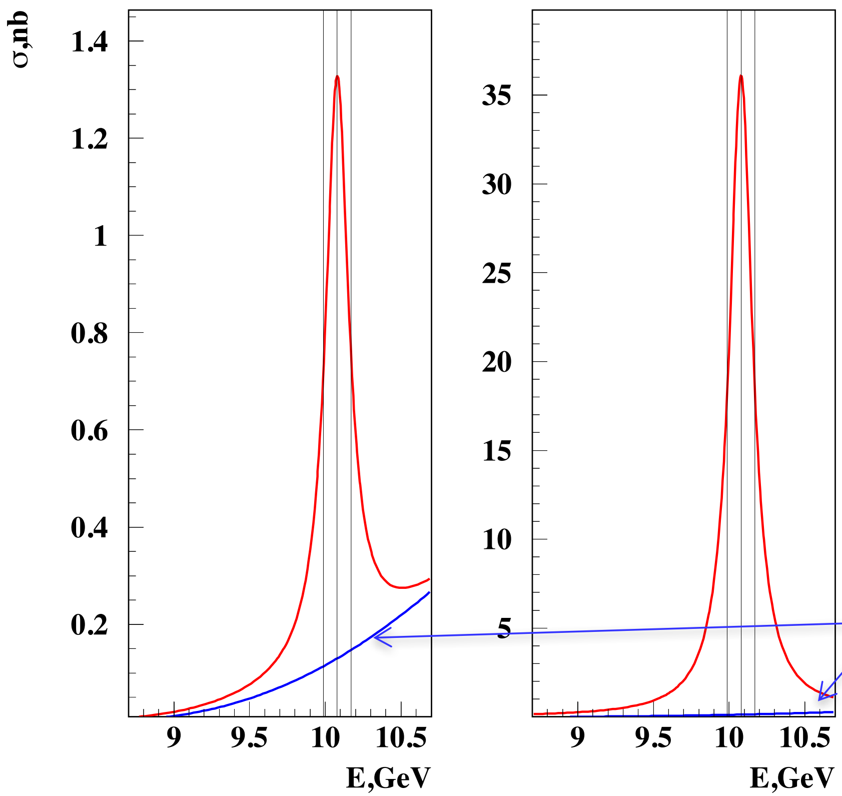
$$\Gamma(P_c \to \gamma + p) = \frac{3\Gamma_{ee}(J/\psi)}{\alpha\, M(J/\psi)} \sum_L f_L \left(\frac{k}{p}\right)^{2L+1} \Gamma_L(P_c \to J/\psi + p)$$

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

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

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



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

$$Br(P_c(4450) \to pJ/\psi) = 0.01$$

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)

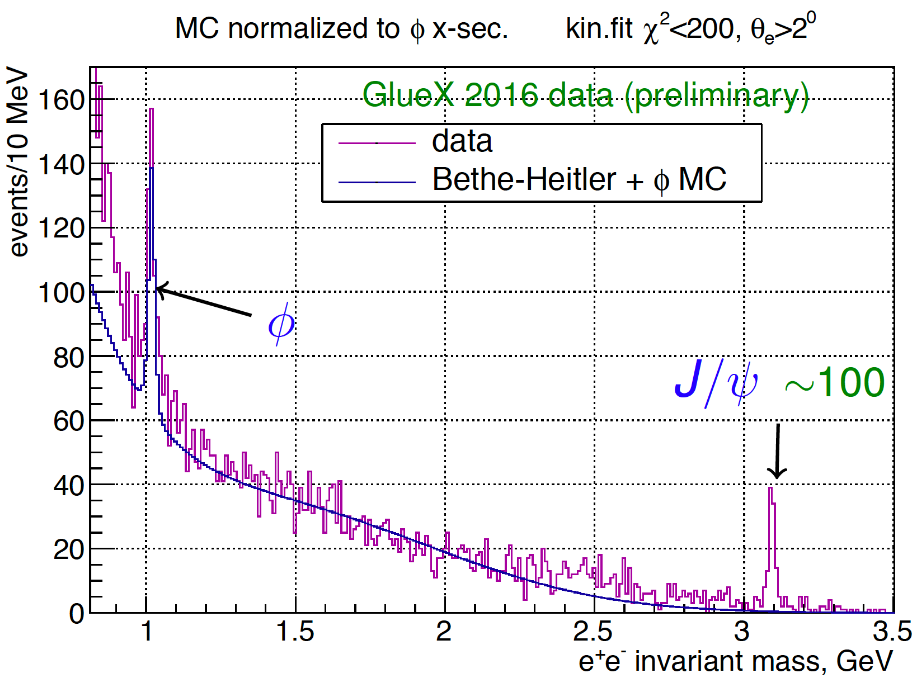
V. Kubarovsky and M.B. Voloshin, arXiv:1508.00888.

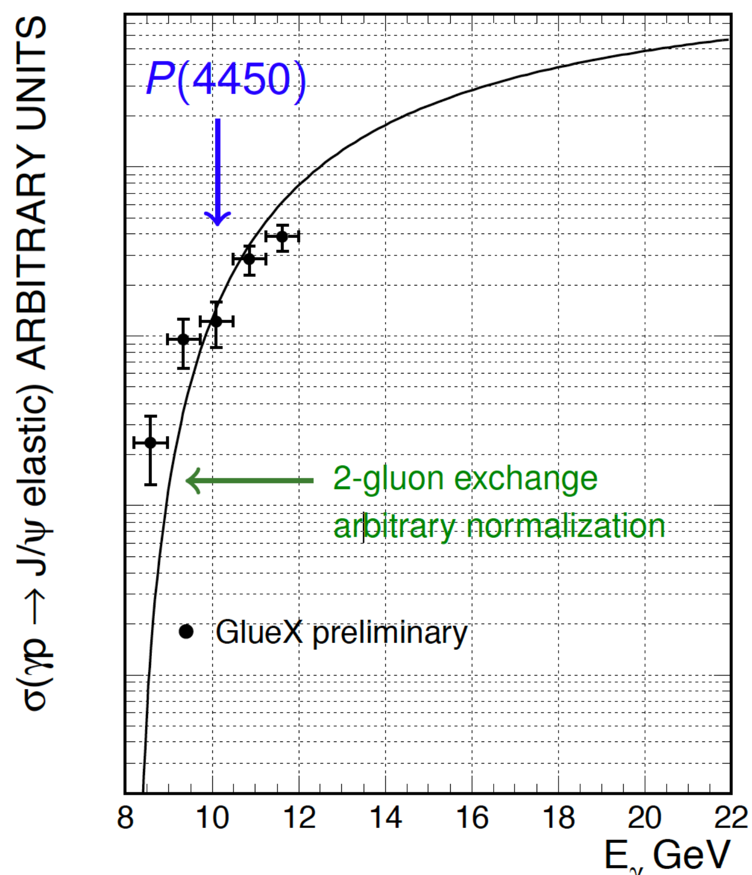
JLAB12 – a new energy regime

- 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

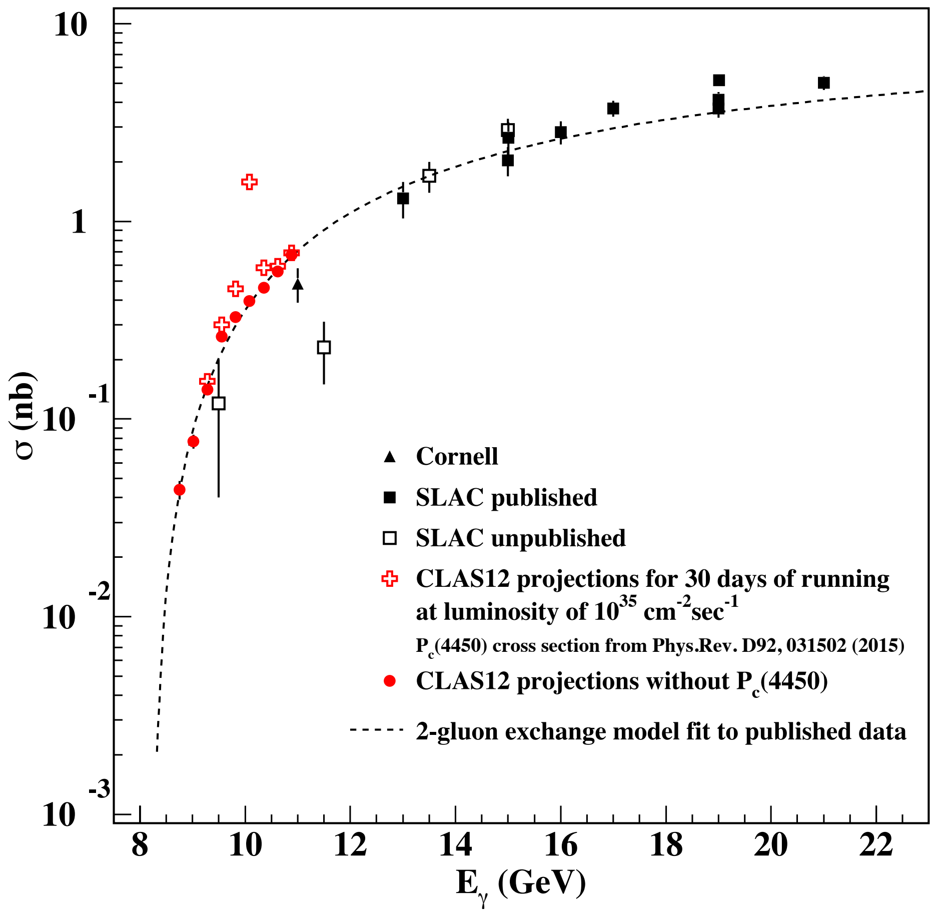
- All 2016 data: exclusive events pe^+e, the e^+e^- PID using the electromagnetic calorimeters BCAL and FCAL. Kinematic fit with the beam energy from the tagger
- Planned measurements, after adding the 2017 Spring data will limit the pentaquark yield (the mass resolution 6 MeV/c^2)





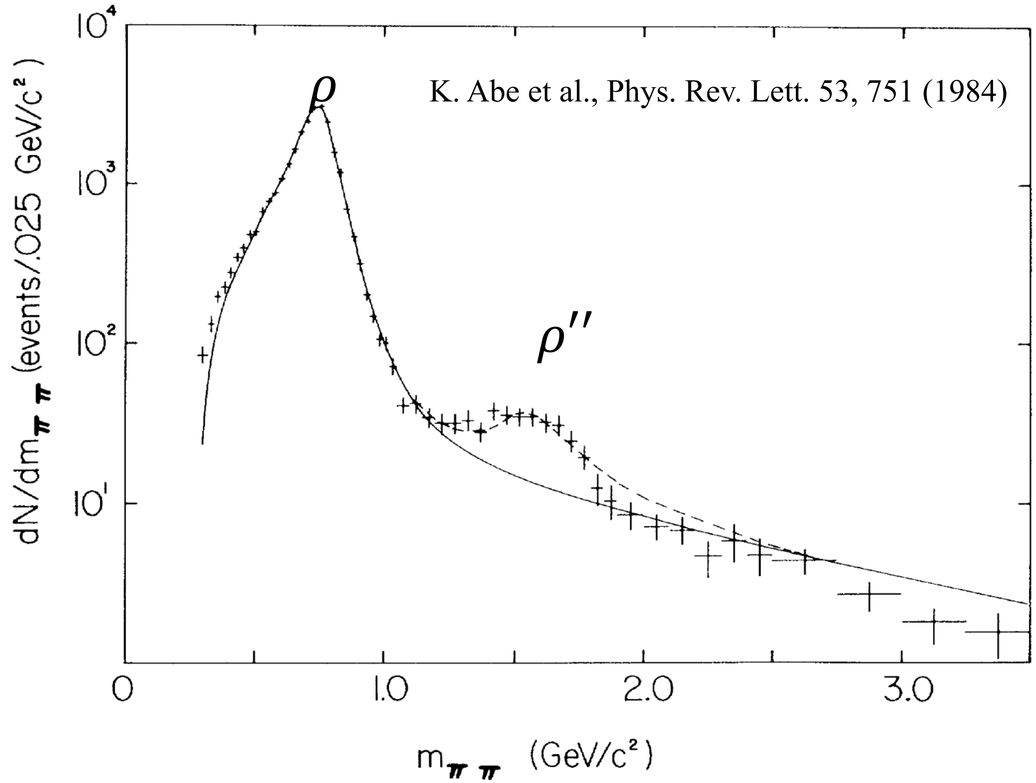
Expectations from JLAB experiments, $J/\psi \rightarrow e^+e^-$

- From the two gluon exchange prediction for cross section, we expect total of 45 J/ψ detected per day in the whole energy rage
- 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 ~42 J/ψ 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 rage $\sigma_{tot}^{\pi\pi} \approx 15\ \mu b$
- The fraction of pion pairs with $M_{\pi\pi}$ > 3 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 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 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