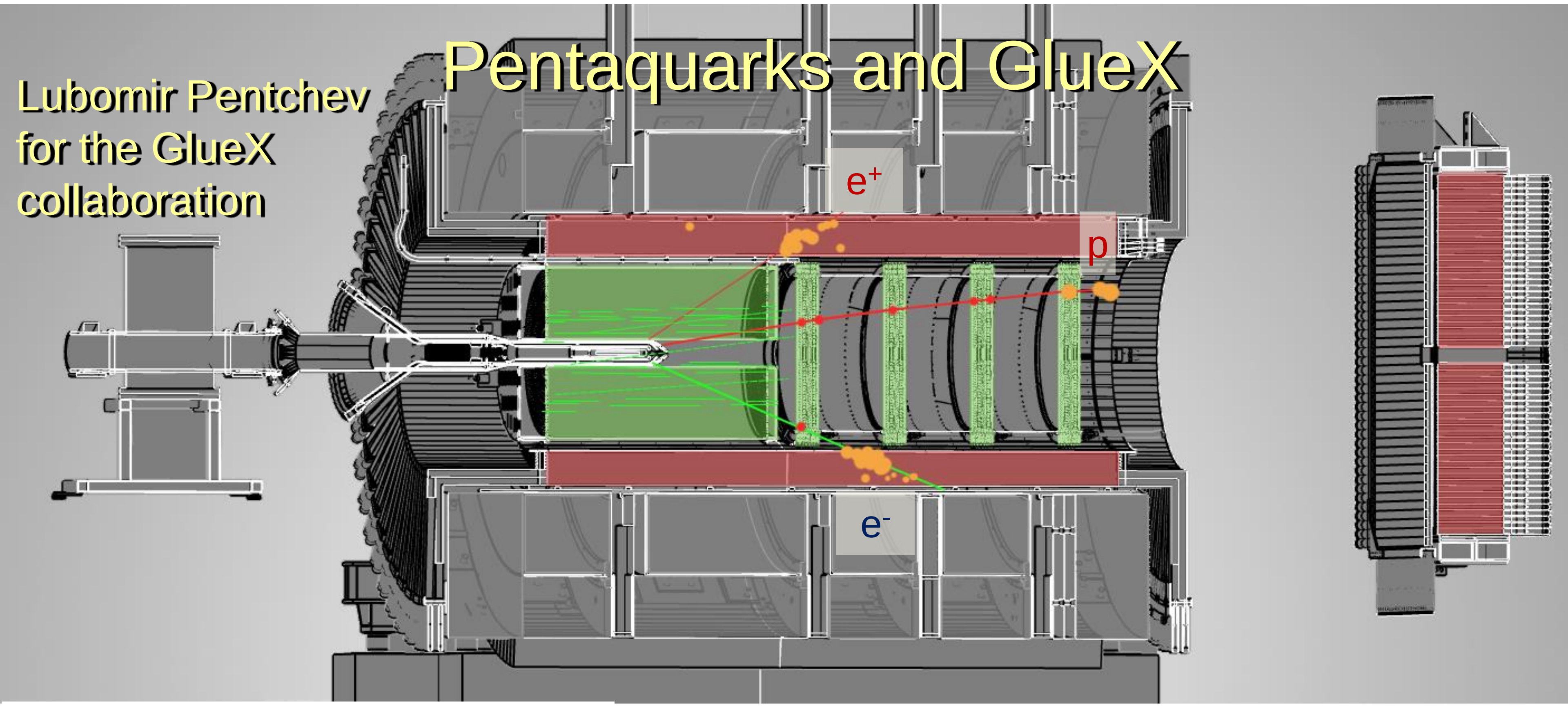
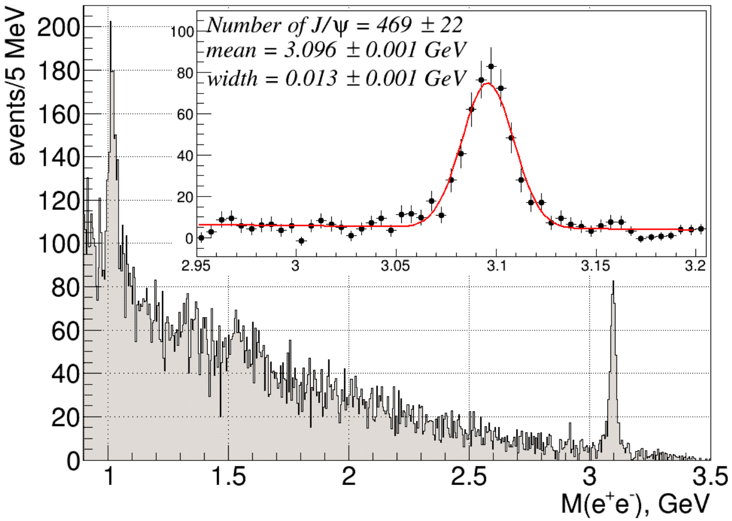
# Pentaquarks and GlueX

Lubomir Pentchev
for the GlueX
collaboration

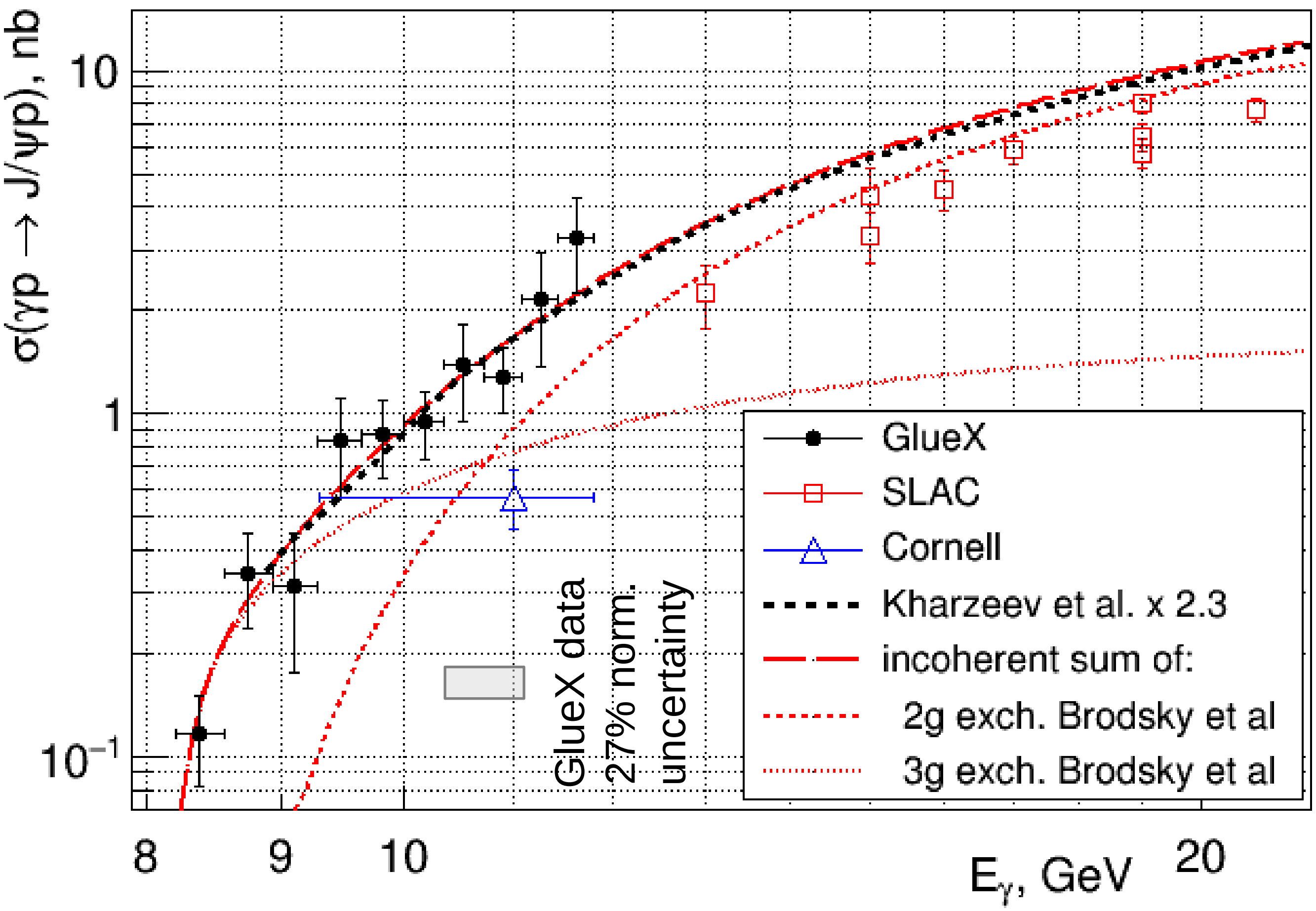



*GlueX collaboration:*
*"First measurement of near-threshold J/ψ exclusive photoproduction off the proton"*

*arXiv:1905.10811 (May 26) submitted to PRL*

# J/ψ total cross-section




GlueX errors: quadratic sums of statistical and systematic ones

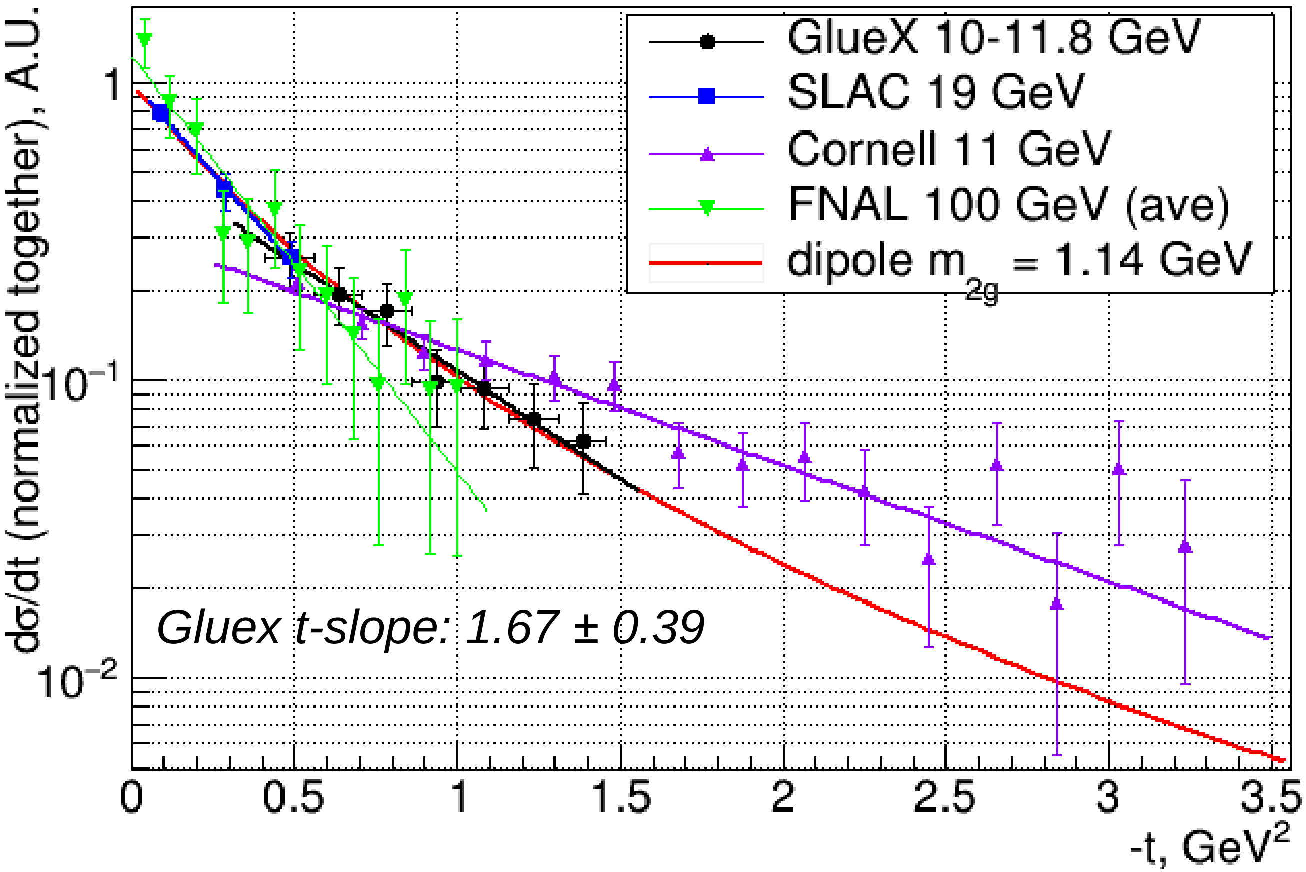
SLAC data: $\gamma d(p) \rightarrow J/\psi X$ calculated from $d\sigma/dt(t=t_{min})$ using:
$F^2(t) = 1/(1-t/m_{2g}^2)^4$
$m_{2g}$ = 1.14 GeV

Cornell data: $\gamma Be \rightarrow J/\psi X$

- *Brodsky et al*.: $\sigma(E_\gamma)$ depending on number of hard-gluons exchanged.
- *Kharzeev et al*.: real part of the amplitude dominates, contains scale anomaly term related to the mass of the proton arising from gluons.

**GlueX data falls toward threshold less steeply than 2g exchange model**

# J/ψ differential cross-section and proton gluonic FF




Using VMD (γ→J/ψ) one can study J/ψ p → J/ψ p and the gluonic form factor (dipole form in analogy with the e.-m. FF):

$$F(t) \sim 1/(1-t/m_0^2)^2$$

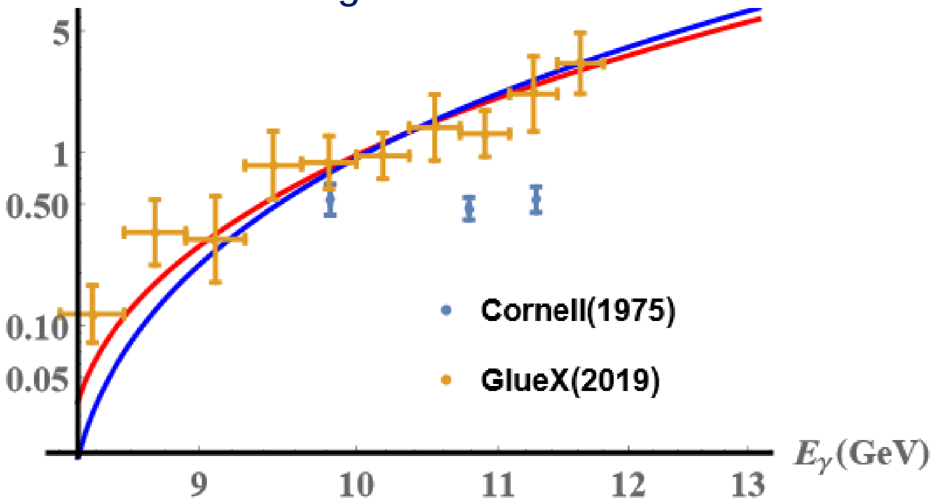
*Frankfurt and Strikman PRD66 (2002)*

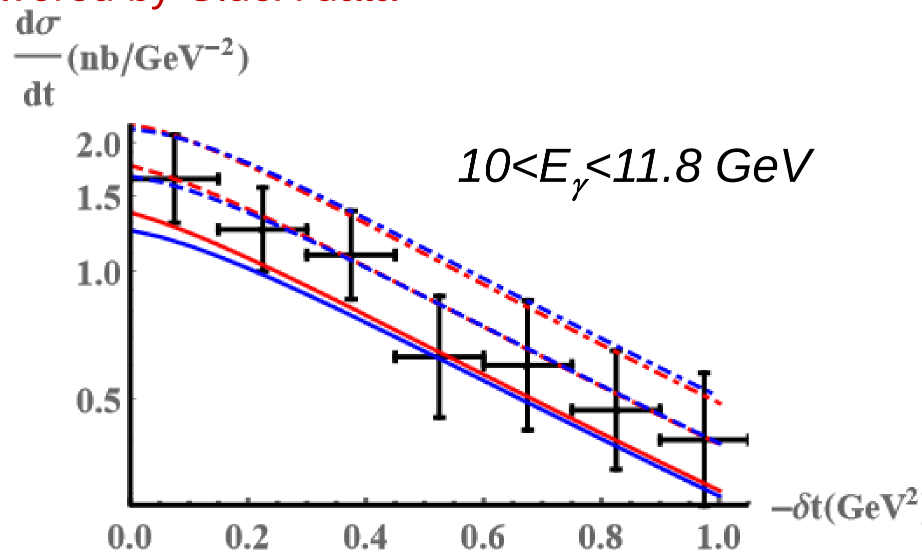
| | e.m. FF | gluonic FF |
|---|---|---|
| reaction | $ep \rightarrow ep$ | $J/\psi p \rightarrow J/\psi p$ |
| transverse size of probe | 0 | $<< 1\ fm$ |
| effective mass scale $m_0$ | 0.84 $GeV$ (vector meson) | ~ 1.1 $GeV$ (two-gluon mass) |

# Near-threshold J/ψ cross-sections and gluonic contribution to the mass of the proton

Red – maximal contribution from gluons favored by GlueX data

Blue – no gluonic contribution




*Y. Hatta, A. Rajan, and D.-L. Yang, https://arxiv.org/abs/1906.00894:*

Proton gluonic FF: "..these are nothing but the gravitational form factors $A_g, B_g, C_g, \bar{C}_g$"

$$\langle P'|(T_g)^\mu_\mu|P\rangle = \langle P'|\left(\frac{\beta(g)}{2g}F^a_{\mu\nu}F^{\mu\nu}_a + m\gamma_m\bar{\psi}\psi\right)|P\rangle$$

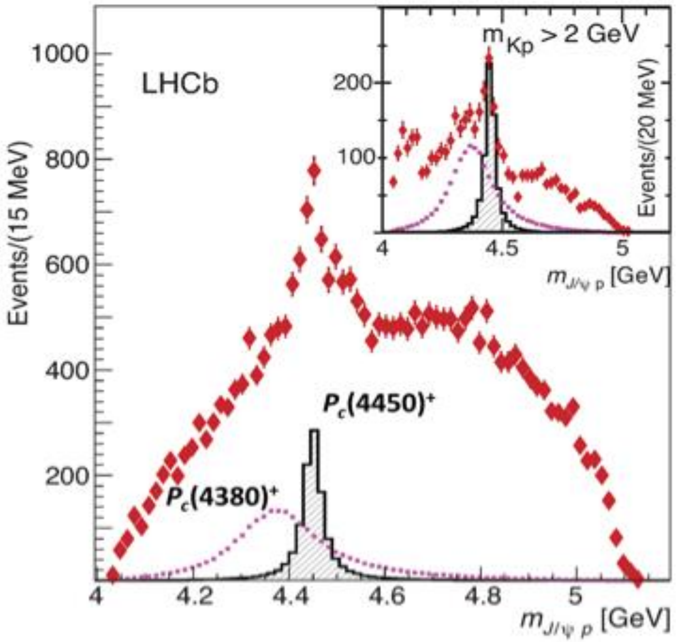
$$= \bar{u}(P')\left[A_g M + \frac{B_g}{4M}\Delta^2 - 3\frac{\Delta^2}{M}C_g + 4\bar{C}_g M\right]u(P)$$

$A_g, B_g, C_g$ were recently calculated on lattice:

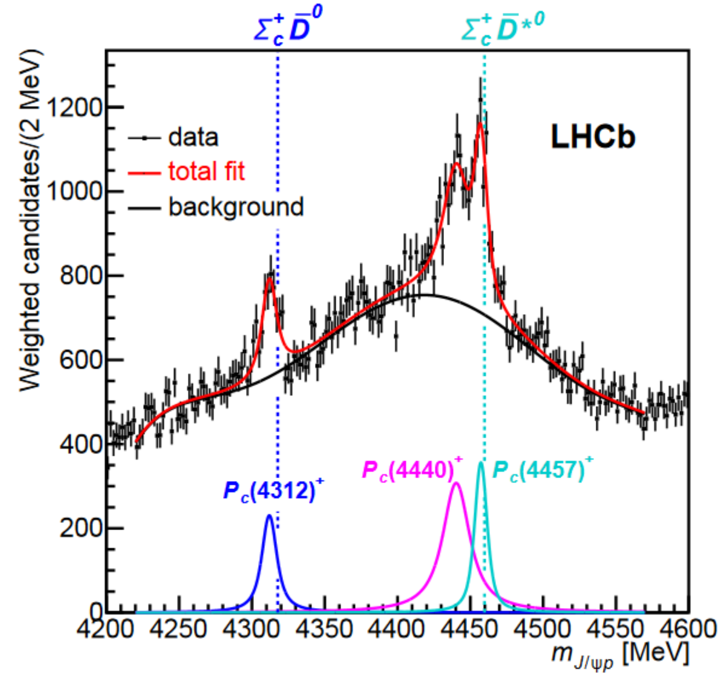
*P. E. Shanahan and W. Detmold, https://arxiv.org/abs/1810.04626*

# LHCb pentaquarks

$$\Lambda_b^0 \to J/\psi p K^-$$




*Phys. Rev. Lett.,115,072001 (2015)*



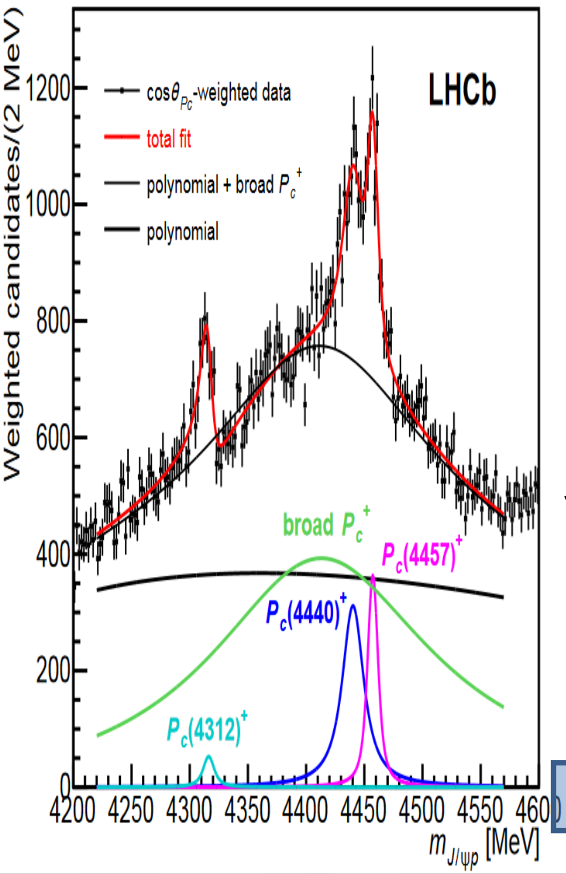

*Phys. Rev. Lett. 122, 222001 (2019)*

- $J^P$ of $P_c$ states not determined yet
- Molecules (most likely), but compact states or rescattering effects not excluded

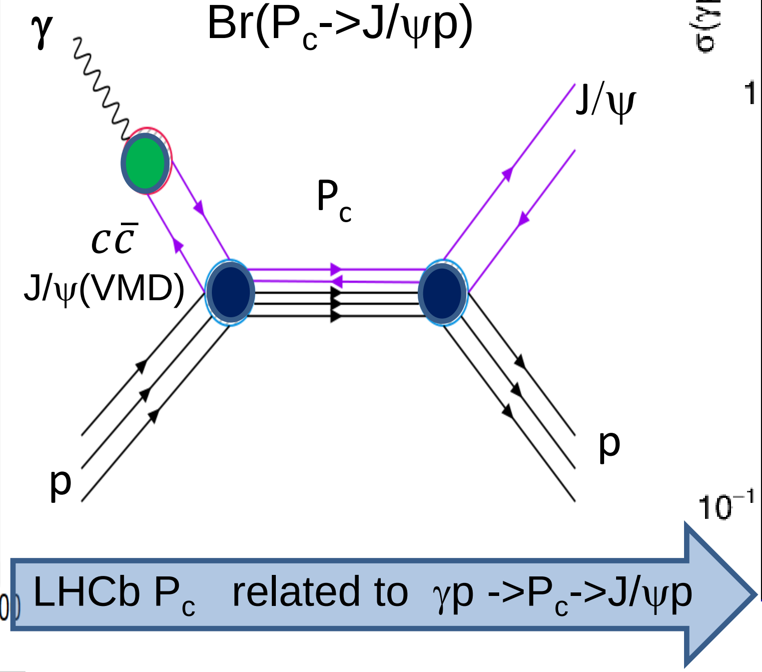
| State | $M$ [MeV] | $\Gamma$ [MeV] | (95% CL) | $\mathcal{R}$ [%] |
|---|---|---|---|---|
| $P_c(4312)^+$ | $4311.9 \pm 0.7^{+6.8}_{-0.6}$ | $9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$ | $(< 27)$ | $0.30 \pm 0.07^{+0.34}_{-0.09}$ |
| $P_c(4440)^+$ | $4440.3 \pm 1.3^{+4.1}_{-4.7}$ | $20.6 \pm 4.9^{+\ 8.7}_{-10.1}$ | $(< 49)$ | $1.11 \pm 0.33^{+0.22}_{-0.10}$ |
| $P_c(4457)^+$ | $4457.3 \pm 0.6^{+4.1}_{-1.7}$ | $6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$ | $(< 20)$ | $0.53 \pm 0.16^{+0.15}_{-0.13}$ |

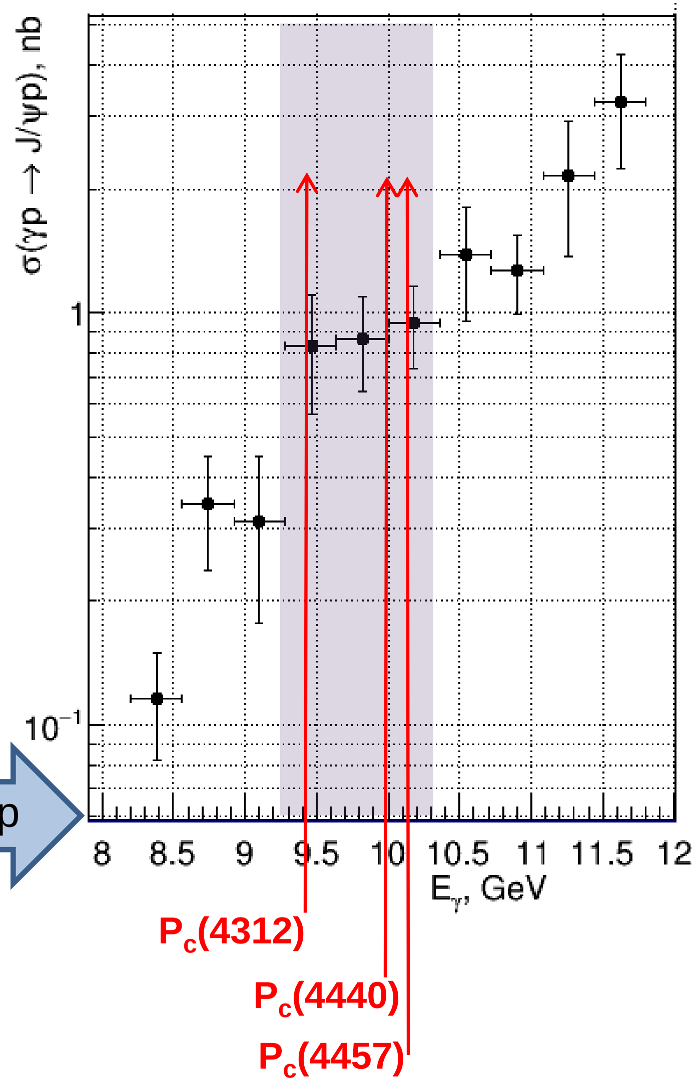
# LHCb pentaquarks and J/ψ photo-production

- If LHCb pentaquarks exist they should be seen in s-channel photoproduction (free of rescattering effects in the final state):



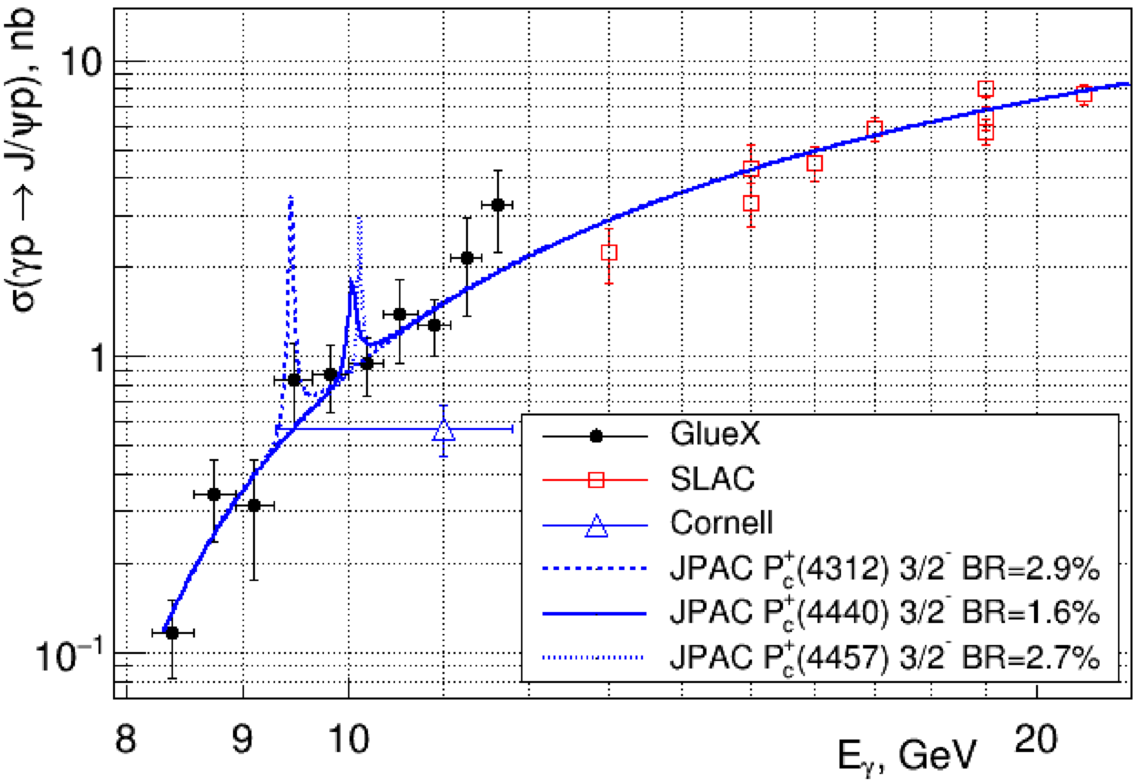

Main uncertainty Br($P_c$->J/ψp)




- *V.Kubarovsky and M.B.Voloshin, PRD 92.031502 (2015).*
- *M.Karliner and J.Rosner, arXiv: PLB 752, 329 (2016).*
- *A.Blin, C.Fernandez-Ramirez, A.Jackura, V.Mathieu, V.Mokeev, A.Pilloni, and A.Szczepaniak, PRD 94,034002 (2016).*

# J/ψ cross-section: model-dependent upper limits



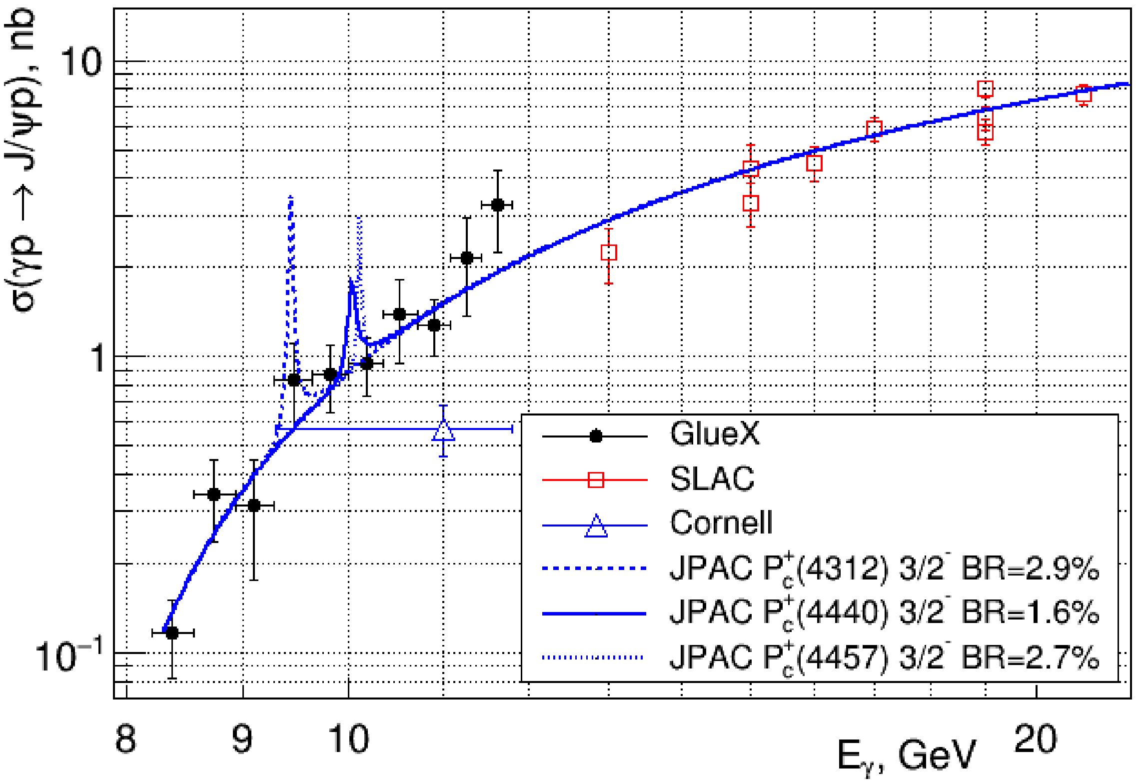

Assuming:

- all $P_c$ independent $J^P = 3/2^-$
- s-channel model: $\sigma(\gamma p \to P_c \to J/\psi p) \approx 0.35\ \mu b\ Br^2(P_c \to J/\psi p)\ (2J+1)$
- JPAC model for t-channel: Pomeron and tensor part extracted at high energies

| | $\mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, % | | $\sigma_{\max} \times \mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, nb | |
|---|---|---|---|---|
| | p.t.p. only | total | p.t.p only | total |
| $P_c^+(4312)$ | 2.9 | 4.6 | 3.7 | 4.6 |
| $P_c^+(4440)$ | 1.6 | 2.3 | 1.2 | 1.8 |
| $P_c^+(4457)$ | 2.7 | 3.8 | 2.9 | 3.9 |

Upper limits at 90% confidence level

# J/ψ cross-section: model-dependent upper limits




Assuming:

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| | $\mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, % p.t.p only | total | $\sigma_{max} \times \mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, nb p.t.p only | total |
|---|---|---|---|---|
| $P_c^+(4312)$ | 2.9 | 4.6 | 3.7 | 4.6 |
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| $P_c^+(4457)$ | 2.7 | 3.8 | 2.9 | 3.9 |

Upper limits at 90% confidence level

# Br($P_c \to J/\psi p$) calculations: pentaquark models

| model | $\Gamma_{P_c}$, MeV | $\Gamma_{J/\psi p}$, MeV | $\mathcal{B}(P_c \to J/\psi p)$ | $J^P$ | reference |
|---|---|---|---|---|---|
| molecular | 21.7 (4450) | 0.03 (4450) | 0.14% (4450) | $1/2^-$ (4312) | M.Eides and V.Petrov |
| (OPE) | | | | $1/2^-$ (4440) | Phys.Rev.D98, 114037 |
| $\Sigma_c \bar{D}^{(*)}$ | | | | $3/2^-$ (4457) | |
| hadro- | – (4312) | suppr.(4312) | suppr. (4312) | $1/2^+$ (4312) | same as above |
| charmonium | 44.8 (4440) | 11 (4440) | 25% (4440) | $1/2^-$ (4440) | and M.Eides, V.Petrov |
| | 16.2 (4457) | 11 (4457) | 68% (4457) | $3/2^-$ (4457) | M.Polyakov,arXiv:1904.1161 |
| compact | – | suppressed | suppressed | $3/2^-$ (4312) | A.Ali, A.Parkhomenko |
| diquark | | | | $3/2^+$ (4440) | Phys.Lett.B793, 365 |
| | | | | $5/2^+$ (4457) | |
| molecular | 9.8* (4312) | 6.5 | 66% | $1/2^-$ (4312) | Z.-H. Guo and J.Oller |
| (ERE) | 20.6* (4440) | 16.3 | 79% | $1(3)/2^-$ (4440) | Phys.Lett.B793, 144 |
| $\Sigma_c \bar{D}^{(*)}$ | 6.4* (4457) | 3.5 | 55% | $1(3)/2^-$ (4457) | |
| molecular | 15.2 (4306) | 4** | 26% | $1/2^-$ (4306) | C.Xiao, J.Nieves, E.Oset, |
| (DSE) | 23.4 (4453) | 18** | 77% | $1/2^-$ (4453) | arxiv:1904.01296 |
| $\Sigma_c \bar{D}^{(*)}$ | 3.0(4453) | 2** | 67% | $3/2^-$ (4453) | Phys.Rev.D88, 056012 |

* The total width measured by LHCb has been used.

** The width calculated from coupling constants.

# Br(Pc → J/ψp) calculations: molecular vs hadrocharmonium

| model | $\Gamma_{P_c}$, MeV | $\Gamma_{J/\psi p}$, MeV | $\mathcal{B}(P_c \to J/\psi p)$ | $J^P$ | reference |
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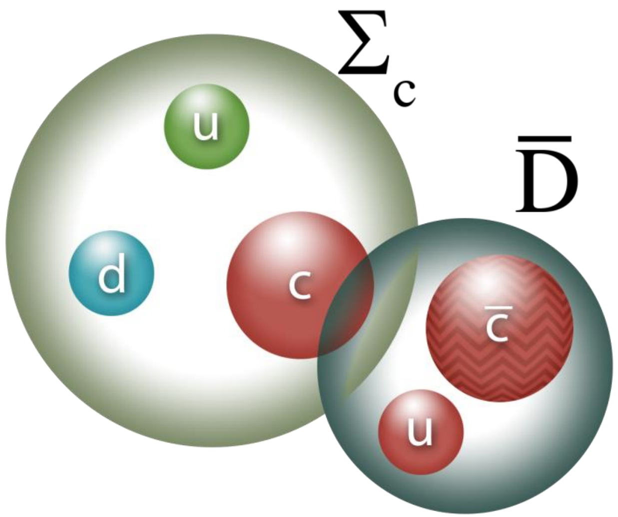
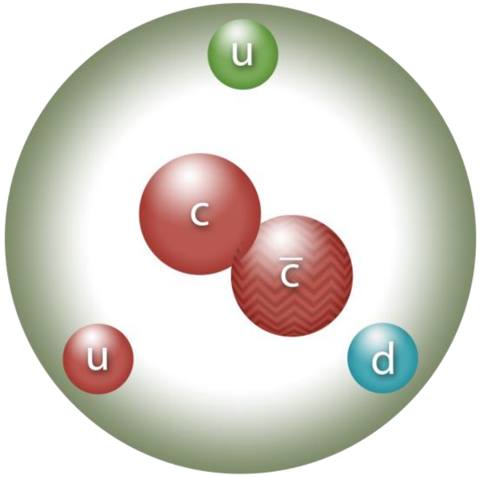
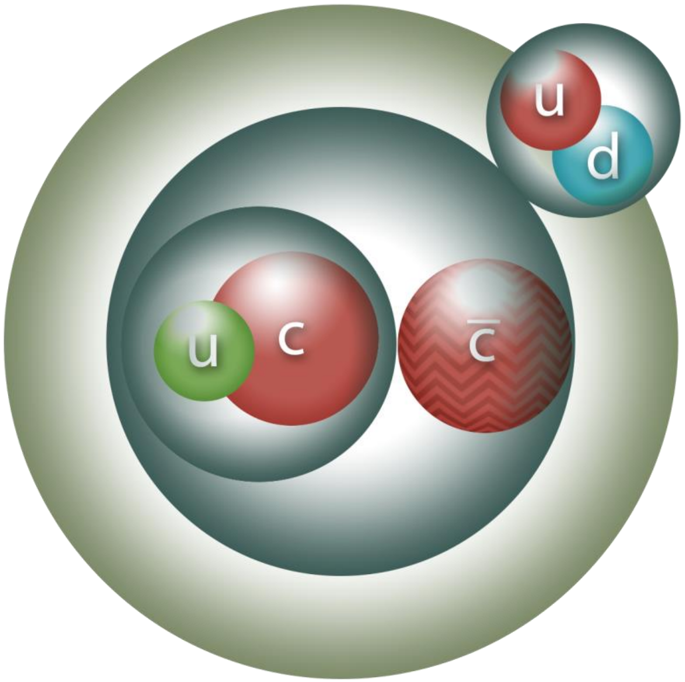
| (OPE) | | | | $1/2^-$ (4440) | Phys.Rev.D98, 114037 |
| $\Sigma_c \bar{D}^{(*)}$ | | | | $3/2^-$ (4457) | |
| hadro- | – (4312) | suppr.(4312) | suppr. (4312) | $1/2^+$ (4312) | same as above |
| charmonium | 44.8 (4440) | 11 (4440) | 25% (4440) | $1/2^-$ (4440) | and M.Eides, V.Petrov |
| | 16.2 (4457) | 11 (4457) | 68% (4457) | $3/2^-$ (4457) | M.Polyakov,arXiv:1904.1161 |



# Br(Pc → J/ψp) calculations: compact diquark

| | | | | | |
|---|---|---|---|---|---|
| compact diquark | – | suppressed | suppressed | $3/2^-$ (4312)<br>$3/2^+$ (4440)<br>$5/2^+$ (4457) | A.Ali, A.Parkhomenko<br>Phys.Lett.B793, 365 |




Diquarks in color anti-triplet states

The bound-state effect in (uC)-diquark reduces the probability to form $C\bar{C}$ -state

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| | | | | $5/2^+$ (4457) | |
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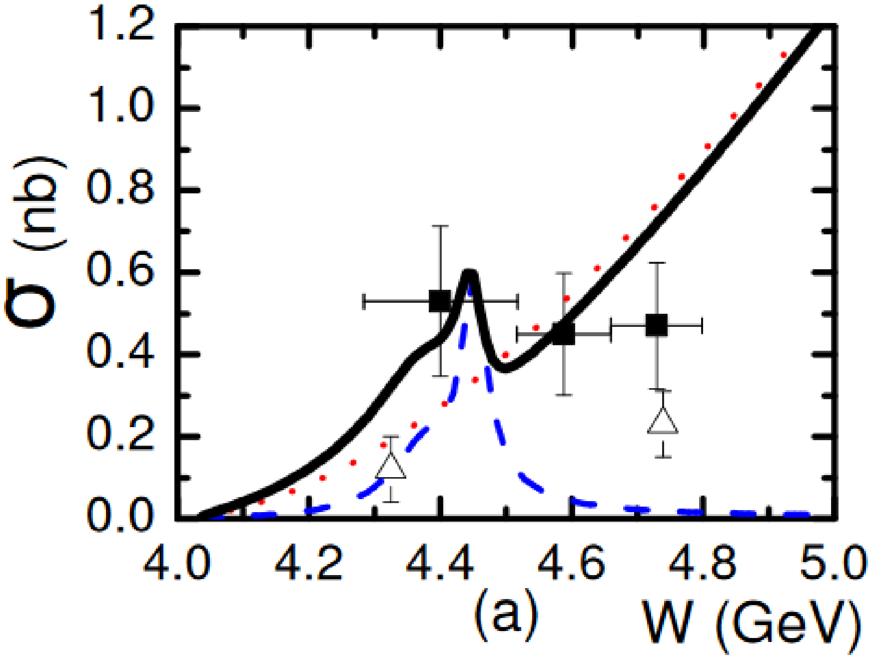
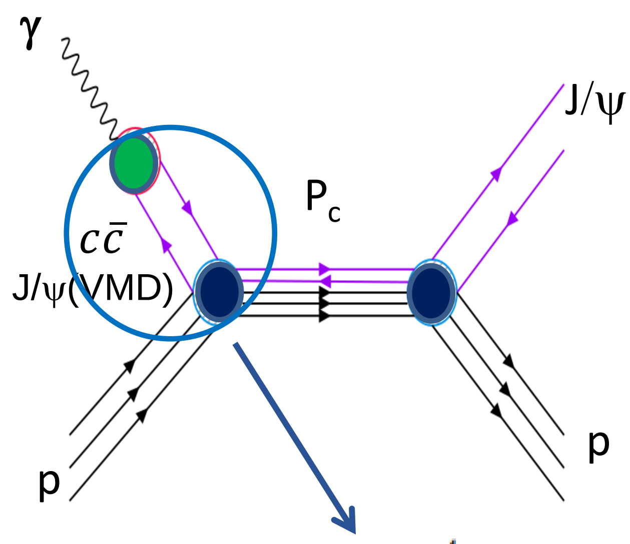
* The total width measured by LHCb has been used.

** The width calculated from coupling constants.

# Attempts to suppress VMD coupling

*J.-J. Wu, T.-S. Lee, B-S. Zou arXiv:1906.05375*



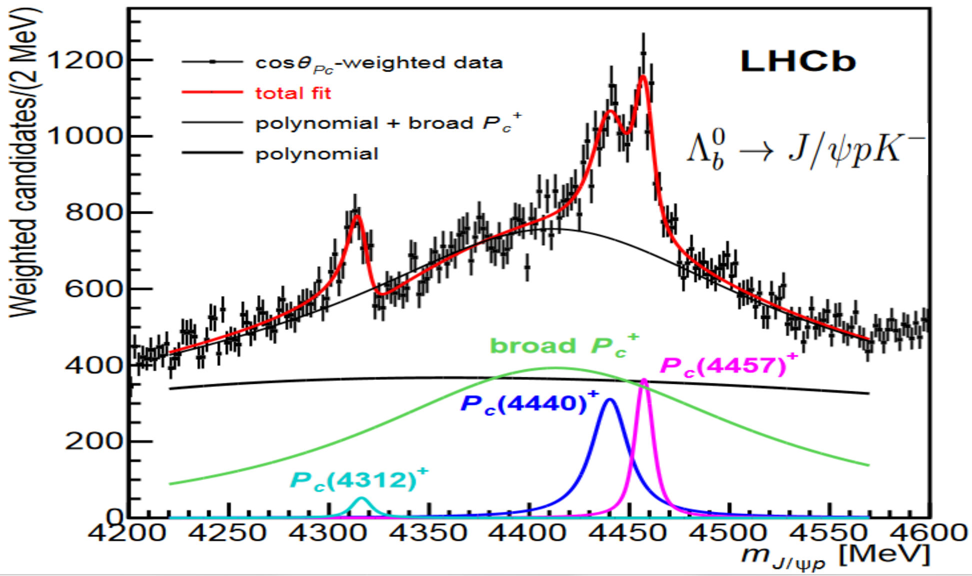




$$F_V(q) = \frac{\Lambda_V^4}{\Lambda_V^4 + (q^2 - m_V^2)^2}$$

$$\Lambda = 0.55 \text{ GeV}$$

- J/ψ is suppressed by $10^{-3}$, VMD coupling dominated by ρ and ω
- How to explain J/ψ photoproduction at high energies with such suppression???
- Other papers (*J. Phys. G4 (1978) 989, Phys. Rev. Lett. 38 (1977) 263)* suggest some moderate suppression (2-3)

# Lower limits on Br($P_c \to J/\psi p$) from data?




X. Cao, J-P. Dai *arXiv:1904.06015*

$$\mathcal{R} = \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

$$\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-) = (3.2^{+0.6}_{-0.5}) \times 10^{-4}$$

$$\mathcal{B}(\Lambda_b \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = \begin{cases} (0.96^{+1.13}_{-0.39}) \times 10^{-6} & \text{for} \quad P_c(4312)^+, \\ (3.55^{+1.43}_{-1.24}) \times 10^{-6} & \text{for} \quad P_c(4440)^+, \\ (1.70^{+0.77}_{-0.71}) \times 10^{-6} & \text{for} \quad P_c(4457)^+. \end{cases}$$

$$\mathcal{B}(\Lambda_b \to P_c^+ K^-) < 10^{-3}$$

at level of $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$ and $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-)$

(model dependent 2-4%) $> \mathcal{B}(P_c^+ \to J/\psi p) > 0.05\%$

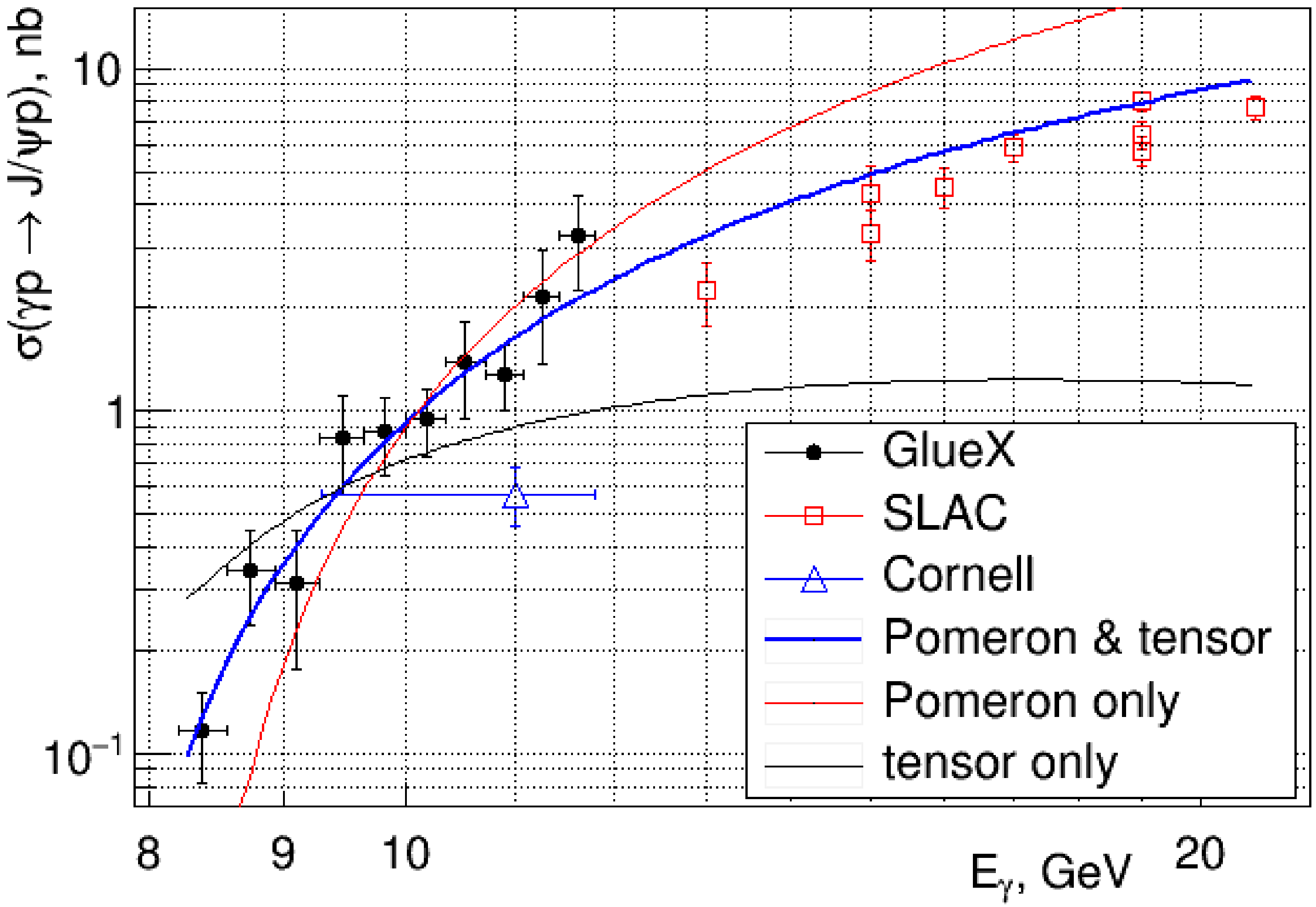
GlueX

# Conclusions

- JLab 12GeV accelerator has unique opportunity (high intensity, correct energy, polarized beam) to study $J/\psi$ photo-production right above the threshold ($E_\gamma$=8.2 GeV) up to 12 GeV
- Do not see evidence for LHCb pentaquarks and set model-dependent limits on $Br(P_c \rightarrow J/\psi p)$ at several percent level, and limits on the $\sigma_{max}(gp \rightarrow Pc)$ $Br(P_c \rightarrow J/\psi p)$ at nb level
- This allows us to discriminate between different pentaquark models. Our results exclude the hadrocharmonium model but not the molecular one
- Extraction of the JP numbers of the penaquark states (by LHCb) will certainly reduce many ambiguities in their interpretation
- Higher statistics results from the other halls will allow to reduce the upper limits or find positive signals
- Depending on these results further experiments might be needed, including polarization observables

# Back-ups

# J/ψ total cross-section: t-channel




JPAC model Pomeron model that includes also tensor part:

A.Blin, C.Fernandez-Ramirez, A.Jackura, V.Mathieu, V.Mokeev, A.Pilloni, and A.Szczepaniak, PRD 94,034002 (2016).