# Near-threshold $J/\psi$ production and $J/\psi$-$N$ interactions

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Physics Opportunities with Heavy Quarkonia at the EIC
October 26th, 2021

# Outline

1. What do we hope to learn from $J/\psi$-N interactions?

2. About the nucleon mass (radius)
3. Scattering length and bound states
4. The search for pentaquark resonances

5. An excursion to existing data so far
6. What we hope to see in future experiments

# 1. What do we hope to learn?

# Heavy quarkonia interacting with nucleons

- **<u>Color van der Waals forces:</u>**
  For $Q\bar{Q}$ systems, which are small on the hadronic scale, a **QCD multipole expansion** is justified in the interaction between nucleons and heavy quarkonium. The leading contribution is a dipole interaction.
- Applicable in $J/\psi$ photoproduction close to threshold (small relative momentum in the final state).
- Attractive force might lead to nucleon/nucleus-quarkonium **bound states**.
  Calculations of binding energies for $J/\psi$ range from 20 MeV down to inexistent even in large nuclei.

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- **Emergence of nucleon mass:**
  from **current quark masses**, **kinetic/potential energy of quarks and gluons** (only fraction of total mass); additionally, **trace anomaly** contribution from QCD energy-momentum tensor (EMT).
  $M_N = M_m + M_q + M_g + M_a$

- Kinetic pieces related to twist-two operators: calculable from DIS data.
  Trace anomaly related to twist-four gluon condensate: near-threshold quarkonium production.

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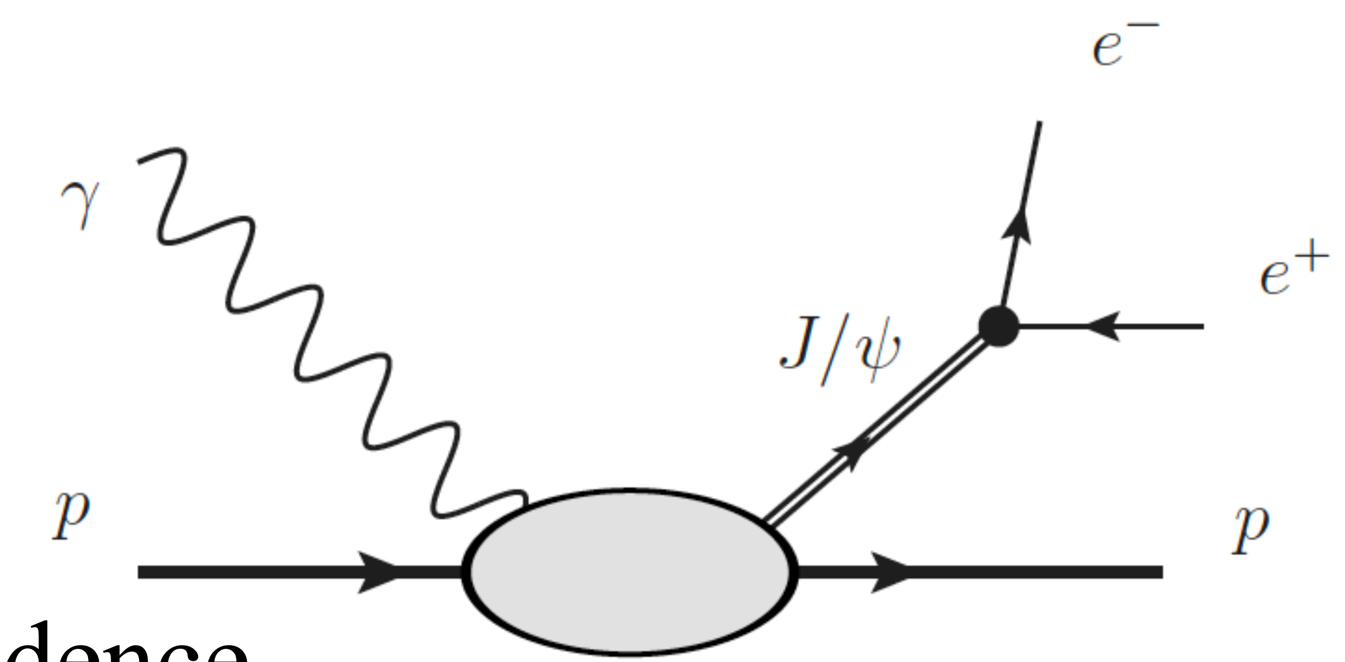
- **Do the quarkonium-nucleon interactions enable the appearance of pentaquark resonances?**

# Near-threshold $J/\psi$ photoproduction at JLab: status




- **GlueX at Hall D:** full $4\pi$ acceptance, no extrapolations needed in $t$ dependence.
  Published analysis of 1D cross sections with $469 \pm 22$ events, ~2000 more events in the pipeline.
  *[Ali et al., PRL 123 (2019) 072001]*

- **CLAS12 at Hall B:** about $2\pi$ acceptance, photoproduction on hydrogen and deuterium.
  Ongoing and planned.
  *[E12-12-001(A); E12-11-003B]*

- **SoLID/SBS at Hall A:** $2\pi$ acceptance and high luminosity.
  To measure inclusive and exclusive electro-/photoproduction, polarization observables.
  *[E12-12-006; LoI12-18-001 (PAC 46)]*

- ***J/ψ*-007 at Hall C:** independent muon and electron decay channels.
  Finalized 2D photoproduction cross sections with ~4000 events, for $P_c$ searches and proton mass radius.
  *[E12-16-007]*

# 2. Proton mass (radius)

# Scrutinizing the nucleon mass (radius)

- The EMT fulfills $\langle p \left| \, T^\alpha_\alpha \, \right| p \rangle = 2M_N^2$.
  In dimensional regularization, $T^\alpha_\alpha = \dfrac{\beta(g)}{2g} F_a^{\alpha\beta} F^a_{\alpha\beta} + m(1+\gamma_m)\bar{\psi}\psi$.

  *[Ji, PRL 74 (1995) 1071; PRD 52 (1995) 271; Front.Phys. 16 (2021) 64601]*

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- Main challenges: what is the anomaly **decomposition** into quark and gluon pieces? Are the **GFF** for each well defined?

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Mass anomalous dimension multiplying **quark** fields comes from regularization of **gluon** fields!

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# Mass decomposition in the proton rest frame

$$M_N = M_m + M_q + M_g + M_a$$

*[Ji, PRD 52 (1995) 271;*
*Hatta and Yang, PRD 98 (2018) 074003]*

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)} b\, m_p$$

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) m_p$$

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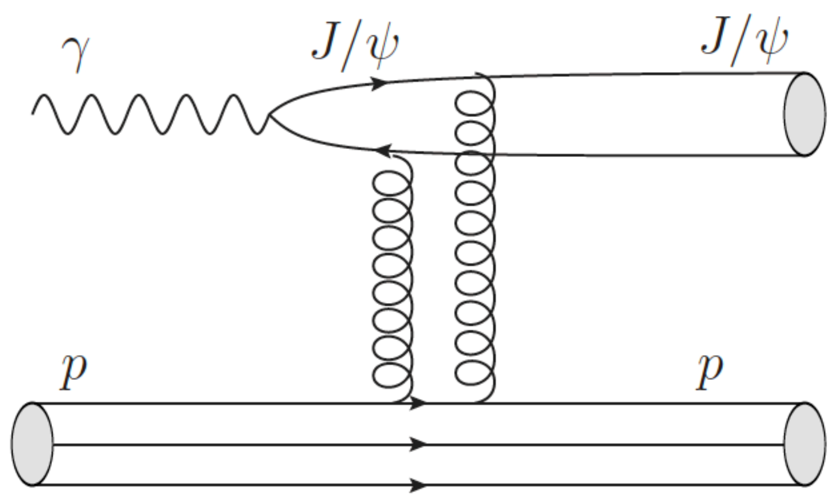
- $a$ and $b$ from lattice QCD or extracted from experiment.
- $M_a$ has not been determined yet:
  $b$ to be assessed in $J/\psi$ production close to threshold,
  which is sensitive to $\left\langle p \middle| F^2 \middle| p' \right\rangle$.
- Many approaches in literature:
  **QCD factorization, lattice QCD, with assumptions of holography, vector-meson dominance, …**
  *[Hatta et al., JHEP 12 (2018) 008;*
  *Hatta and Yang, PRD 98 (2018) 074003;*
  *Hatta et al., PRD 100 (2019) 014032;*
  *Shanahan and Detmold, PRD 99 (2019) 014511;*
  *Sugiura et al., JPS Conf. Proc. 26 (2019) 031015;*
  *Boussarie and Hatta, PRD 101 (2020) 114004;*
  *Guo et al., PRD 103 (2021) 096010;*
  *Lorcé et al., 2109.11785 [hep-ph];*
  *Sun et al., PLB 822 (2021) 136655]*

# Vector-meson dominance (VMD)

- $J/\psi$ elastic scattering is estimated from and directly related to $J/\psi$ photoproduction.

$$\frac{d\sigma}{dt}(\gamma p \to J/\psi p) = \frac{3\Gamma(J/\psi \to e^+e^-)}{\alpha\, m_{J/\psi}} \frac{d\sigma}{dt}(J/\psi p \to J/\psi p) \frac{q^2_{J/\psi p}}{q^2_{\gamma p}} \frac{g^2_{J/\psi}(m_{J/\psi^2})}{g^2_{J\psi}(0)}$$



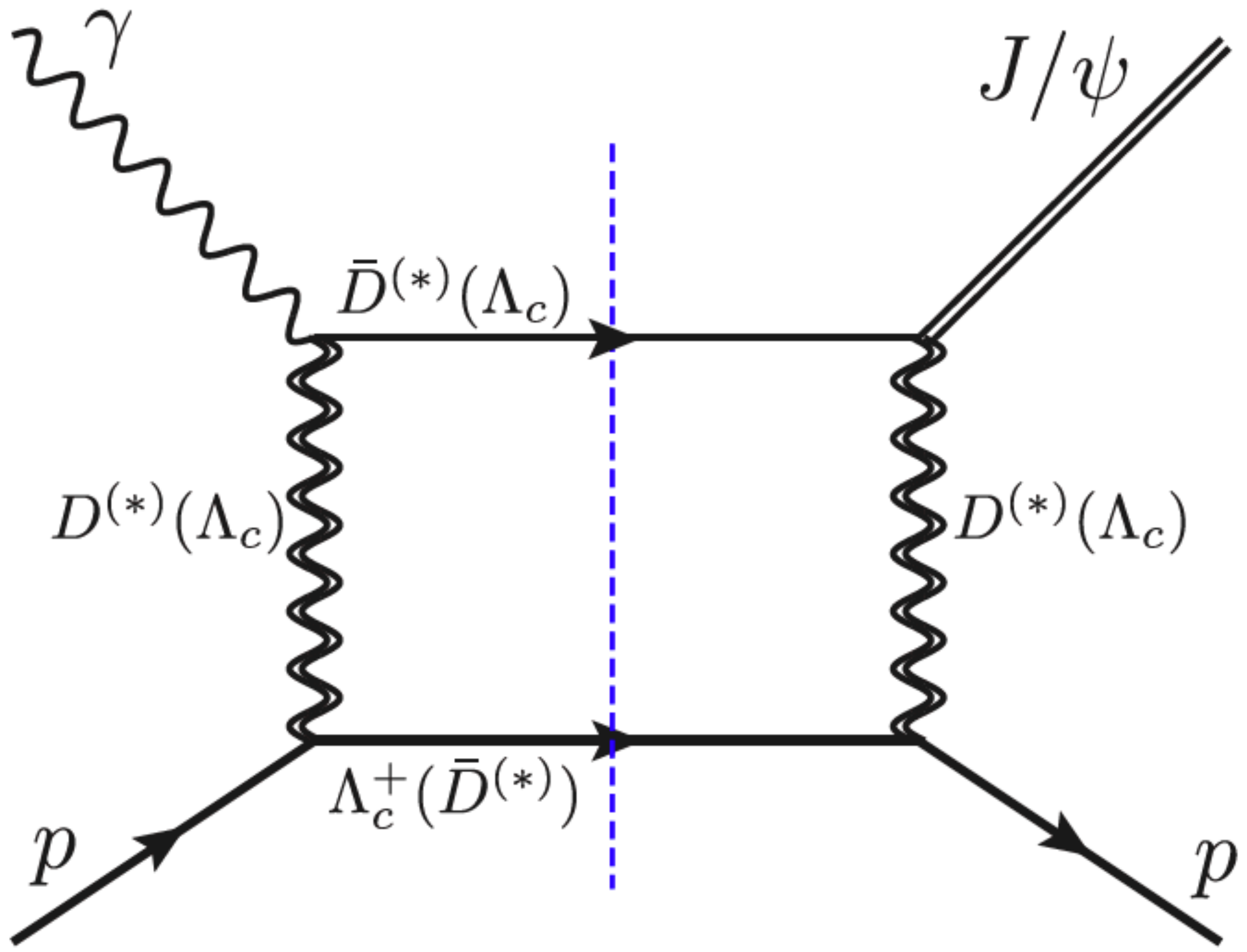

- VMD is an extremely good approximation for light mesons.

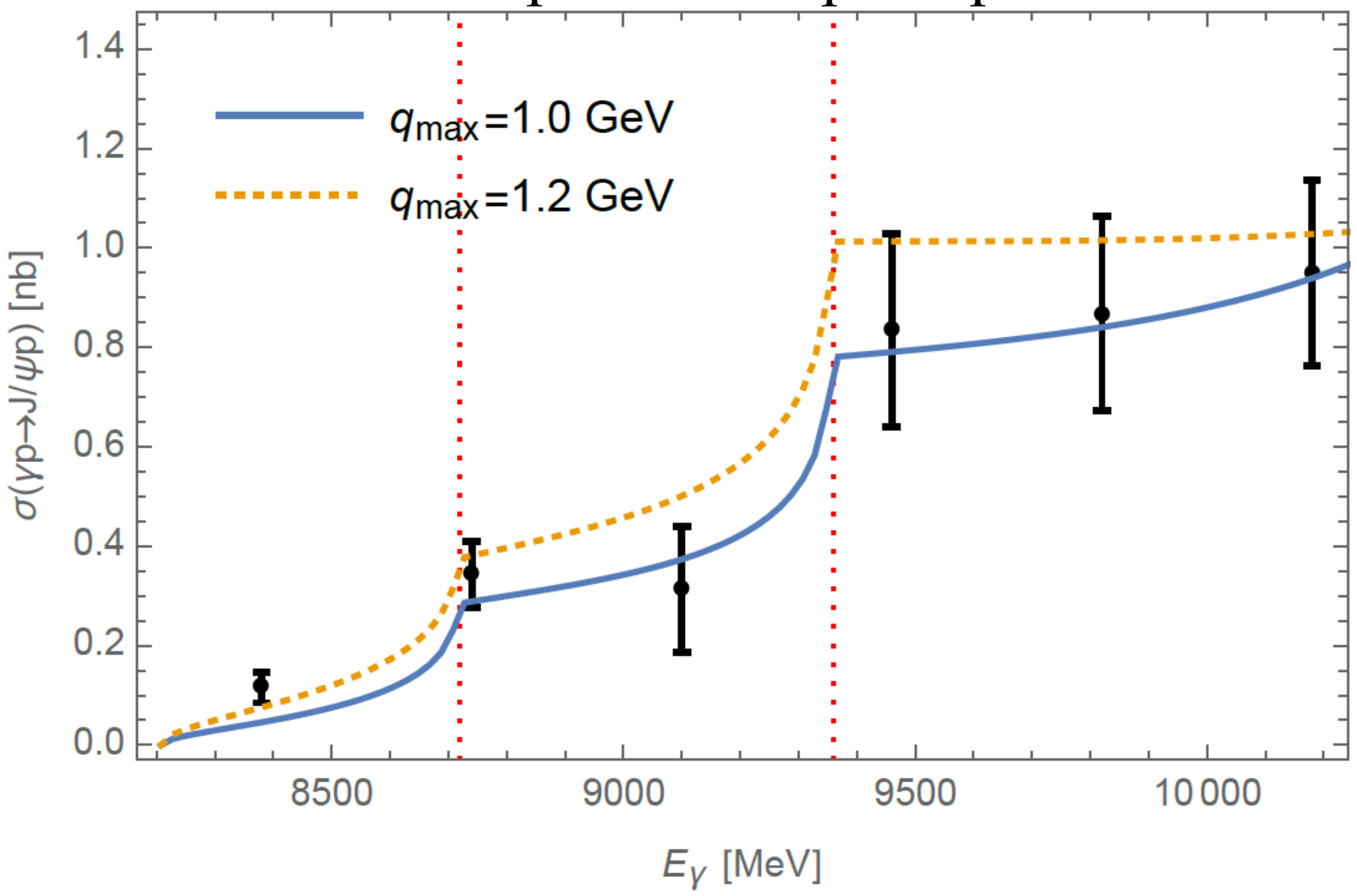
- Heavy mesons:
  large gap between measured photoproduction ($Q^2 = 0$) and on-shell VMD coupling ($Q^2 = -m^2_\psi$).
  It has been shown that kinematic corrections and appropriate $Q^2$ dependence are needed.
  Leads to scaling up of $J/\psi\, p \to J\psi\, p$ cross section: therefore, corrections to VMD limited by data!
  *[Barger and Phillips, PL 58B (1975) 433]*

# Excursion: alternative production mechanism

- Open charm exchanges: motivated by proximity between $\Lambda_c^+ \bar{D}^0$ and $J/\psi\, p$ thresholds and larger $\gamma\, p \to c\bar{c}X$ than $\gamma\, p \to J/\psi\, p$ cross sections. *[Du et al., EPJ C80 (2020) 1053]*

- Cusps would be seen in data — possibly visible at GlueX? Confirm in open-charm photoproduction.




- Would obscure the relation between $J/\psi$ photoproduction and trace anomaly contribution to proton mass.

# Mass radius

- **Charge radius** from spatial distribution of **quarks**: form factors in **electron scattering** experiments.
- **Gluon distributions** cannot be assessed this way: **mass radius** from **GFF** in $J/\psi$ **photoproduction**!
  In the non-relativistic limit:

$$\langle R_m \rangle = \frac{6}{m_p} \frac{dG}{dt}\bigg|_{t=0}$$

, and $G$ approximately given by the EMT trace $T$.

Then, the radius is obtainable from $\frac{d\sigma_{\gamma p \to J/\psi p}}{dt} \propto \left| \langle p' | T | p \rangle \right|^2$.

*[Kharzeev, PRD 104 (2021) 054015; Wang et al., PRD 103 (2021) L091501; Mamo and Zahed, PRD 101 (2020) 086003; PRD 103 (2021) 094010]*

# 3. Bound states?

# Calculating the scattering length

- Broad range of binding energies (including none) found in literature: bound states correspond to sufficiently large values of scattering length.
  *[Luke et al., PLB 288 (1992) 355; Brodsky and Miller, PLB 412 (1997) 125; Beane et al., PRD 91 (2015) 114503; Gryniuk and Vanderhaeghen, PRD 94 (2016) 074001; Sugiura et al., JPS Conf. Proc. 26 (2019) 031015; Skerbis and Prelovsek, PRD 99 (2019) 094505]*

- Scattering length from cross section at threshold: $\sigma_{J/\psi\, p} = 4\pi\, a^2_{J/\psi\, p}$.
  Sign fixed e.g. in dispersion relations (DR).

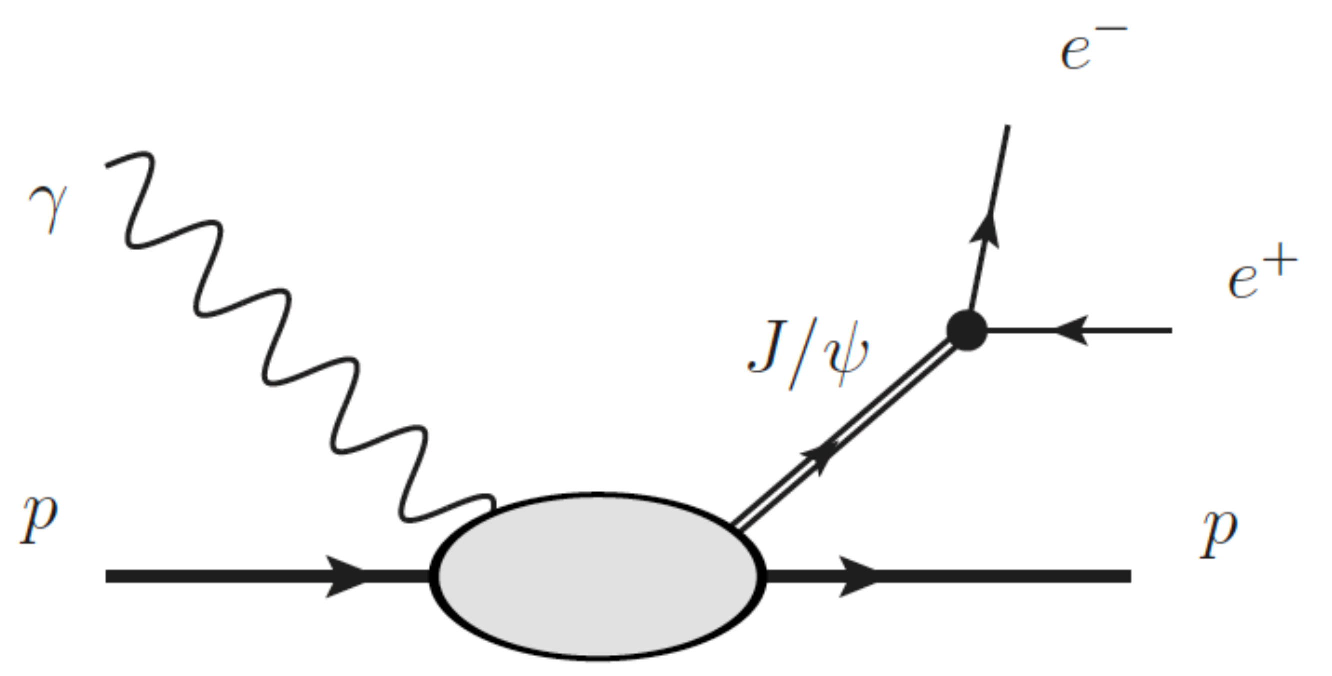
- Imaginary part of $J/\psi\, p$ scattering amplitude can be related to elastic and inelastic $J/\psi\, p$ cross sections, using $\gamma\, p \to J/\psi\, p$ and $\gamma\, p \to c\bar{c}X$ data and VMD. Real part from once-subtracted DR.
  *[Gryniuk and Vanderhaeghen, PRD 94 (2016) 074001]*

# Assessed quantities

- **Scattering length:**

$$a_{J/\psi\, p} = \frac{1}{8\pi(m_p + m_{J/\psi})} \mathscr{M}_{J/\psi\, p \to J/\psi\, p}(\nu = \nu_{\rm el}) = (0.046 \pm 0.005)\ \text{fm}$$

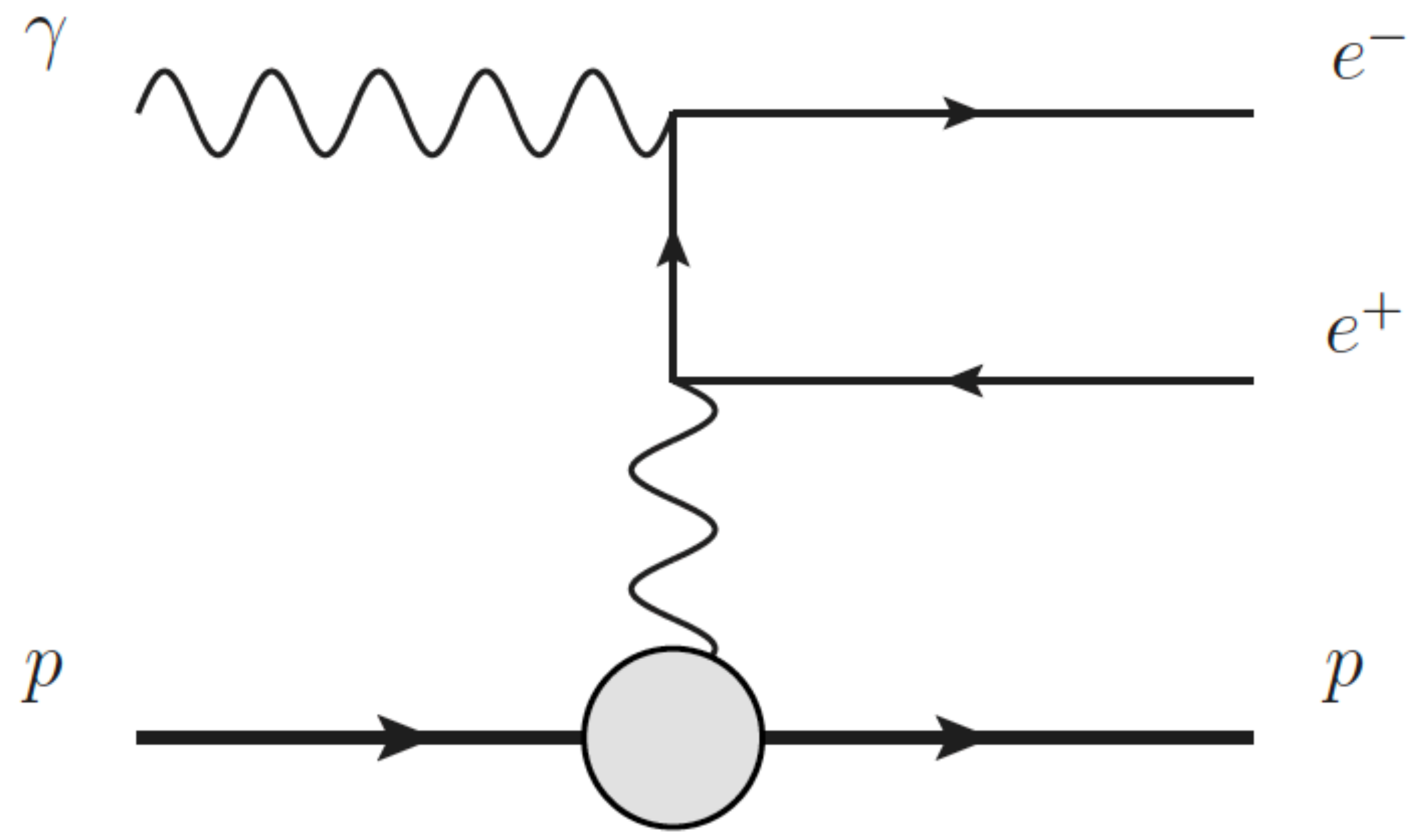
Range in literature: up to 0.37 fm.




- **Binding energy** in nuclear matter, in linear density approximation:

$$B_{J/\psi} \approx 3\ \text{MeV}$$

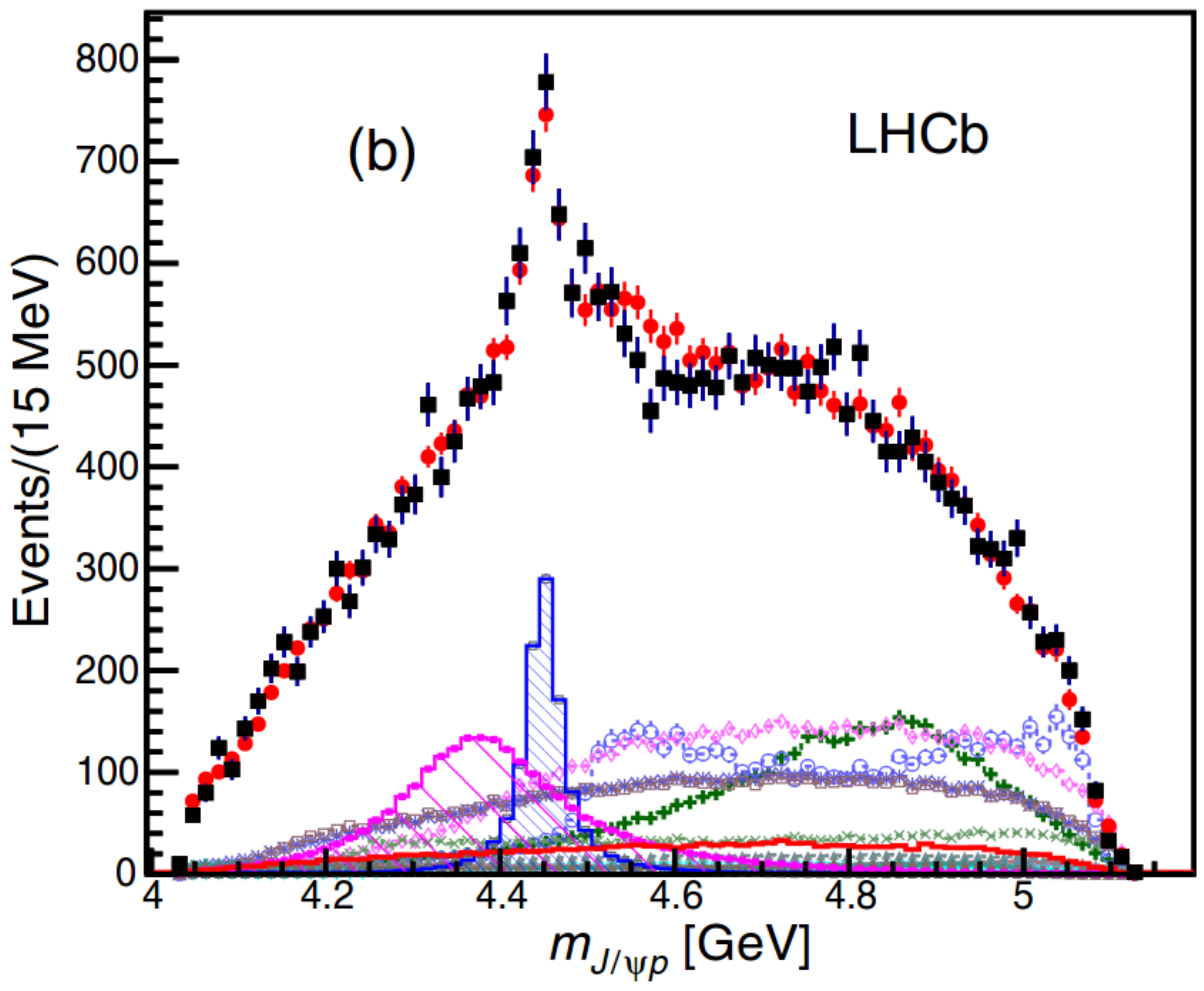
- Interference in $l^+l^-$ reconstruction with competing Bethe-Heitler mechanism leads to **forward-backward asymmetry** in $\gamma\, p \to e^+e^-p$ around the $J/\psi$ peak.
- Asymmetry sensitive to $a_{\psi p}$ , approximately linearly: promising for refined experimental extraction!

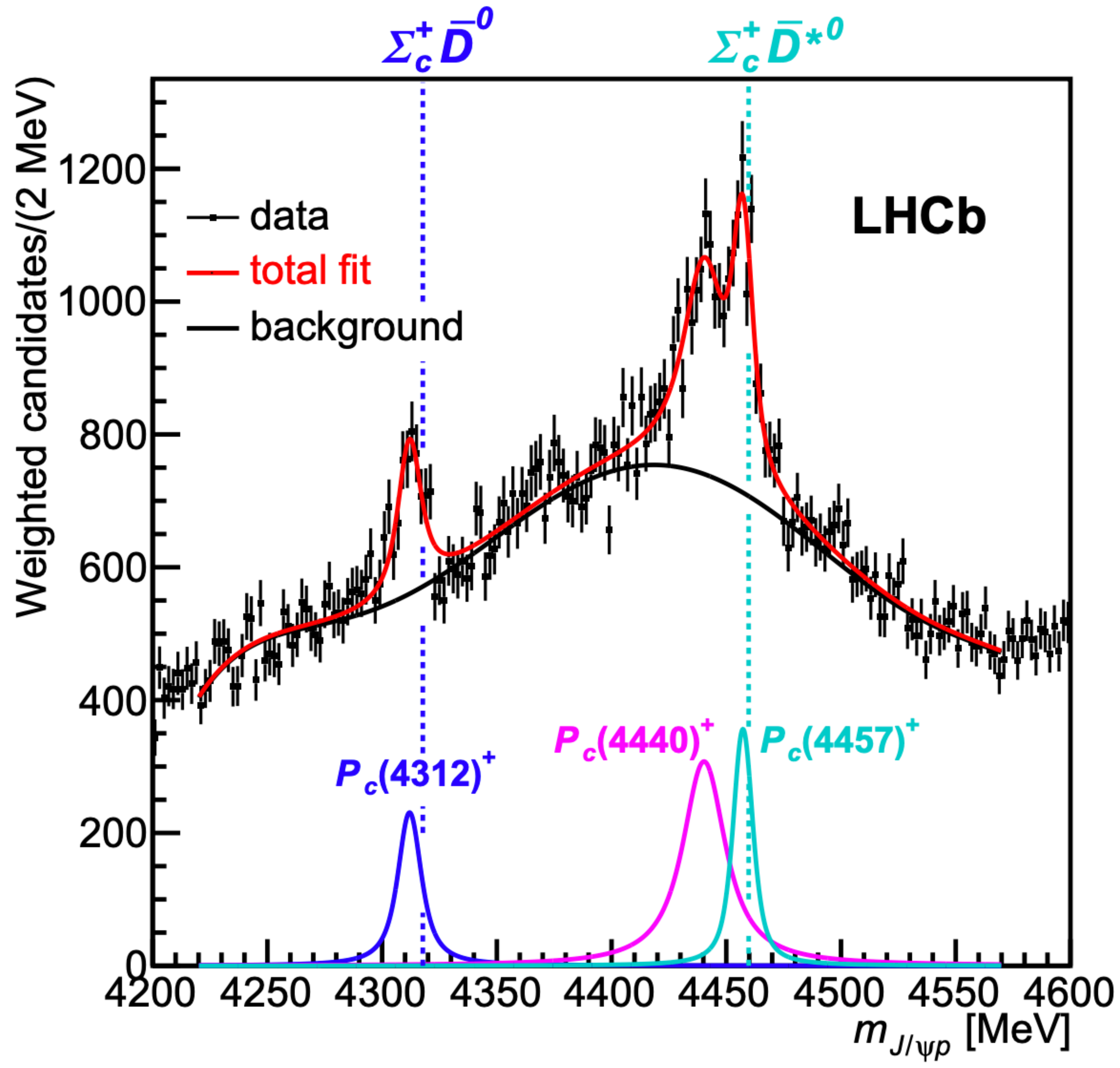


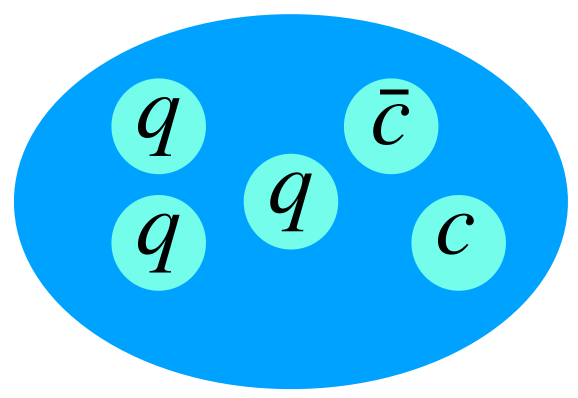
# 4. Oh pentaquark, where aret thou?

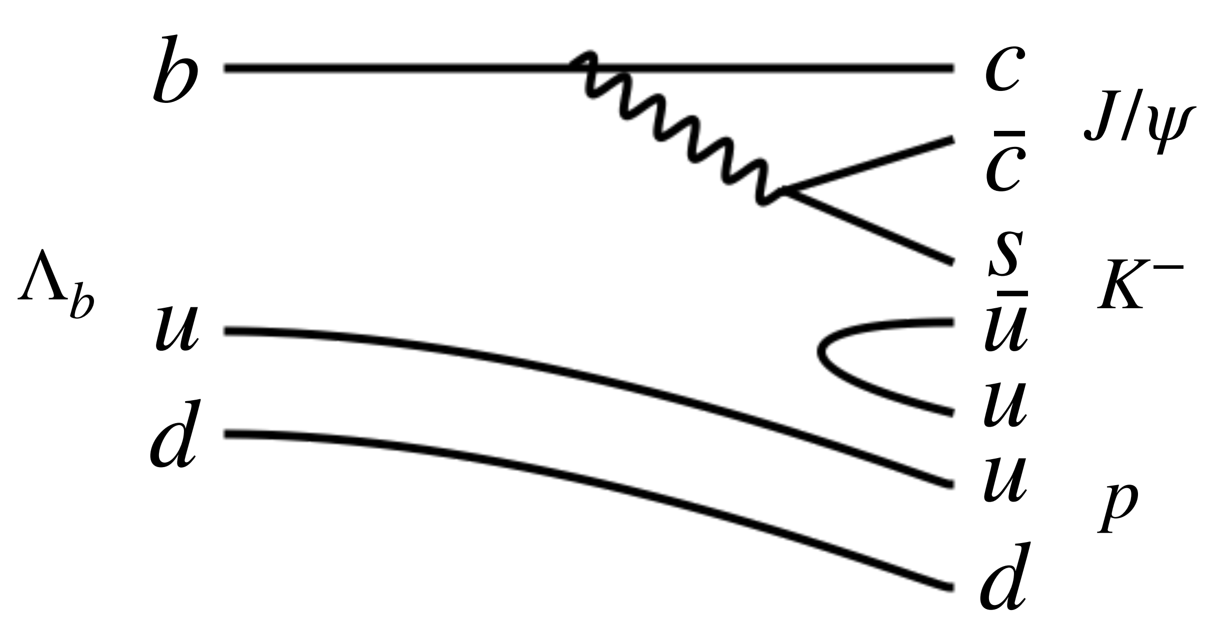
# Exotic baryon candidates

- In 2015, exotic-like structures in the $J/\psi\, p$ channel were found. *[Aaij et al. [LHCb], PRL 115 (2015) 072001; Aaij et al. [LHCb], PRL 122 (2019) 222001]*



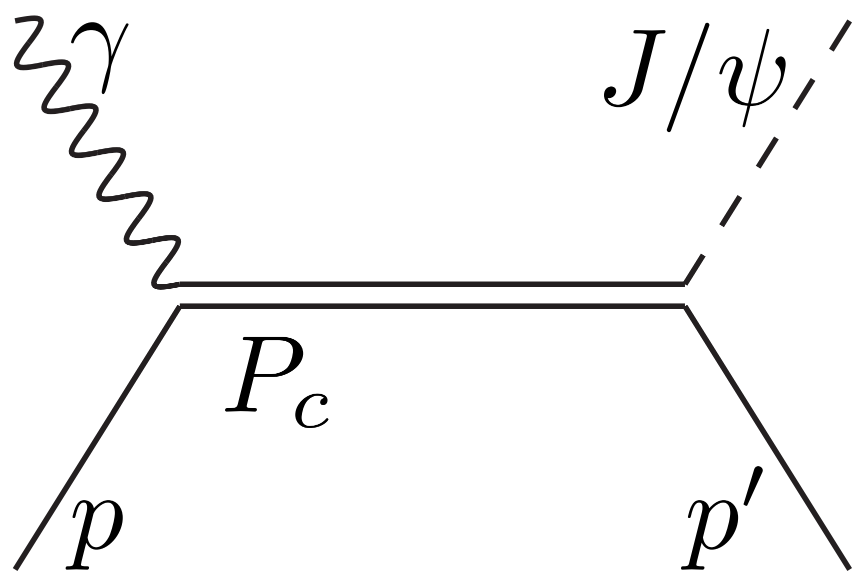



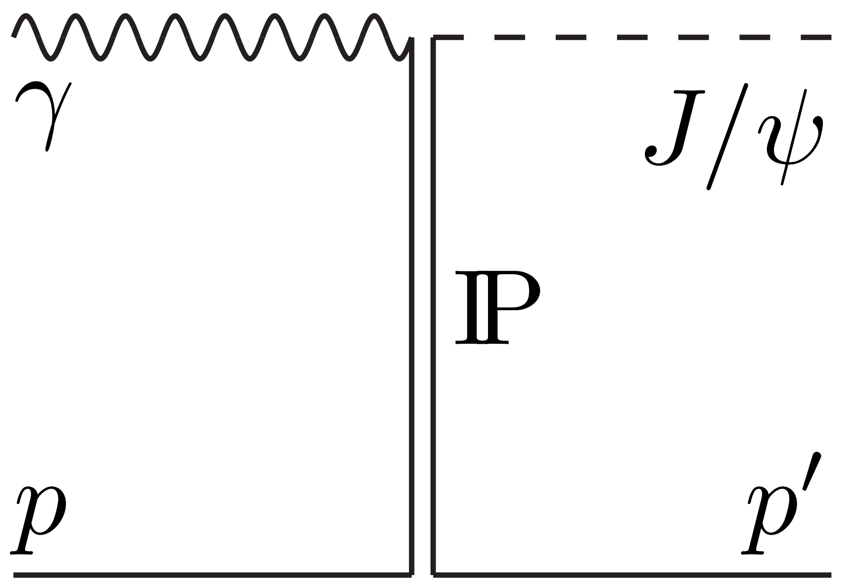

$P_c \equiv c\bar{c}uud$

# Possible interpretations

- Compact 5-quark states.
- Weakly-bound $\bar{D}^*\Sigma_c^{(*)}$ molecule.
- Kinematic final-state rescattering effects (triangle singularities).
- Confirm resonant nature with photoproduction.

*[Wang et al., PRD 92 (2015) 034022;*
*ANHB et al., Phys. Rev. D 94 (2016) 034002;*
*Huang et al., Chin.Phys.C 40 (2016) 124104;*
*LoI12-18-001 (PAC 46);*
*Wang et al., PRD 99 (2019) 114007;*
*Winney et al., PRD 100 (2019) 034019;*
*Wu et al., PRC 100 (2019) 035206;*
*Cao and Dai, PRD 100 (2019) 054033;*
*Cao et al., PRD 101 (2020) 074010]*



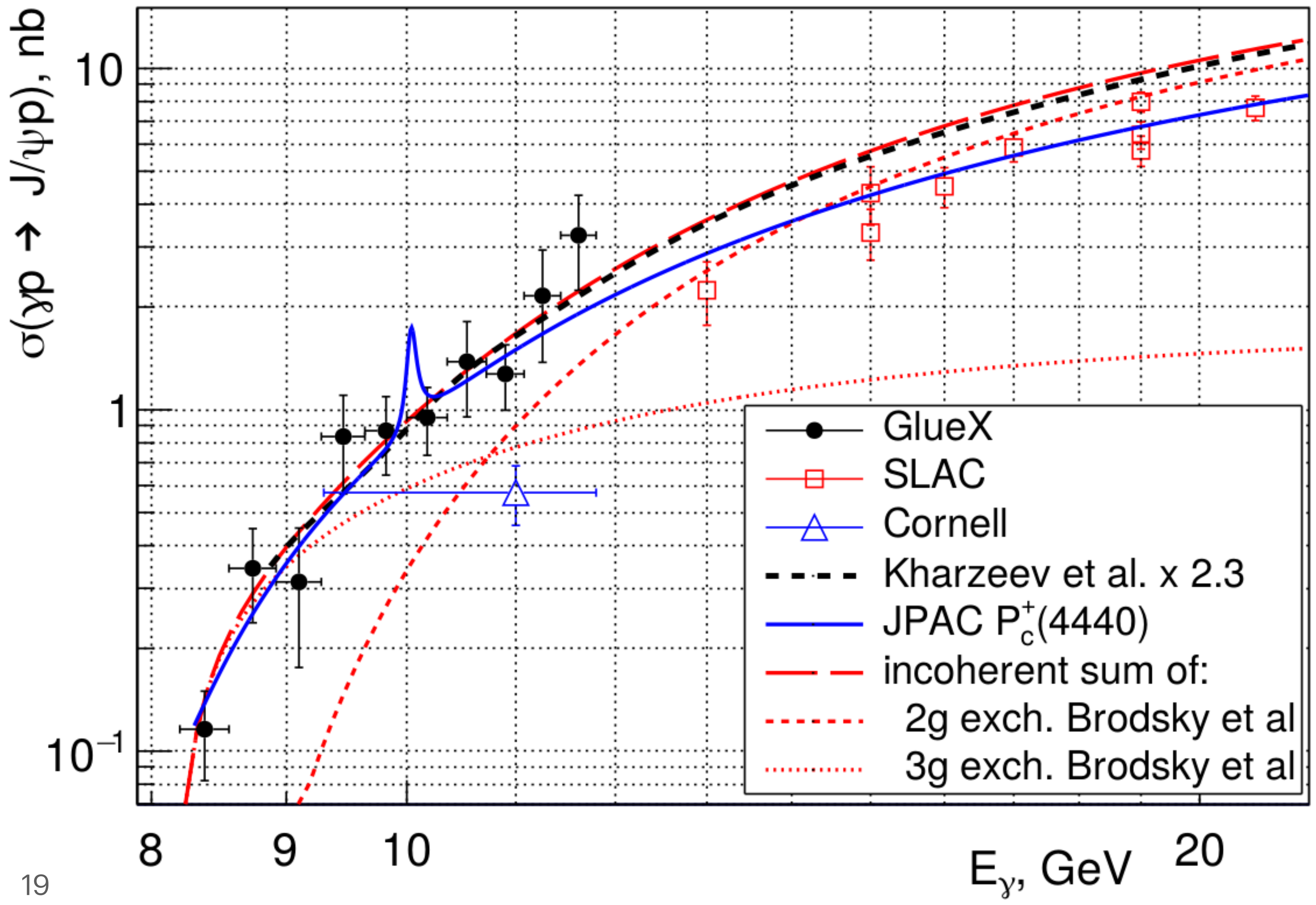




- Moving forward, measurement of **polarization observables** (sensitive even to broader and overlapping signals) and **open-charm** production might be most promising.

# 5. JLab data

# GlueX data

- GlueX data showed that 2-gluon exchange alone is not sufficient to describe $J/\psi$ production at threshold. *[Ali et al., PRL 123 (2019) 072001; Brodsky et al., PLB 498 (2001) 23]*
- Set upper limits to $\sigma(\gamma p \to P_c) \times \mathcal{B}(P_c \to J/\psi\, p)$, model-dependent limits to $\mathcal{B}(P_c \to J/\psi\, p) < 2.0\,\%$. *[Hiller Blin et al., PRD 94 (2016) 034002; Winney et al., PRD 100 (2019) 034019]*




- Excludes predictions of hadrocharmonium model, still allows for hadronic molecule. Challenges several theory models. *[Eides et al., EPJ C78 (2018) 36; Eides and Petrov, PRD 98 (2018) 114037; Eides et al., MPL A35 (2020) 2050151]*
- **New results expected based on 2200 $J/\psi$ events.**

# Studies based on GlueX data

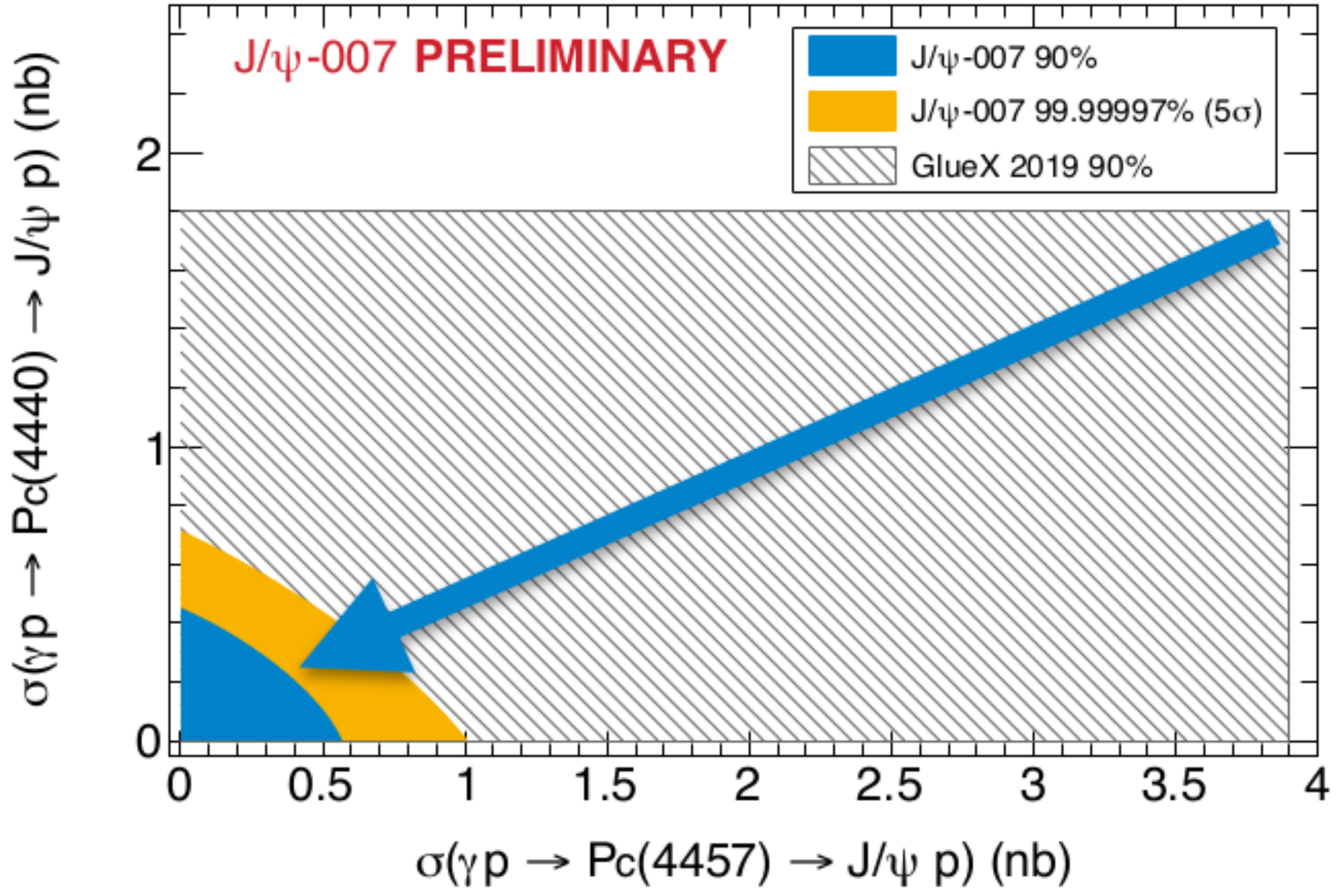
- $t$ dependence for extracting trace anomaly contribution to nucleon mass (radius) and gravitational form factors (GFF): $R_m \sim 0.5 - 0.6$ fm.
*[Kharzeev, PRD 104 (2021) 054015; Wang et al., PRD 103 (2021) L091501; Mamo and Zahed, PRD 101 (2020) 086003; PRD 103 (2021) 094010; Guo et al., PRD 103 (2021) 096010; Kou et al., 2104.12962 [hep-ph]; Sun et al., PLB 822 (2021) 136655; Wang et al., EPJ C80 (2020) 507]*

- Comparison of scattering lengths extractions within different models:
*[Strakovsky et al., PRC 101 (2020) 042201; Pentchev and Strakovsky, EPJ A57 (2021) 56]*
$|a_{J/\psi\, p}| \sim 0.003 \ldots 0.025$ fm
(upper value from update to *[Gryniuk and Vanderhaeghen, PRD 94 (2016) 074001]*).

- Global dipole fit for extraction of two-gluon exchange mass and tests of two-gluon exchange models.
*[Pentchev, JPS Conf.Proc. 26 (2019) 021022; Zeng et al., EPJ C80 (2020) 1027]*

# $J/\psi$-007 data *[See S. Joosten's talk at DNP2021]*

- Upper limit for $P_c$ cross section almost order of magnitude more stringent than GlueX limit!



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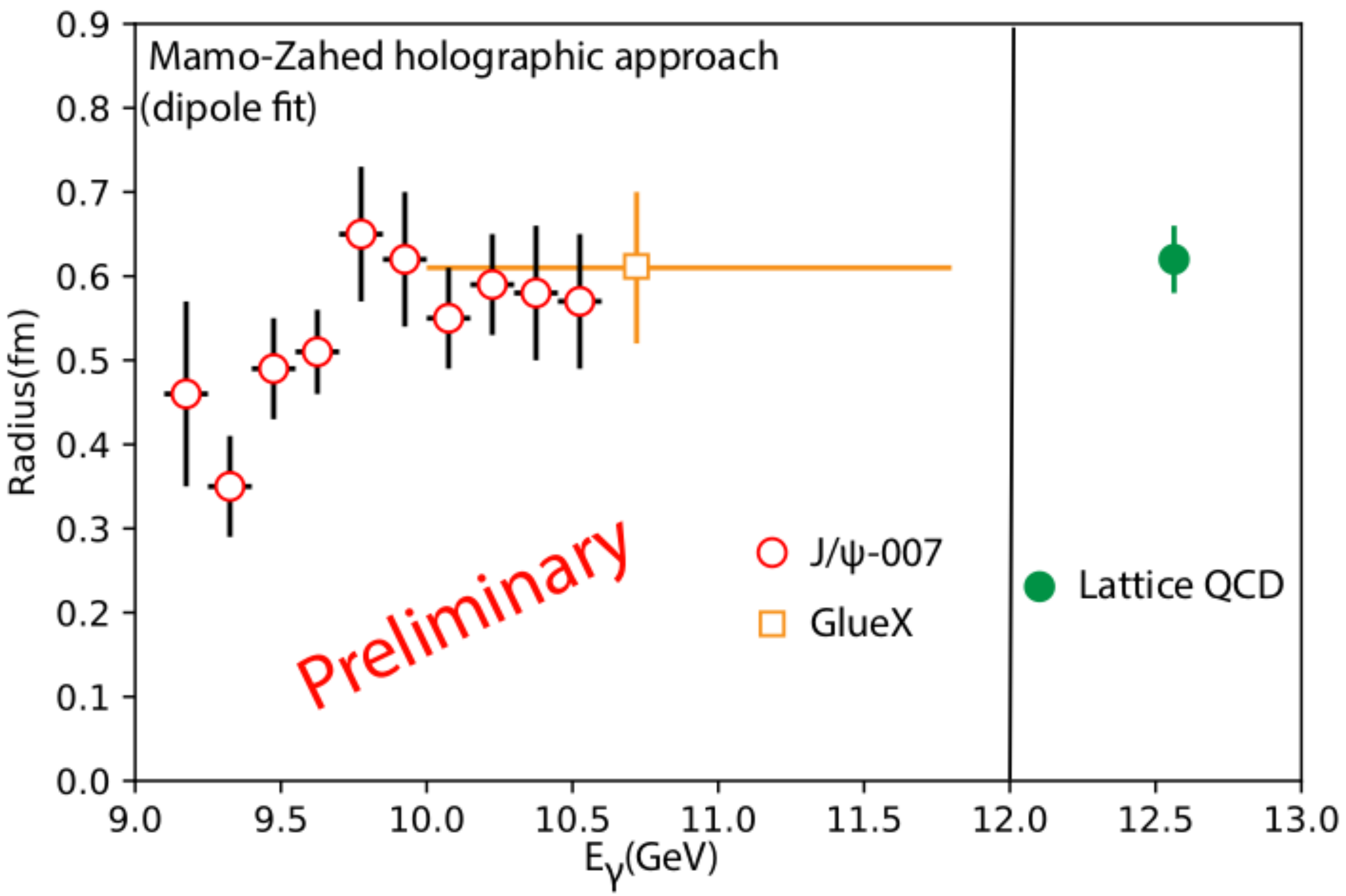


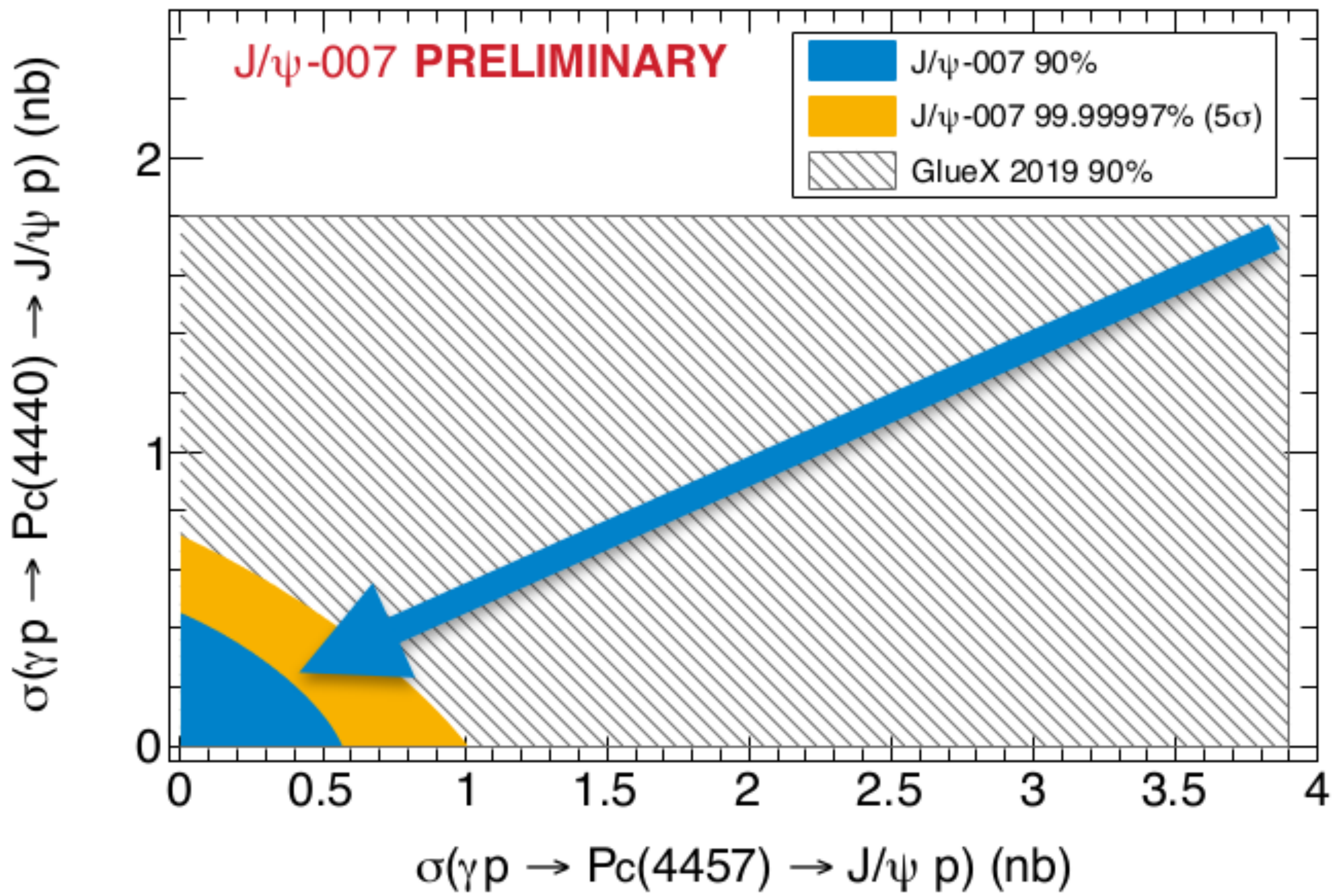


- Mass radii extracted from $t$ dependence in each energy bin, by a dipole fit in the holographic approach. *[Mamo and Zahed, PRD 101 (2020) 086003]*

# 6. EIC and future directions

# The unique possibilities of electron-ion colliders

- Lepton-nucleon/nucleus collisions are great quarkonium laboratories:
  cleaner than hadronic collisions, richer than $e^+e^-$ annihilation.

- High luminosities at the EIC allow for multi-differential exploration of kinematic regimes.
  This might disentangle production mechanisms.

- $J/\psi$ and $\Upsilon$ production to bring further insight into proton mass decomposition and binding energies.
  The larger bottomonium mass leads to negligible uncertainty from higher order corrections.
  *[Anderle et al., EicC, Front.Phys.(Beijing) 16 (2021) 64701;
  Abdul Khalek et al., EIC Yellow Report, 2103.05419 [physics.ins-det];
  Joosten, 1803.08615 [hep-ph]]*

- Hidden-bottom pentaquark searches and hidden-charm searches in open-charm decays.
  *[Cao and Dai, PRD 100 (2019) 054033]*

- Leptoproduction: large momentum transfer near threshold can be treated perturbatively!
  *[Boussarie and Hatta, PRD 101 (2020) 114004; Sun et al., PLB 822 (2021) 136655]*

# Summary

- Photo- and leptoproduction of heavy quarkonium off nucleon targets can give insight about **gluon distributions** in the nucleon, **trace anomaly contribution** to the proton mass and **mass radius**.
- It can give insight into the **binding energy** of nucleon-heavy-quarkonium states.
- Might shed light onto the nature of LHCb **pentaquarks** and enable independent confirmation.
- GlueX and $J/\psi$-007 data already led to great advances in the field.
- The EIC is crucial and ideal for further studies.

# Dispersion relations

- Imaginary part:

$$\Im \mathscr{M}_{J/\psi\, p \to J/\psi\, p} \propto \sigma_{J/\psi\, p \to X}, \qquad \sigma(J/\psi\, p \to J/\psi\, p, c\bar{c}X) \propto \left(\frac{\nu}{\nu_{\text{el,inel}}}\right)^{a_{\text{el,inel}}} \left(1 - \frac{\nu_{\text{el,inel}}}{\nu}\right)^{b_{\text{el,inel}}}$$

- Real part from (once-subtracted) dispersion relation:

$$\Re \mathscr{M}_{J/\psi\, p \to J/\psi\, p}(\nu) = \mathscr{M}_{J/\psi\, p \to J/\psi\, p}(0) + \frac{2\nu^2}{\pi} \int_{\nu_{\text{el}}}^{\infty} d\nu' \frac{\Im \mathscr{M}_{J/\psi\, p \to J/\psi\, p}(\nu')}{\nu'(\nu'^2 - \nu^2)}$$

$$\left.\frac{d\sigma}{dt}\right|_{t=0} (J/\psi\, p \to J/\psi\, p) \propto |\mathscr{M}_{J/\psi\, p}|^2$$

Subtraction constant: model dependent/from lattice QCD/fitted to data with VMD assumption.