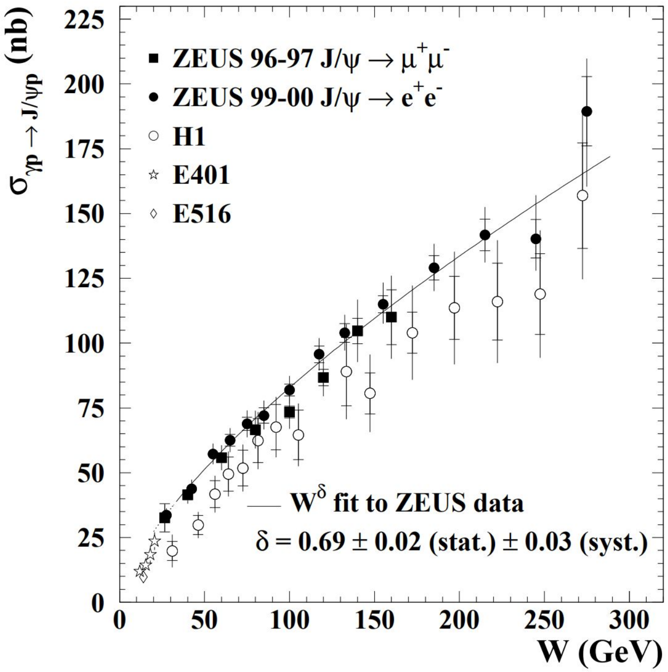
# $J/\psi$ photoproduction near threshold

**Daniel Winney**
**Universität Bonn**

**Physics opportunities with proton beams at SIS100**
6 February 2024

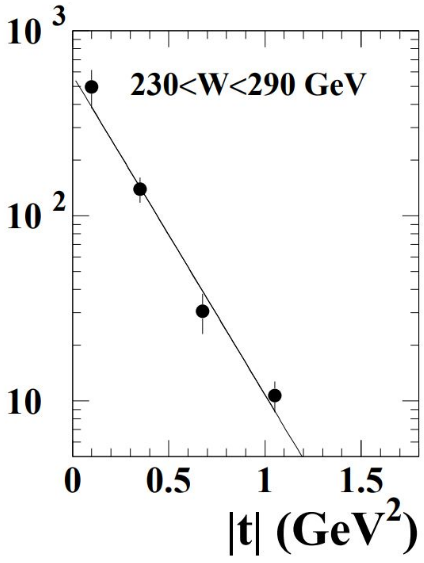
# $J/\psi$ photoproduction (at high energies)

Historically $J/\psi$ photoproduction well explored at high energies ($W$ > 20 GeV) at HERA.




ZEUS [Eur. Phys. J. C24:345-360, 2002]

Production dominated by low |*t*| and exponential decay from forward angles -- i.e. the **"diffractive peak"**




Diffractive production via **gluon exchanges**

Variety of theoretical models:

- Pomeron Exchange

**Donnachie & Landshoff [Phys.Lett. B437 (1998) 408-416]**

- Color dipole

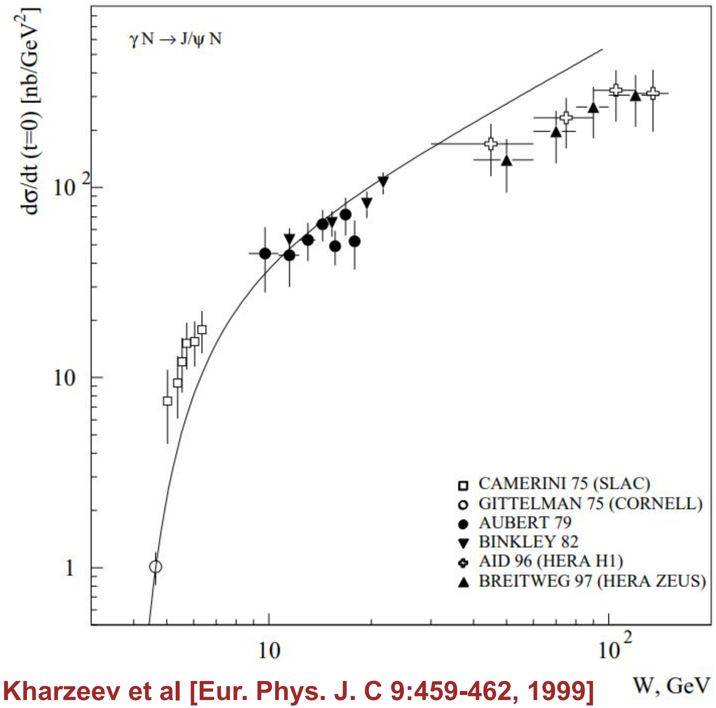
**Caldwell & Soares [Nucl.Phys. A696 (2001) 125-137]**

- pQCD

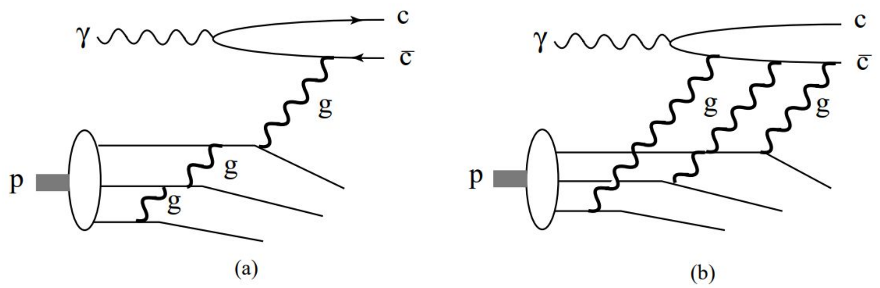
**Ivanov et al. [Eur.Phys.J.C 34 (2004) 3, 297-316]**

# $J/\psi$ photoproduction (near threshold)

S. Brodsky et al. [Phys. Lett. B 498 (2001) 23-28]




D. Kharzeev et al [Eur. Phys. J. C 9:459-462, 1999]




No other obviously contributing process:

- Small $J/\psi \rightarrow \bar{N}N$ (**no baryon exchanges**)
- OZI Suppression (**no light meson exchanges**)
- Heavy quark mass (**no heavy meson exchanges**)

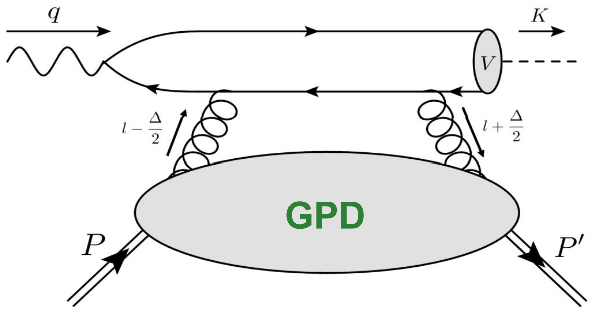
**"*J/ψ* probes non-perturbative gluonic distributions"**

# *J/ψ* photoproduction (near threshold)

Measurements at energies near threshold have attracted a lot of attention as potentially sensitive to key quantities relevant to **proton structure**.

Based on factorization arguments in perturbative and holographic QCD can be used to extract:

- Gravitational form factors
  - **Mamo & Zahed [Phys. Rev. D 101, 086003 (2020)]**
  - **Guo, Ji & Liu [Phys. Rev. D 103, 096010 (2021)]**
- Mass radius
  - **Kharzeev [Phys. Rev. D 104, 054015 (2021)]**
  - **Mamo & Zahed [Phys. Rev. D 103, 094010 (2021)]**
- Trace anomaly contribution to proton mass
  - **Wang, Chen, & Evslin [Eur.Phys.J.C 80 (2020) 6, 507]**
  - **Hatta & Yang [Phys. Rev. D 98, 074003 (2018)]**

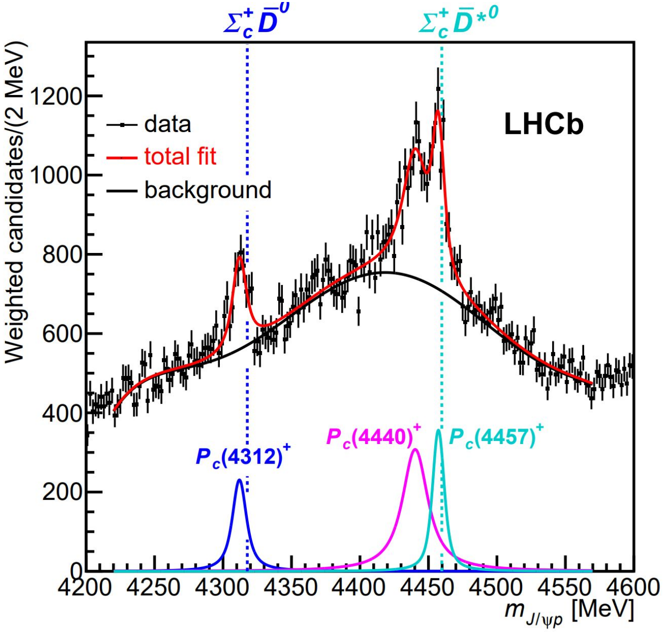



$$M = M_q + M_g + M_m + M_a$$

$$\langle R_{\mathrm{m}}^2 \rangle = \frac{6}{M} \frac{dG}{dt}\Big|_{t=0},$$

# $J/\psi$ photoproduction (near threshold)

Measurements at energies near threshold have attracted a lot of attention as potentially sensitive to key quantities relevant to **exotic hadrons**.

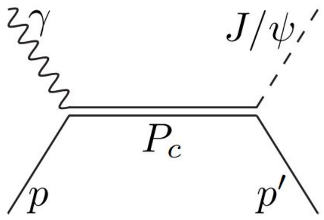


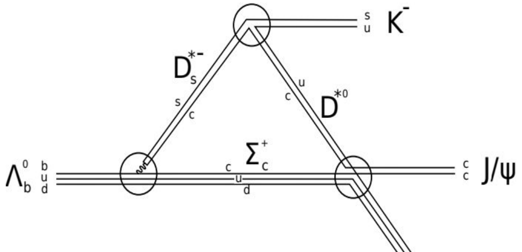

**LHCb [Phys.Rev.Lett. 122 (2019) 22, 222001]**

Observation of hidden charm pentaquark candidates by LHCb sparked interest in photoproduction searches.

**Q. Wang et al [Phys. Rev. D 92 (2015) 034022]**
**M. Karliner & J. Rosner [Phys.Lett.B 752 (2016) 329-332]**
**A. N Blin et al [Phys. Rev. D 94 (2016) 3, 034002]**

Independent confirmation, **free of triangle singularities**, polarization information allows determination of quantum numbers



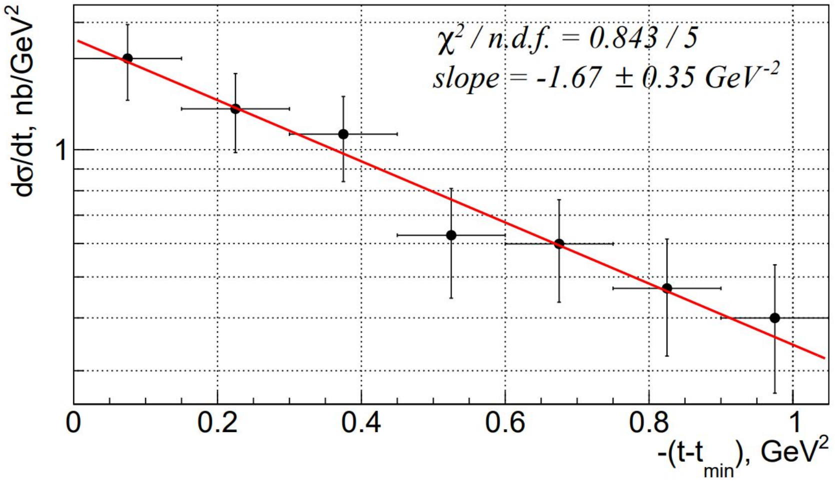



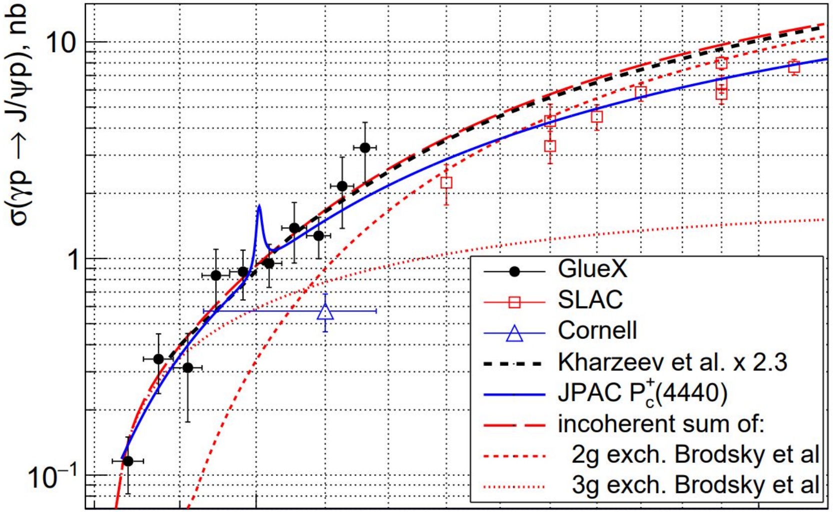

**M. Mikhasenko [arXiv:1507.06552]**

# First measurement near threshold

GlueX [Phys.Rev.Lett. 123 (2019) 7, 072001]

GlueX observes diffractive scattering with no sign of pentaquarks!



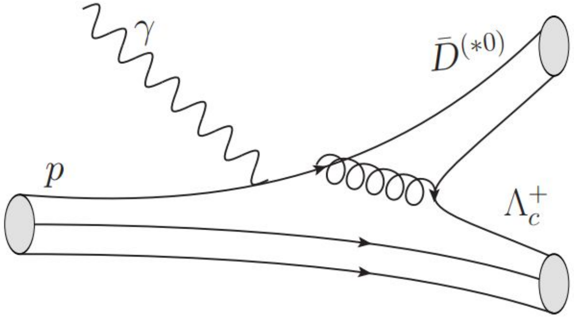

| | $\mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, % | |
|---|---|---|
| | p.t.p. only | total |
| $P_c^+(4312)$ | 2.9 | 4.6 |
| $P_c^+(4440)$ | 1.6 | 2.3 |
| $P_c^+(4457)$ | 2.7 | 3.8 |

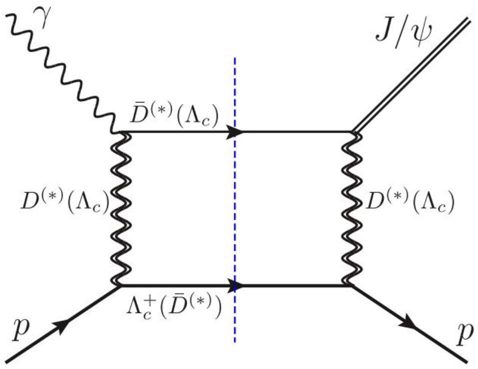
Confirmation of **gluon dominated dynamics**?

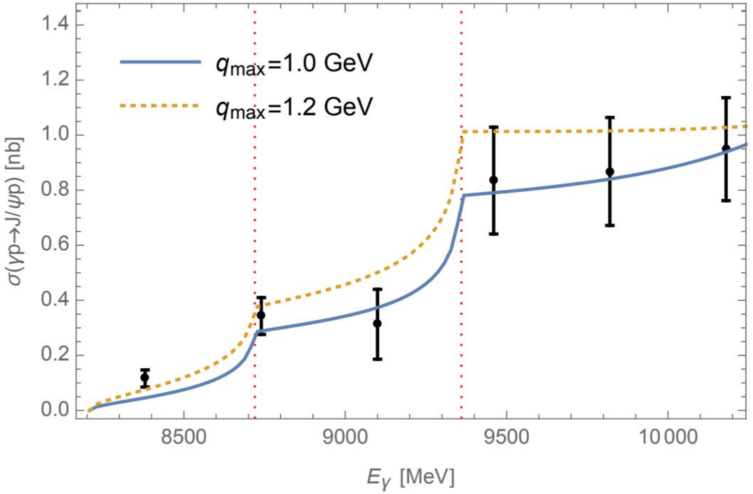
# Coupled-channel contributions

Observation of potential structure in integrated cross section coinciding with open-charm threshold.

Although kinematically suppressed, coupled channel mechanism expected to be compensated by much **larger photoproduction rates of open charm**.

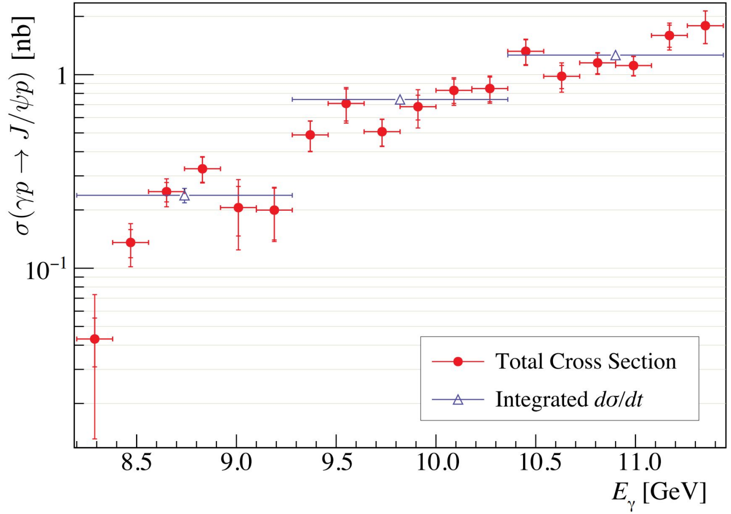



Du et al. [Eur. Phys. J. C 80 (2020) 1053]

# New Jefferson Lab Data

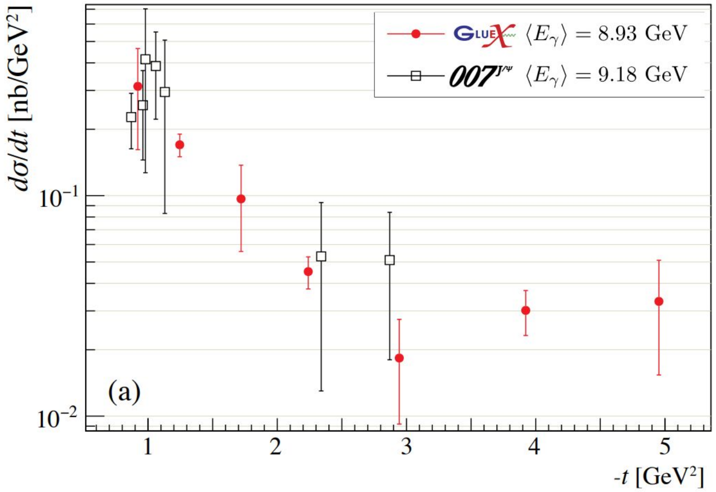


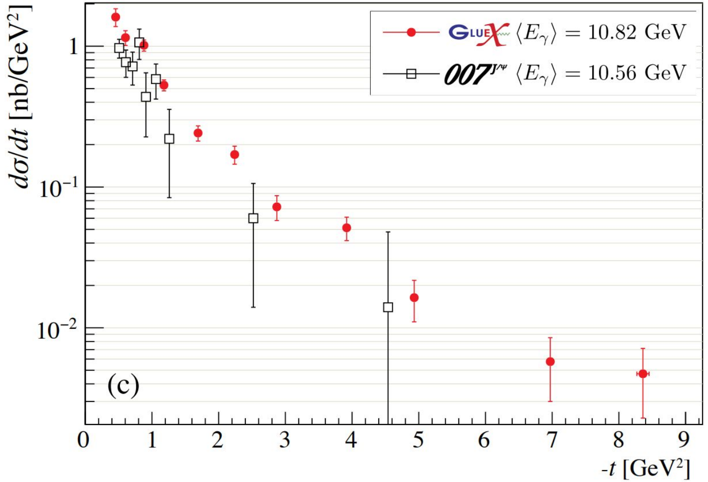

007 J/ψ

[Nature 615 (2023) 7954, 813-816]

GlueX

[Phys.Rev.C 108 (2023) 2, 025201]



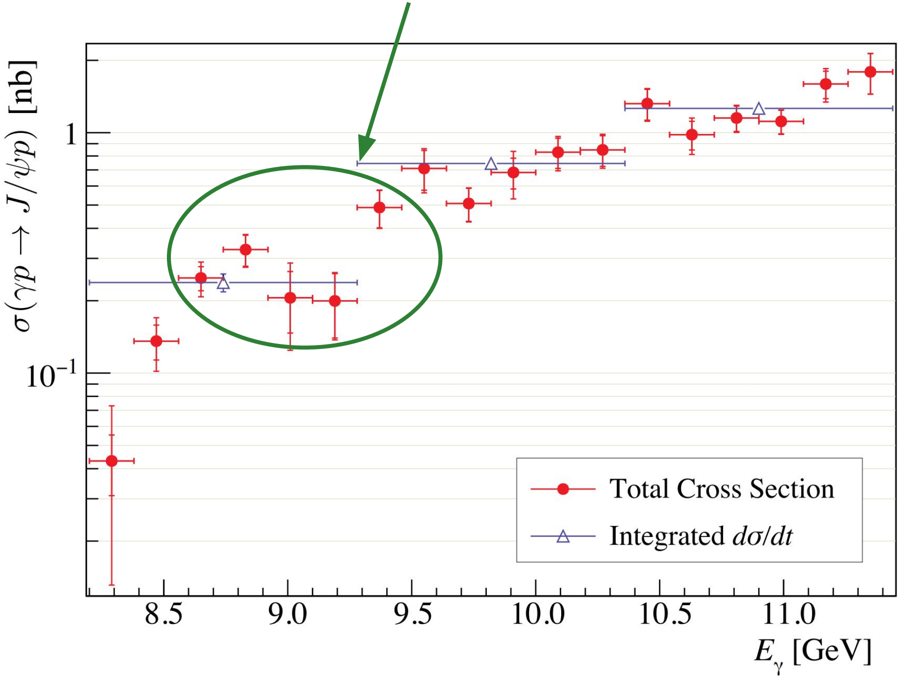



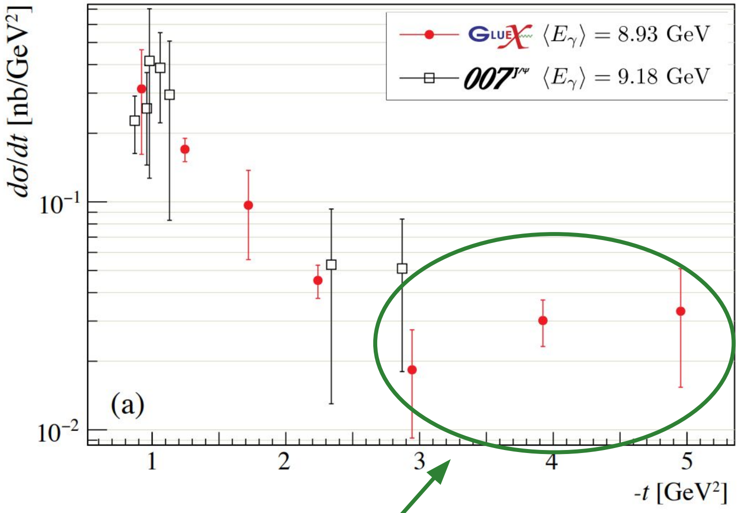

Much larger data set available, incorporating both integrated and differential cross sections.

The latter at from GlueX covers the **full kinematic range**

# New Jefferson Lab Data

"Dip" now established at ~2.6$\sigma$ compared to a smooth fit




Flattening of *t*-distribution at large momentum transfer also at ~2.3$\sigma$ compared to a dipole

**Coupled-channels? Pentaquarks?**

JPAC [Phys.Rev.D 108 (2023) 5, 5]

# K-matrix analysis

Larger data set allows for the first time a comprehensive analysis using **minimally model dependent** parameterizations to test common underlying assumptions regarding the J/$\psi$ photoproduction.

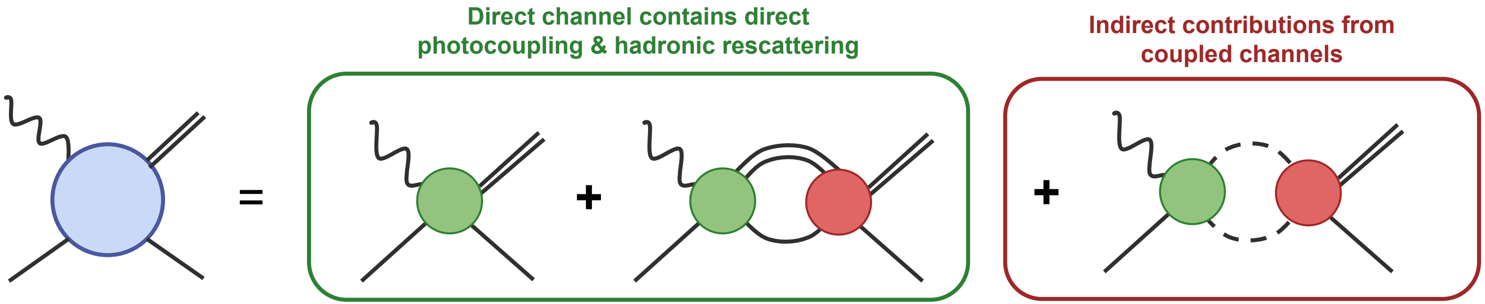
Close to threshold, we expand the amplitude into **s-channel partial waves** which are parameterized to satisfy **low-energy unitarity.**

$$F(s,t) = \sum_{\ell} (2\ell+1)\, P_\ell\,(\cos\theta)\; F_\ell(s)$$

$$\operatorname{Im} F_\ell = F_\ell\, \rho\, T_\ell^\dagger$$

$$\operatorname{Im} T_\ell = T_\ell\, \rho\, T_\ell^\dagger$$

$$\Rightarrow \quad F_\ell = f_\ell\,(1 - G\, T_\ell) \quad \text{with} \quad T_\ell = \frac{1}{K_\ell^{-1} + G}$$



JPAC [Phys.Rev.D 108 (2023) 5, 5]

# K-matrix analysis

Much fewer underlying model assumptions:

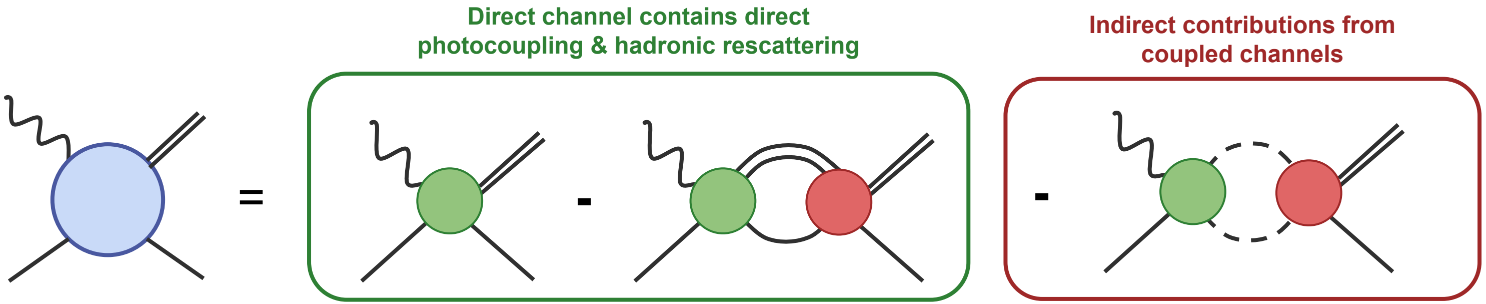
- Angular dependence saturated by few terms partial waves expansion — ***L* ≤ 3 works well!**
- Energy dependence saturated by few terms in near threshold expansion

**Scattering length and/or effective range works well!**

$$K_S^{ij} = \alpha_S^{ij} + \beta_S^i \, q_i^2 \, \delta_{ij} \qquad K_\ell = q^{2\ell} \, \alpha_\ell$$

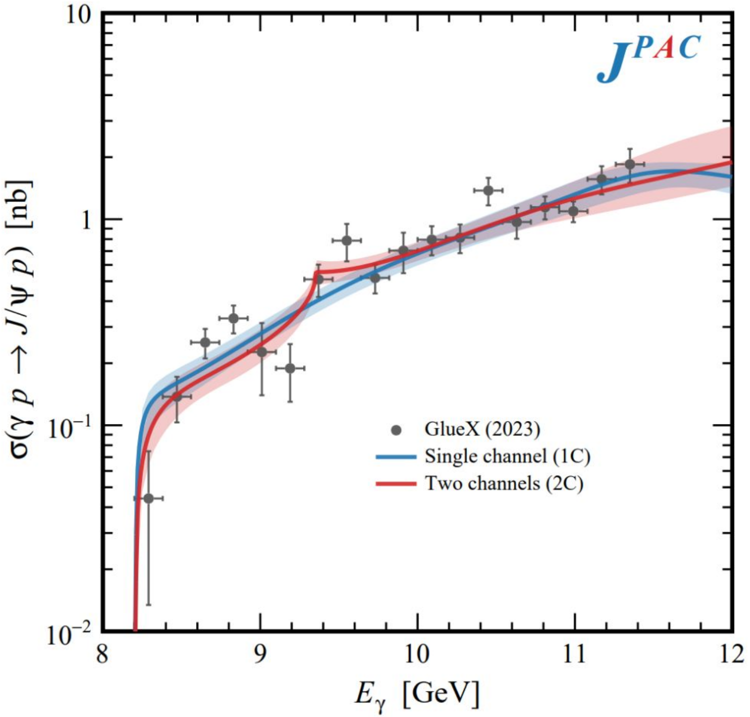
$$f_\ell = (pq)^\ell \, n_\ell$$

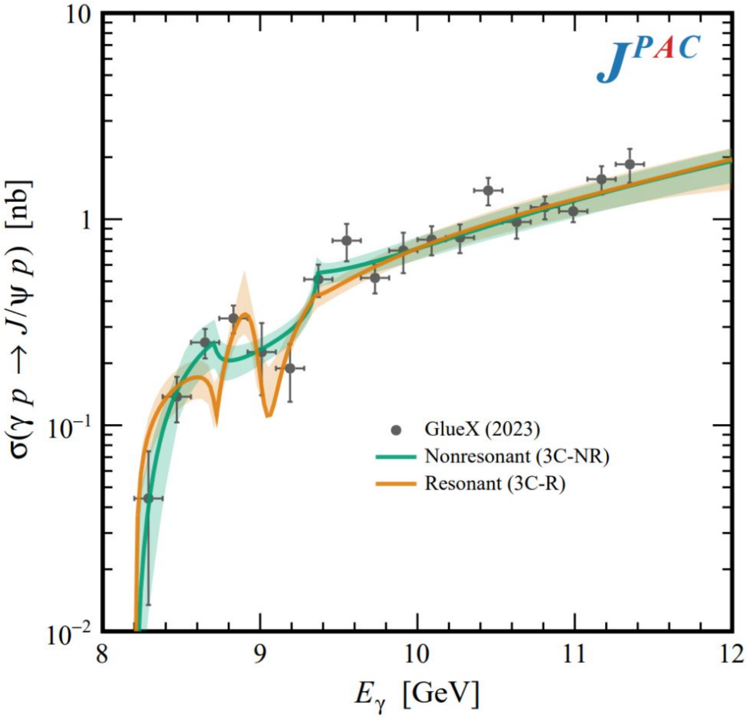
**Fully data driven analysis considering all data simultaneously.**



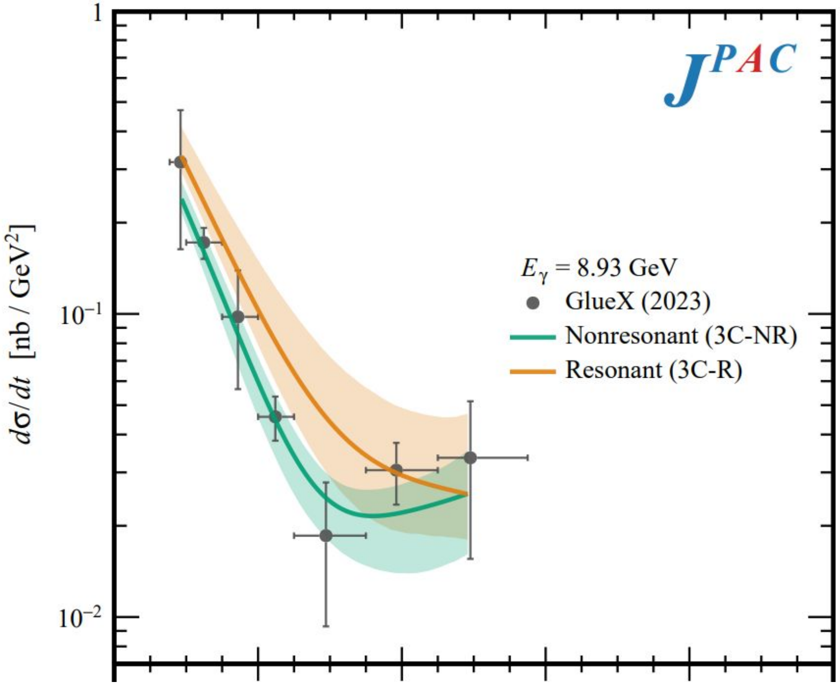
# Integrated cross section

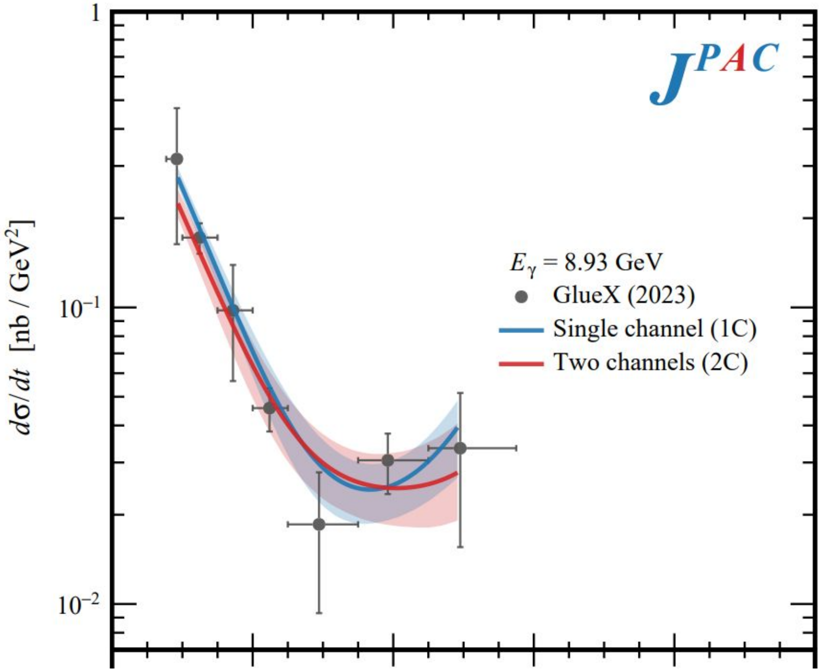
**Four solutions** with different dynamical pictures found to be consistent with full data with similar statistical significance.



# Differential cross section

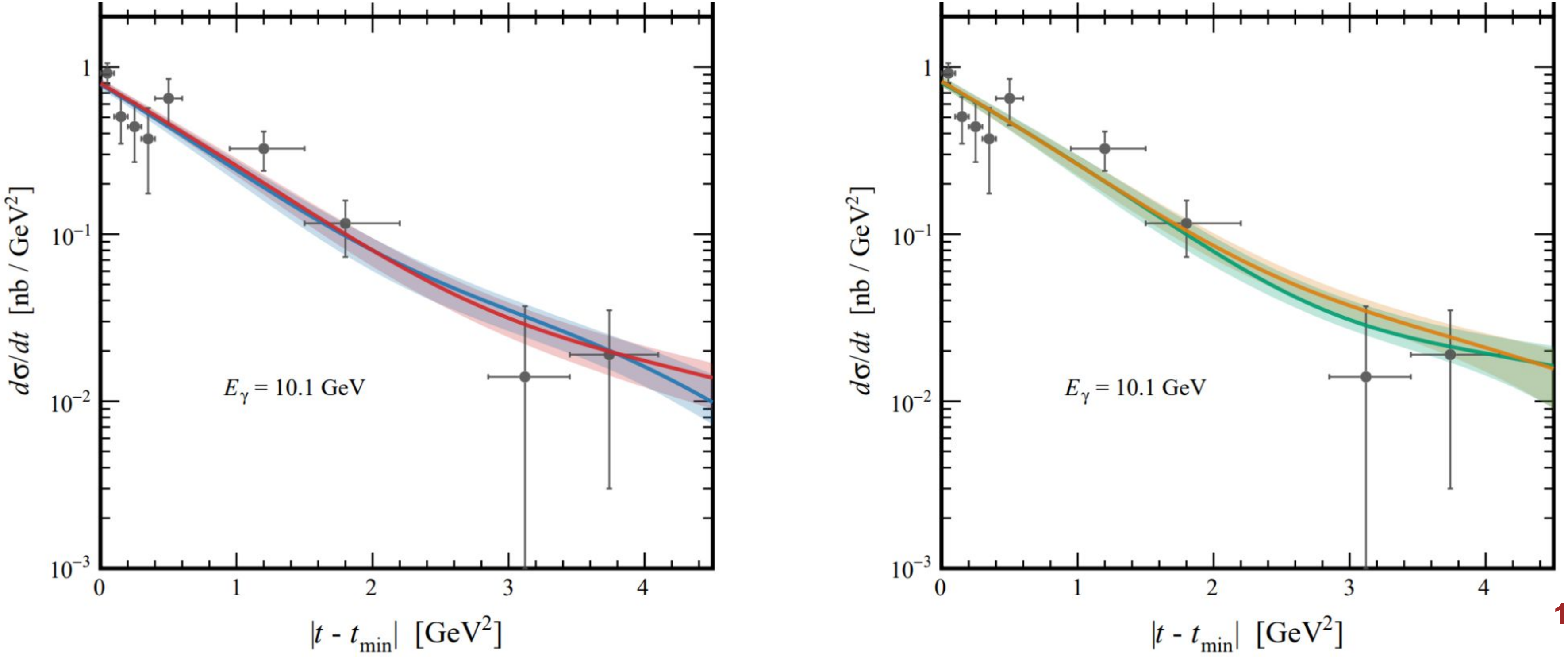



All reproduce apparent enhancement at large |t|!

# Differential cross section

Exponential t behavior captured with only a **few partial waves** (completely analytic is t)



JPAC [Phys.Rev.D 108 (2023) 5, 5]

# Production mechanisms

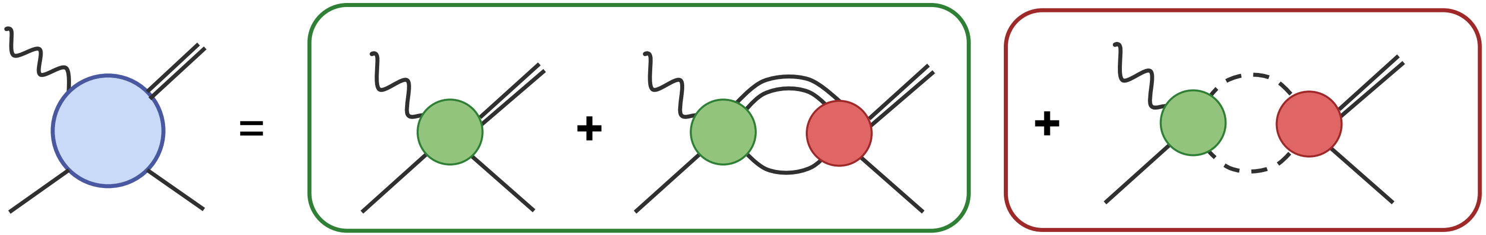
Define the ratio of direct J/$\psi$ photocoupling to all other intermediate channels. Figure of merit measuring the **"directness"** the total production occurs at threshold.

$$\zeta_{\text{th}} = \frac{\left| F^{\psi p}_{\text{direct}}(s_{\text{th}}) \right|}{\left| F^{\psi p}_{\text{direct}}(s_{\text{th}}) \right| + \left| F^{\psi p}_{\text{indirect}}(s_{\text{th}}) \right|}$$

When included, "**factorization violating**" contributions make up > 25% at 90% CL!

**90% CL**

| | |
|---|---|
| **1C** | 1 |
| **2C** | [0.56, 0.74] |
| **3C-NR** | [0.36, 0.63] |
| **3C-R** | [0.03, 0.62] |

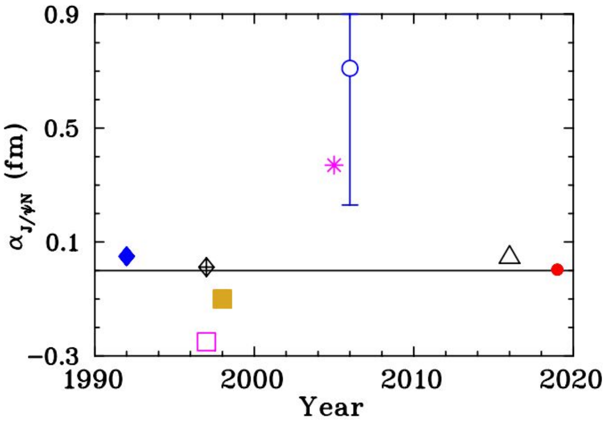


JPAC [Phys.Rev.D 108 (2023) 5, 5]

# Elastic scattering length

First extraction of the elastic J/$\psi$p scattering length without the use of VMD.

Analysis favors large values on the **order of Fermi**!




Strakovsky et al [Phys. Rev. C 101, 042201 (2020)]

**Scattering length [fm]**

| | |
|---|---|
| **1C** | [0.56 1.00] |
| **2C** | [0.11, 0.76] |
| **3C-NR** | [-2.77, 0.35] |
| **3C-R** | [-0.04, 0.19] |

$$T_S^{\psi p, \psi p} = \frac{8\pi\sqrt{s_{\rm th}}}{-a_{\psi p}^{-1} - i\,q} + O(q^2)$$

Possibly indicated **typical hadronic interaction** between nucleon and charmonia but poorly constrained 3C results still consistent with zero!

# Pentaquark poles

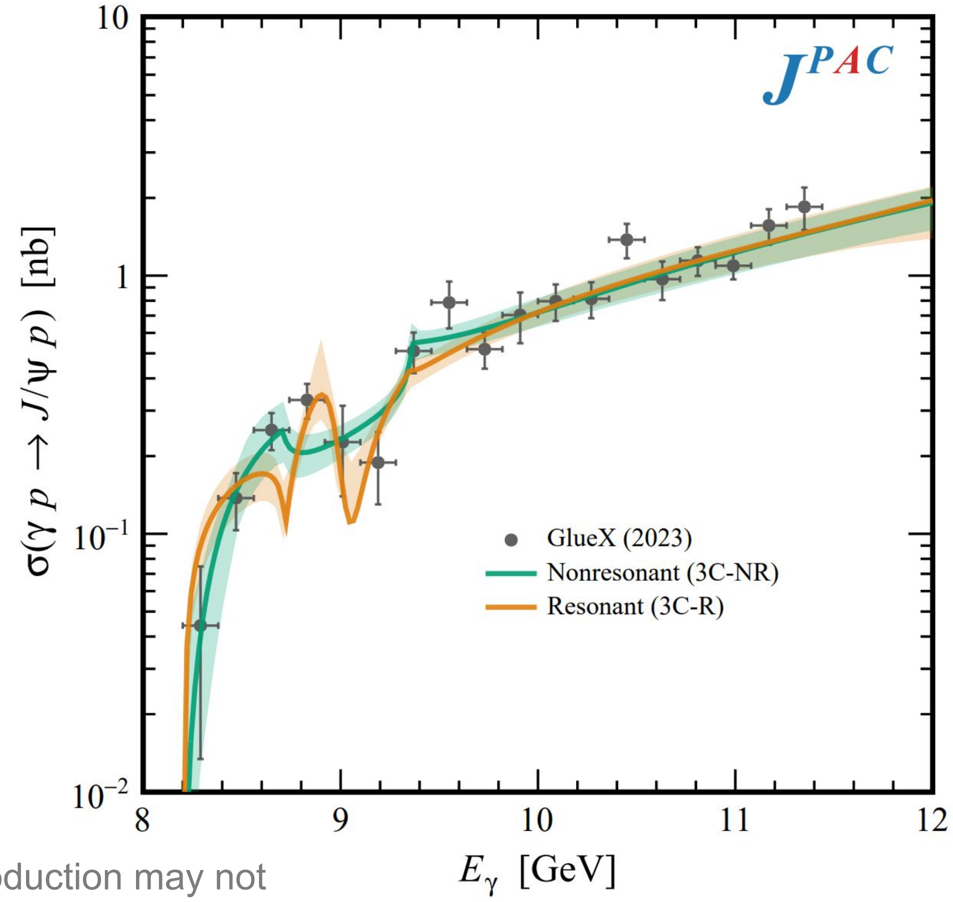
JPAC [Phys.Rev.D 108 (2023) 5, 5]

Pronounced dip in 3C-R found to correspond to a narrow pole on RS = (- - +) making it consistent with an ***S*-wave pentaquark state**.

$M = 4211\text{MeV} \qquad \Gamma = 48\text{MeV}$

Two other poles also found but on more remote Reimann sheets.

When considering all uncertainties pole **very unconstrained** but leaves room for solutions with poles in **strongly coupled channel scenarios**!




Failure of VMD means nonobservation in photoproduction may not immediately kill possibility of pentaquarks in $J/\psi p$ spectrum

# Experimental prospects

Currently every Hall of JLab has proposal or active experiment for near-threshold measurement!

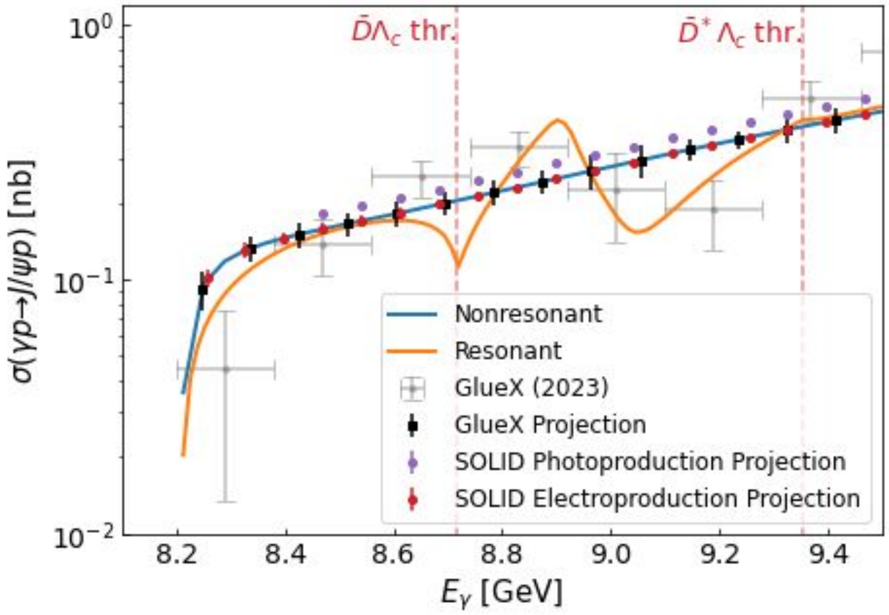
**Hall A (SBS) [LOI12-18-001 PAC 46] (SoLID) [arXiv:2209.13357]**
**Hall B (CLAS12) [E12-12-001A]**
**Hall C [PR12-07-10 PAC 32]**
**Hall D (Gluex Phase-II) & (Extension) [LOI-12-23-010 PAC 51]**

Next generation facilities, e.g. EIC / EicC and JLab24 also interested in this reaction.

Study at peripheral pp collisions collisions possible!

**[See J. Taylor's talk yesterday]**

**Key measurement is the photoproduction of open charm channels!**



# Theoretical prospects

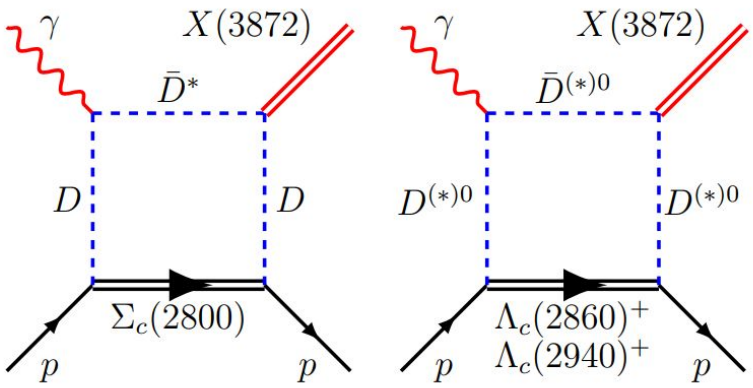
X-H Cao, M-L Du, F-K Guo [arXiv:2401.16112]

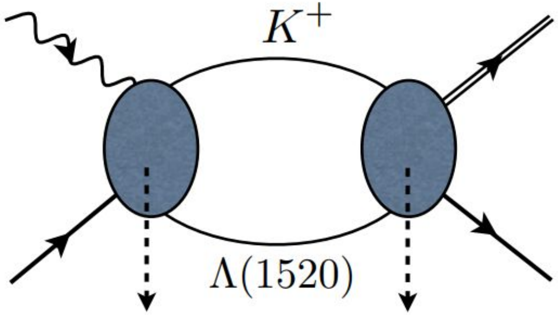
K-matrix demonstrates non-negligible contribution from nearby thresholds but theory should now go back to looking for **microscopic explanation**.

GPD, holographic, and/or effective Pomeron models cannot incorporate additional thresholds…

Hadronic box models cannot incorporate glue and (so far) completely ignore non-trivial differential distribution…

**Need prediction for helicity dependence**




H-Y Rui et al [PTEP 2014 (2014) 023D03]

# Conclusions

Despite abundance of new data, determining exact nature of underlying physics still uncertain!

- Is proton structure accessible? **Maybe**
- Are there still pentaquarks? **Possibly**
- Are there cusps? Open charm? **Perhaps**
- Tiny scattering length? **Conceivably**
- VMD-like production? **Could be**

Call for re-evaluation of model assumptions and uncertainties.

**Y. Guo et al [Phys.Rev.D 108 (2023) 3, 034003]**
**Y. Guo, X. Ji, & F Yuan [arxiv:2308.13006]**

Too simple models may not have enough discriminating power and may lead to false-positives.