Dynamics in J/ψ photoproduction near threshold

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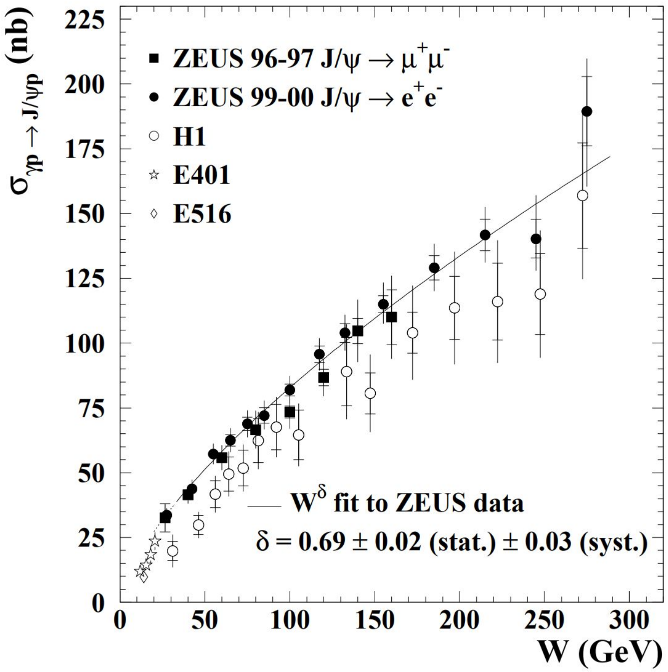
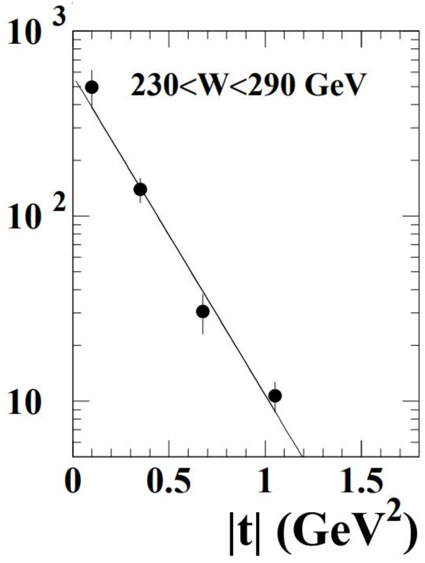
J/ψ photoproduction (at high energies)

Historically J/ψ 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 **gluonic 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/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**.

Potentially effective probe of **gluonic content of proton** based on factorization arguments in perturbative and holographic QCD.

- Gravitational form factors

  Mamo & Zahed [Phys. Rev. D 101, 086003 (2020)]

  Guo, Ji & Liu [Phys. Rev. D 103, 096010 (2021)]

- Mass radius

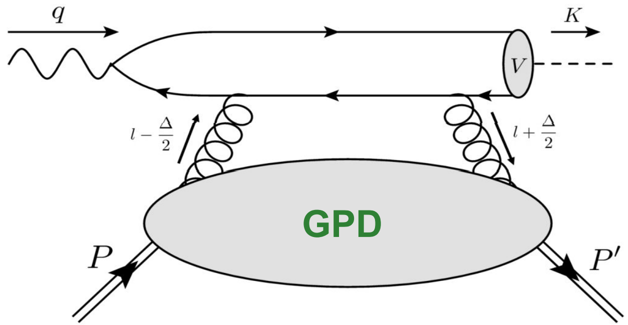
  Kharzeev [Phys. Rev. D 104, 054015 (2021)]

  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)]

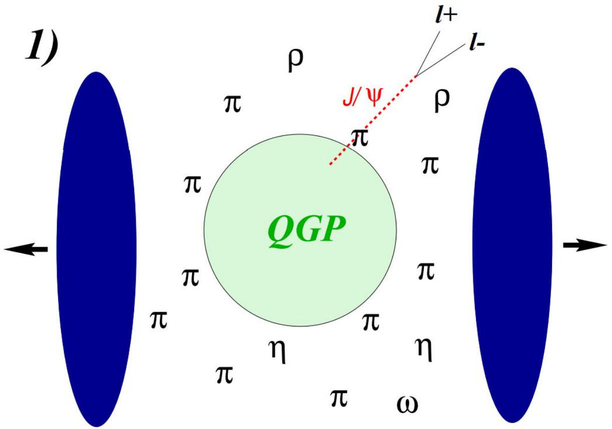


$$\langle R_{\rm m}^2 \rangle = \frac{6}{M} \left. \frac{dG}{dt} \right|_{t=0},$$

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

J/ψ photoproduction (near threshold)

Measurements at energies near threshold have attracted a lot of attention as potentially sensitive to key quantities relevant to **nature of charmonium-nucleon interactions**.



Near threshold the J/ψ-N interaction expected to be dominated by gluonic Van der Waals forces. Interaction strength predicted to be **attractive** and possibly strong enough to bind in nuclei

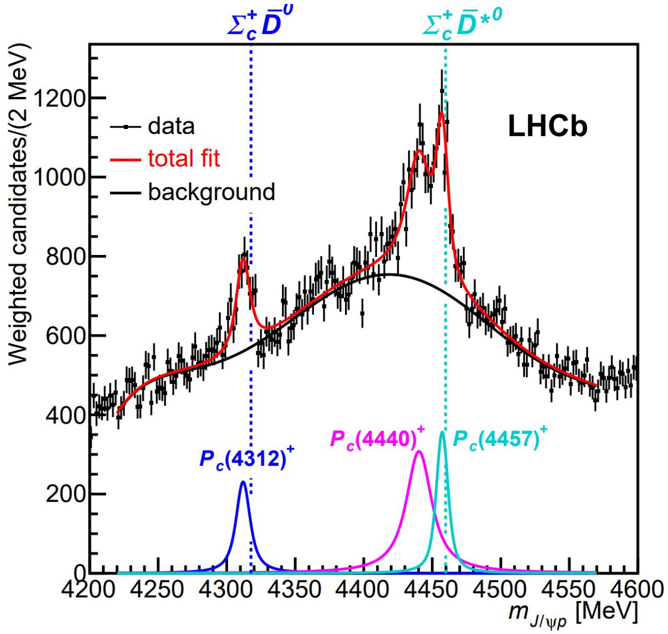
Brodsky & Miller [Phys.Lett.B 412 (1997) 125-130]
Brodsky, Schmidt, & de Teramond [Phys.Rev.Lett. 64 (1990) 1011]

Charmonium absorption cross sections an important ingredient to in searches for **quark-gluon plasma** signatures via charmonium suppression at heavy ion collisions.

Barnes [Eur.Phys.J.A 18 (2003) 531]
Matsui & Satz [Phys.Lett.B 178 (1986) 416-422]

J/ψ photoproduction (near threshold)

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

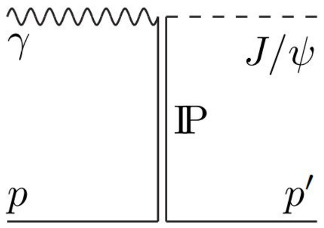


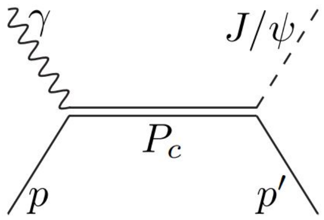
LHCb [Phys.Rev.Lett. 122 (2019) 22, 222001]

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

Q. Wang et al [Phys.Rev.D 92 (2015) 034022]
JPAC [Phys.Rev.D 100 (2019) 3, 034019]

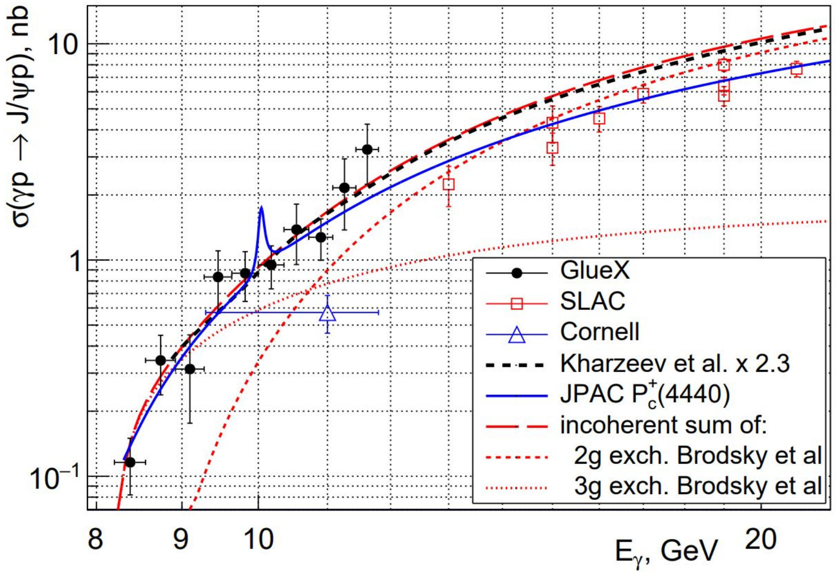
Independent confirmation, **free of triangle singularities**, polarization information allows determination of quantum numbers

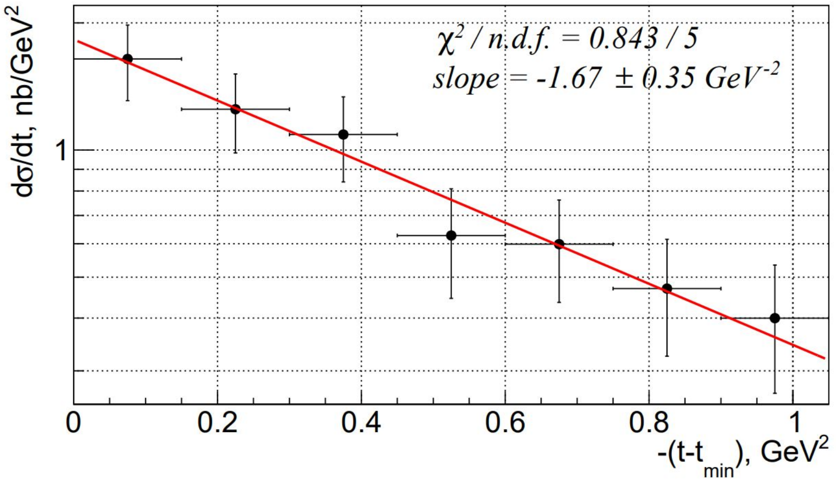




GlueX 2019 data

First measurement near threshold by GlueX in 2019 seemed to observe the same behavior.





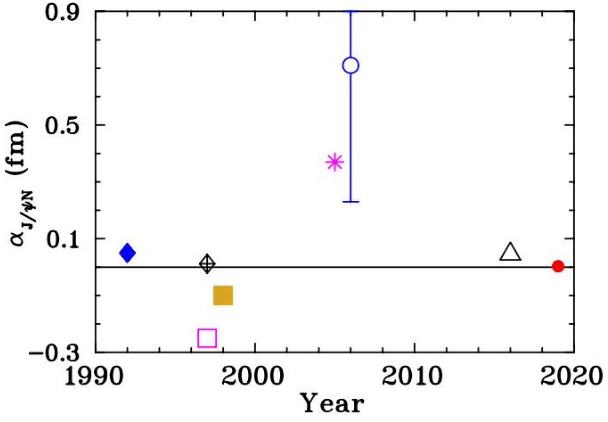
GlueX [Phys.Rev.Lett. 123 (2019) 7, 072001]

Confirmation of **gluon dominated dynamics**?

Unclear dynamics

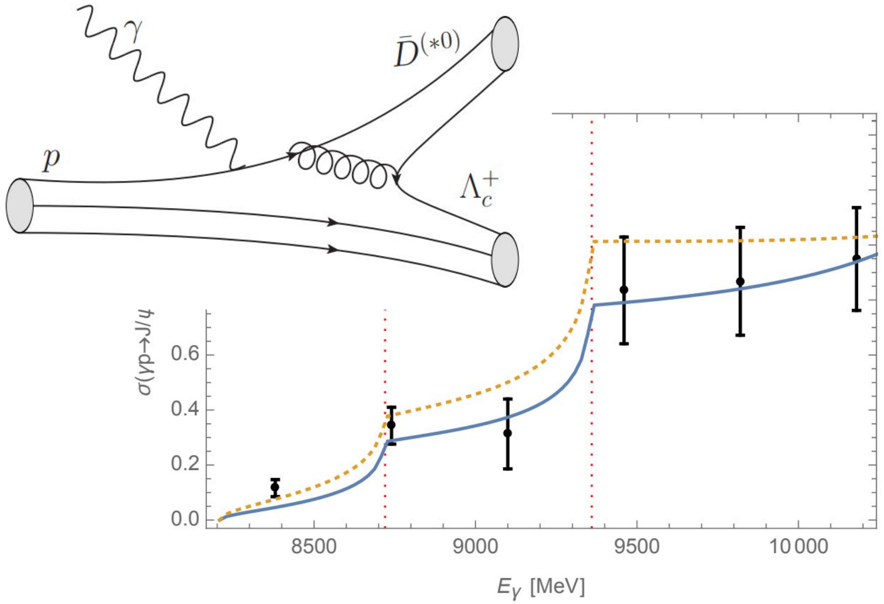
Process may not be as simple as it seems.

- Anomalously small scattering length?
- Are there cusps? **Open charm**?
- Where are the pentaquarks?
- Are GFFs actually accessible?



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

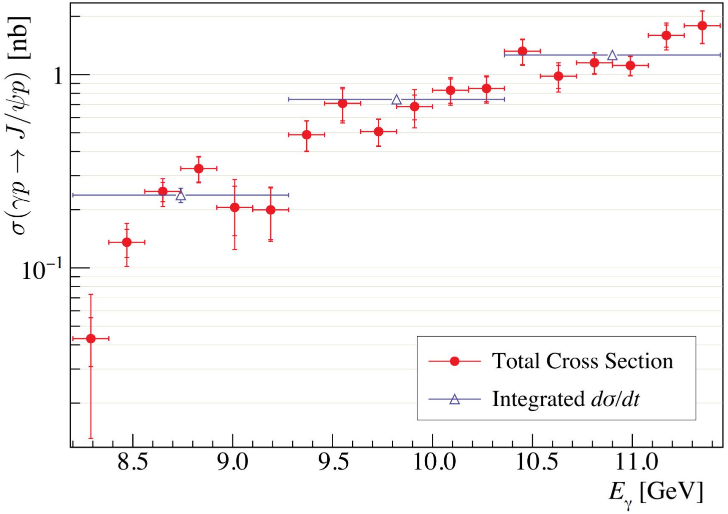
Du et al [Eur.Phys.J.C 80 (2020) 11, 1053]



	$\mathcal{B}(P_c^+ \to J/\psi p)$ 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

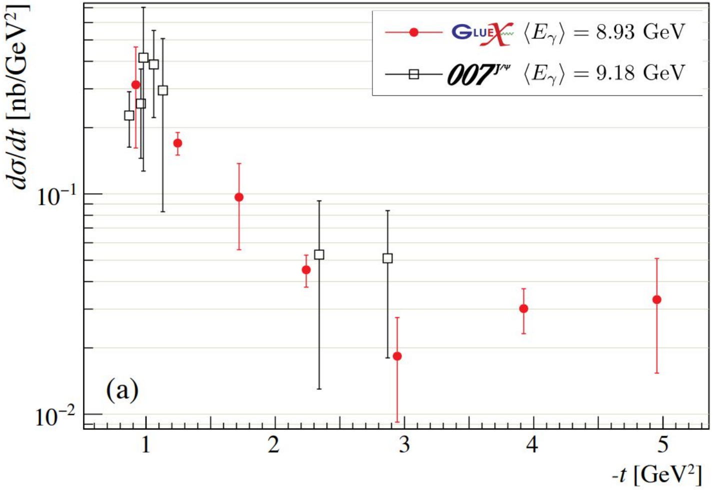
GlueX [Phys.Rev.Lett. 123 (2019) 7, 072001]

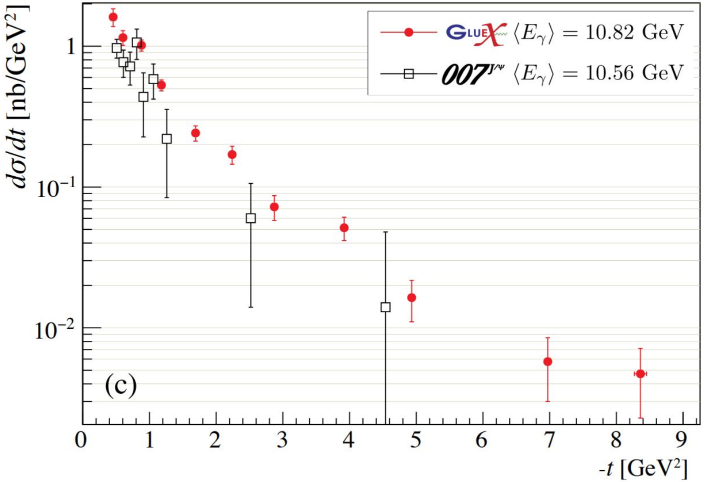
New Jefferson Lab Data



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

[arXiv:2304.03845]





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

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

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/ψ photoproduction.

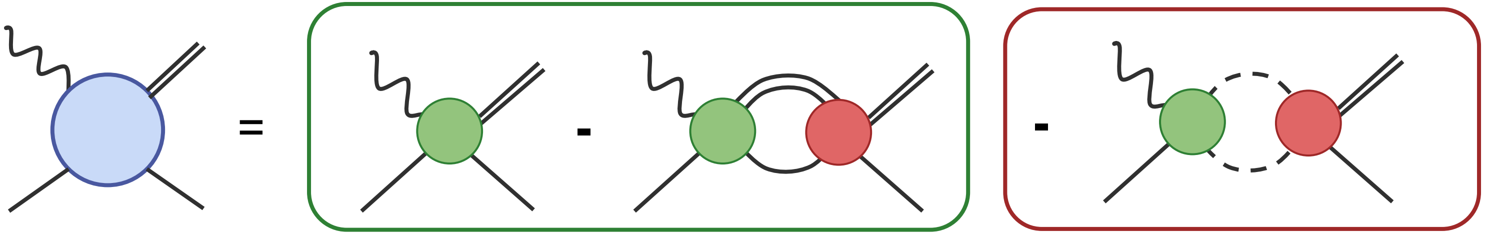
Close to threshold, we expand the amplitude into **s-channel partial waves** which are parameterized to satisfy **low-energy unitarity.**

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

$$\left.\begin{aligned} \mathrm{Im}\; F_\ell &= F_\ell\, \rho\, T_\ell^\dagger \\ \mathrm{Im}\; T_\ell &= T_\ell\, \rho\, T_\ell^\dagger \end{aligned}\right\} \longrightarrow \quad F_\ell = f_\ell\,(1 - G\,T_\ell) \quad \text{with} \quad T_\ell = \frac{1}{K_\ell^{-1} + G}$$

Direct channel contains direct photocoupling & hadronic rescattering

Indirect contributions from coupled channels



JPAC [arxiv:2305.01449, submitted to PRD]

K-matrix analysis

Much fewer underlying model assumptions:

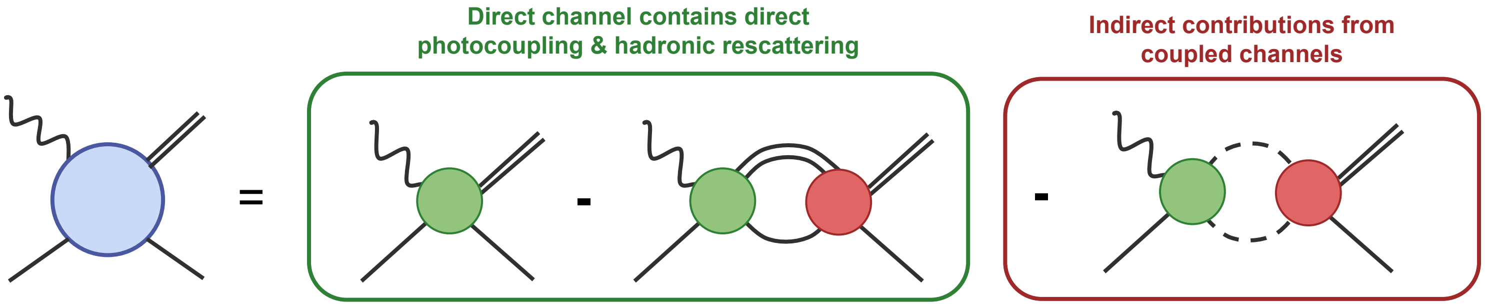
- Angular dependence saturated by few terms partial waves expansion **$L \leq 3$ works well!**
- Energy dependence saturated by few terms in near threshold expansion

Scattering length and/or effective range works well!

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

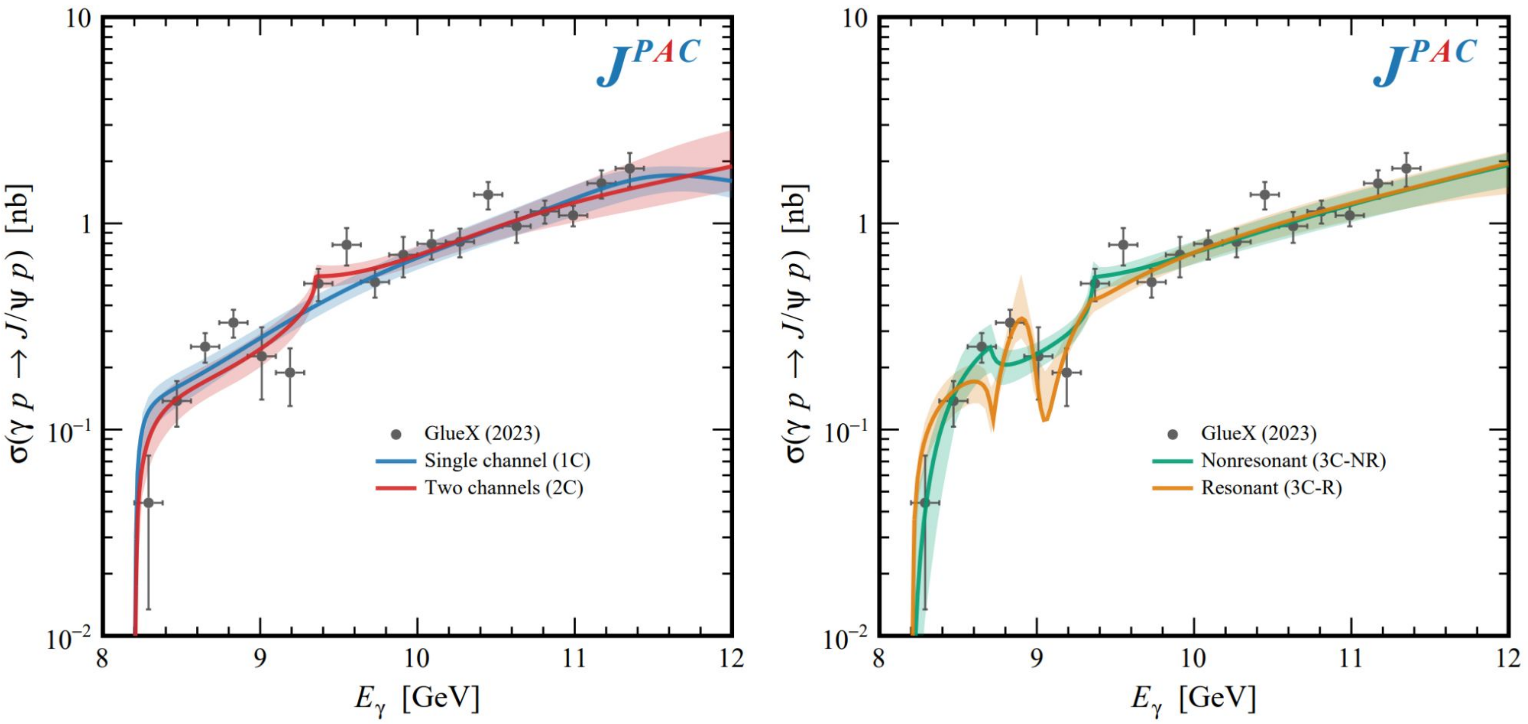
$$f_\ell = (pq)^\ell \, n_\ell$$

Fully data driven analysis considering all data simultaneously.



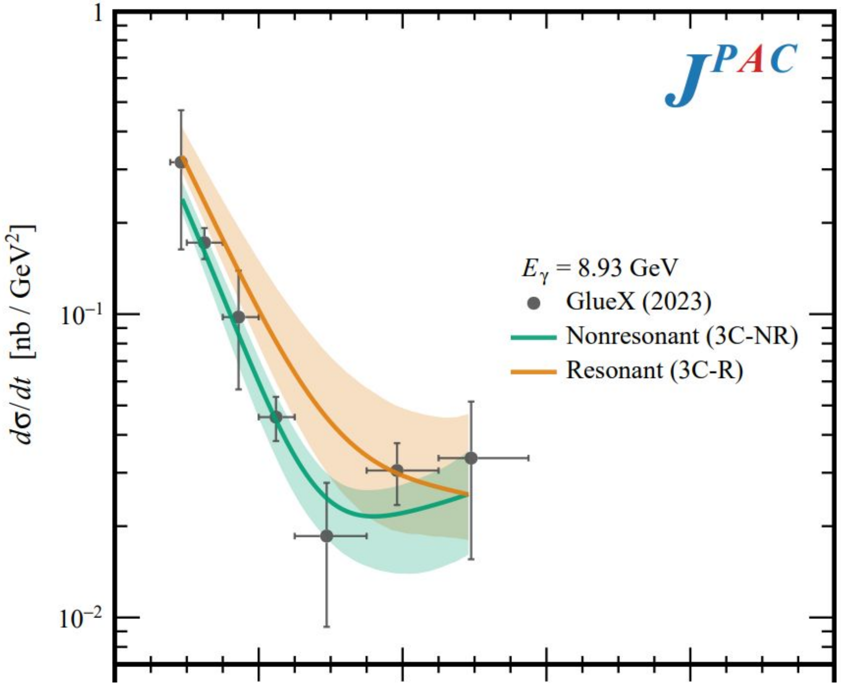
Integrated cross section

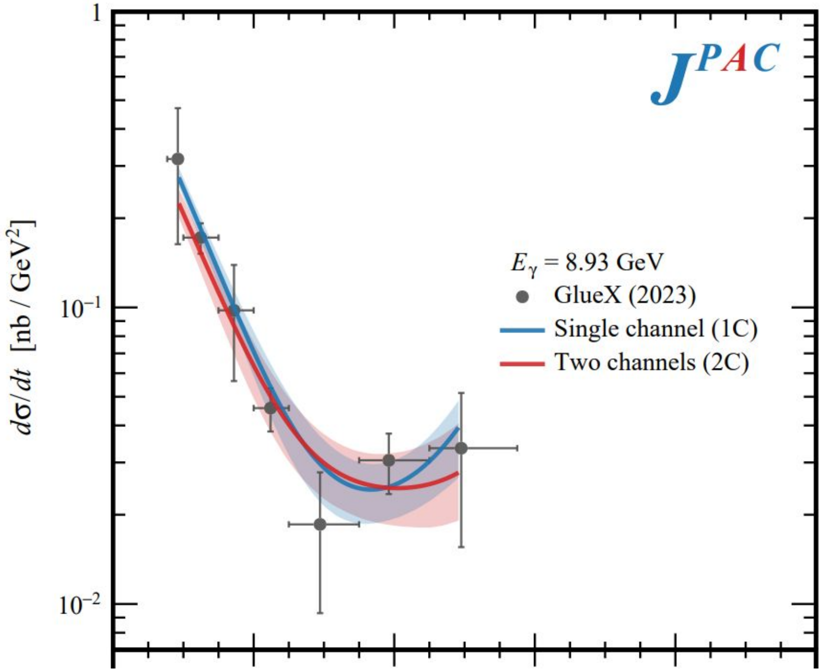
Four solutions with different dynamical pictures found to be consistent with full data with similar statistical significance.



JPAC [arxiv:2305.01449, submitted to PRD]

Differential cross section

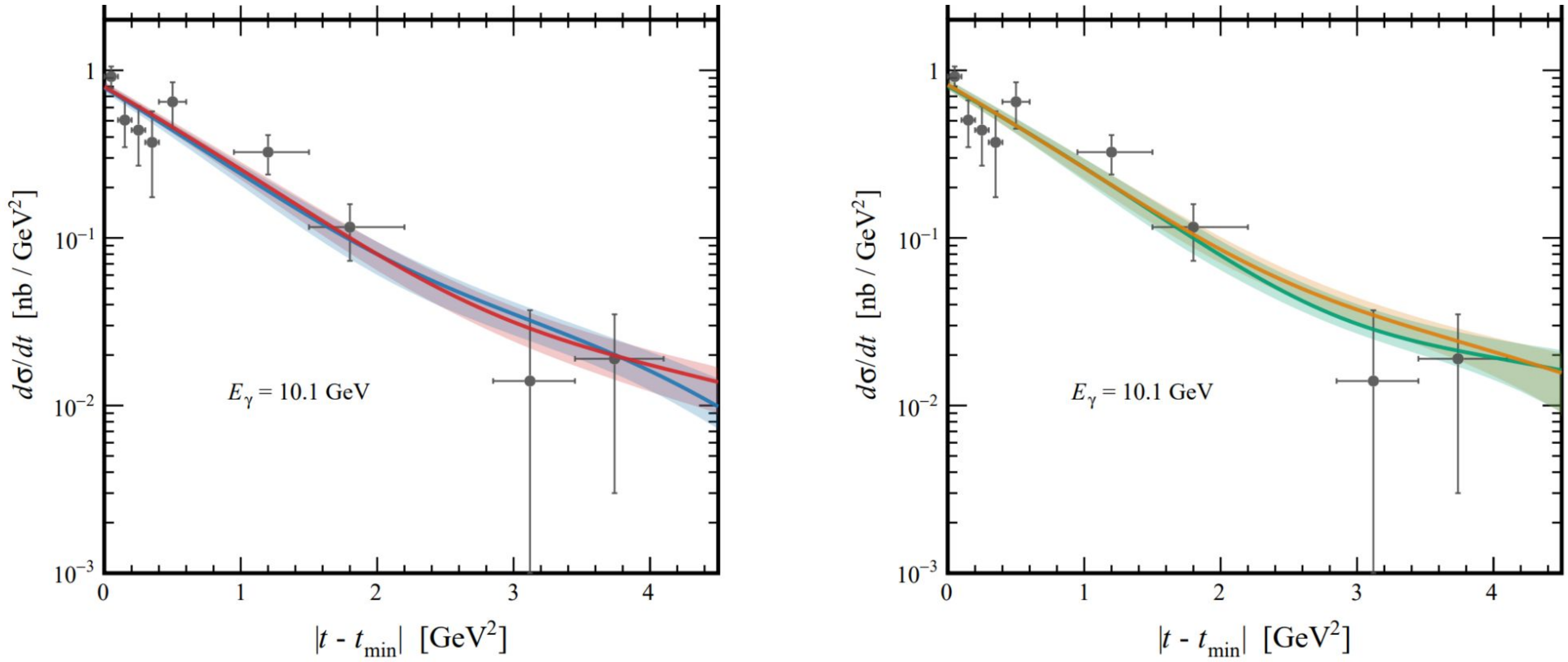




All reproduce apparent enhancement at large |t|!

Differential cross section

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



Production mechanisms

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

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

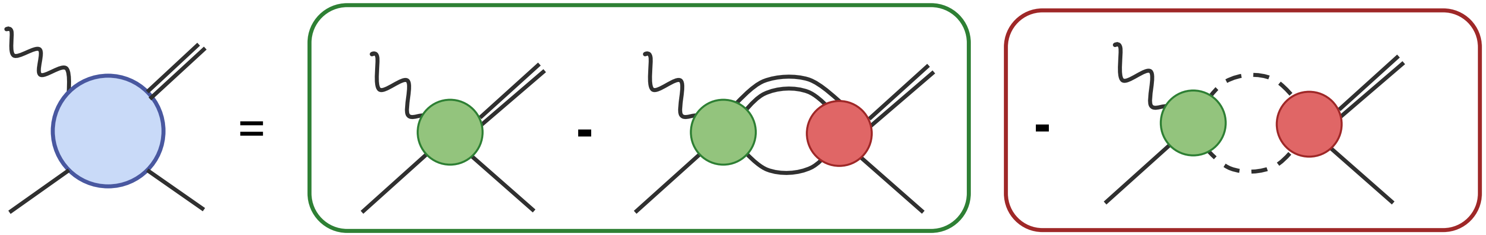
When included "**factorization violating**" contributions make up > 25% at 90% CL!

90% CL

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

Direct channel contains direct photocoupling & hadronic rescattering

Indirect contributions from coupled channels



JPAC [arxiv:2305.01449, submitted to PRD]

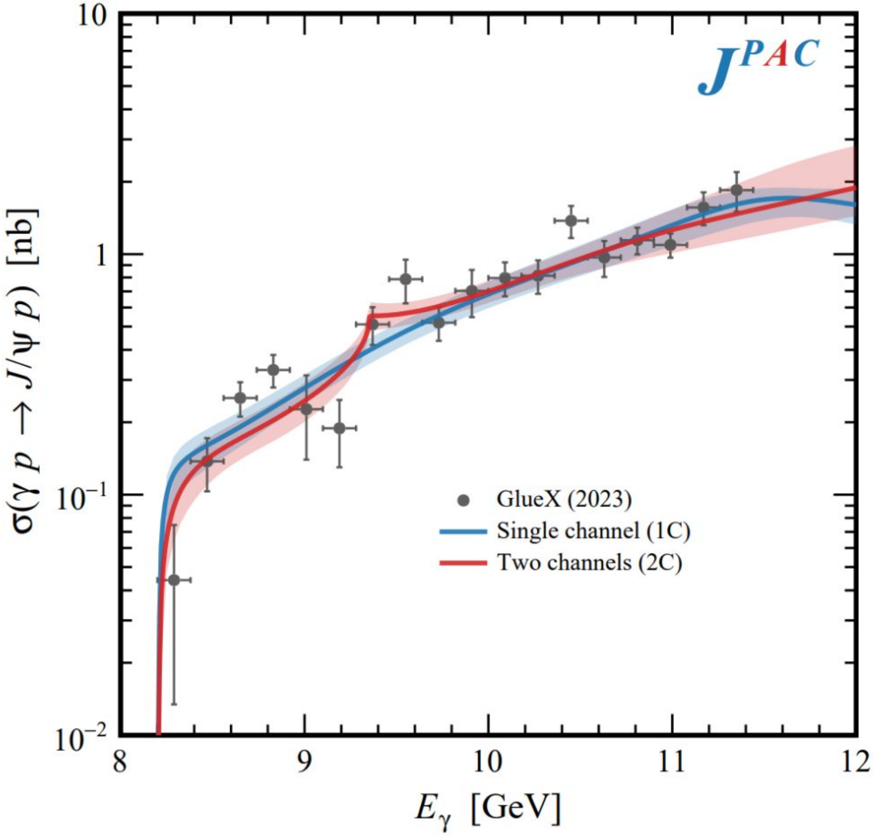
Production mechanisms

Presence of cusps may indicate large contributions from open charm channels (i.e. **charm exchange processes**) which may complicate the connection to proton structure quantities.

90% CL

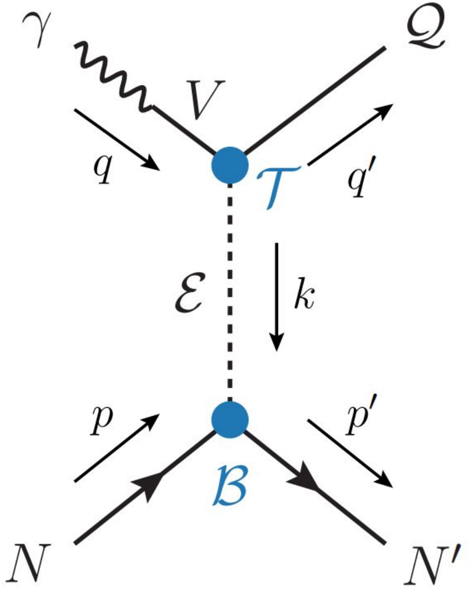
1C	1
2C	[0.56, 0.74]
3C-NR	[0.36, 0.63]
3C-R	[0.03, 0.62]

Solution with nearby pentaquark pole even consistent with entirely charm exchange dominated production!



Vector meson dominance

VMD used extensively in the phenomenology of photoproduction processes. Provided lightweight connection between production and **elastic scattering**.



VMD: $$F^{\psi p}(s,x) = g_{\gamma\psi}\, T^{\psi p,\psi p}(s,x)$$

Low-energy Unitarity: $$F_\ell(s) = f_\ell\,(1 + G\,T_\ell)$$

This constitutes a very specific model for the production:

Photon acts as spectator in the final state J/ψ production

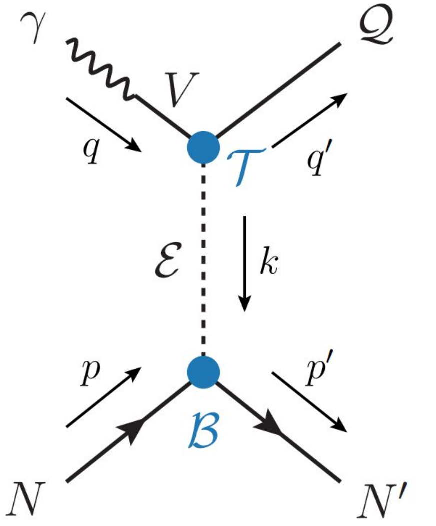
Use of VMD is not an exact science but has been hoped to be reliable up order of magnitude. Explicit tests in heavy states near threshold has never been conducted.

JPAC [arxiv:2305.01449, submitted to PRD]

Vector meson dominance

K-matrix formalism allows us to extract the **elastic J/ψp amplitude** directly (obeying unitarity). Define test ratio to check the validity of the VMD assumption:

$$R_{\text{VMD}}(x) = \left| \frac{F^{\psi p}(s_{\text{th}}, x)/g_{\gamma\psi}}{T^{\psi p, \psi p}(s_{\text{th}}, x)} \right|$$



VMD found to underestimate elastic scattering by 2 orders of magnitude in all cases except those containing a nearby pole!

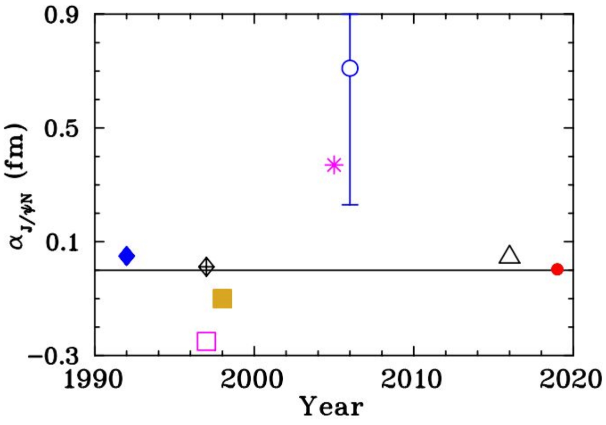
1C	[0.45 0.73] x 10^{-2}	[1.3, 2.0] x 10^{-2}
2C	[0.39, 1.69] x 10^{-2}	[1.3, 5.1] x 10^{-2}
3C-NR	[0.03, 1.74] x 10^{-2}	[0.08, 8.9] x 10^{-2}
3C-R	[1.4 x 10^{-2}, 0.58]	[5.4 x 10^{-2}, 1.8]

JPAC [arxiv:2305.01449, submitted to PRD]

Elastic scattering length

First extraction of the elastic J/ψp 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

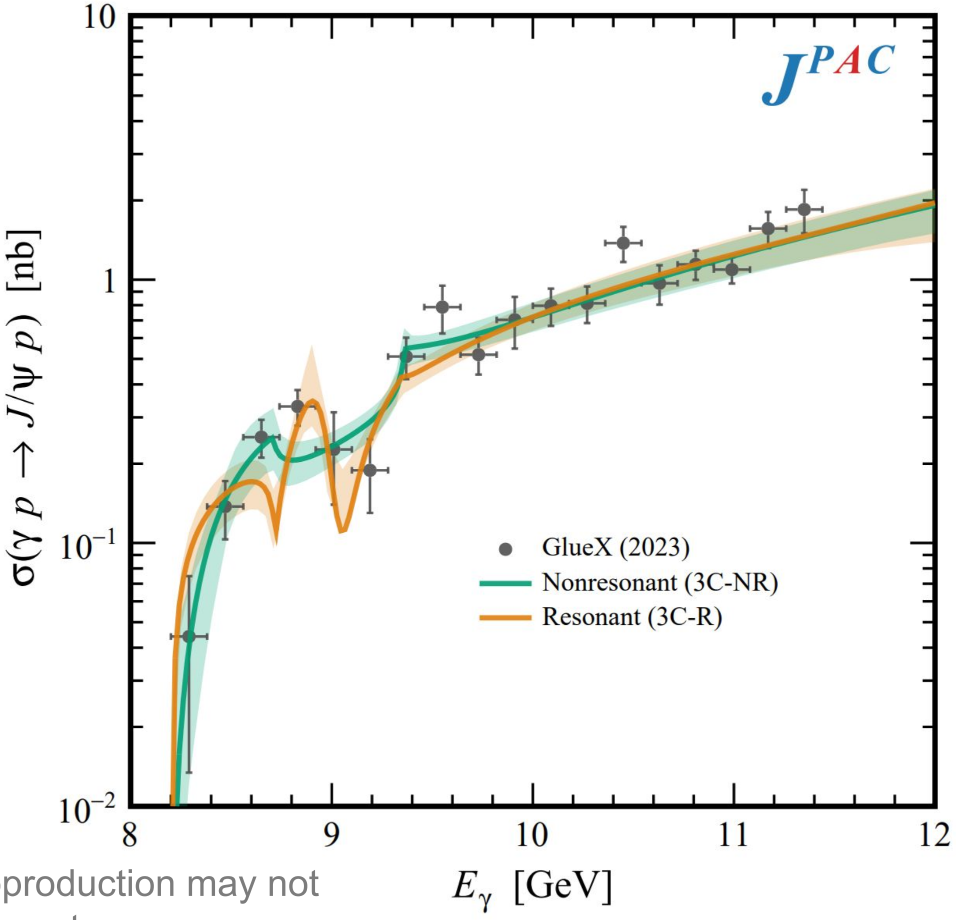
JPAC [arxiv:2305.01449, submitted to PRD]

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**!



VMD result also indicates nonobservation in photoproduction may not immediately kill possibility of pentaquarks in $J/\psi p$ spectrum

Conclusions

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

- Anomalously small scattering length?
- Are there cusps? Open charm?
- Where are the pentaquarks?
- Are GFFs actually accessible?

???

Calls for further study both experimentally and theoretically to understand model limitations and assumptions!

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)

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

Key measurement is the photoproduction of open charm channels!