Heavy meson spectroscopy in photoproduction

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PWA 13 / ATHOS 8
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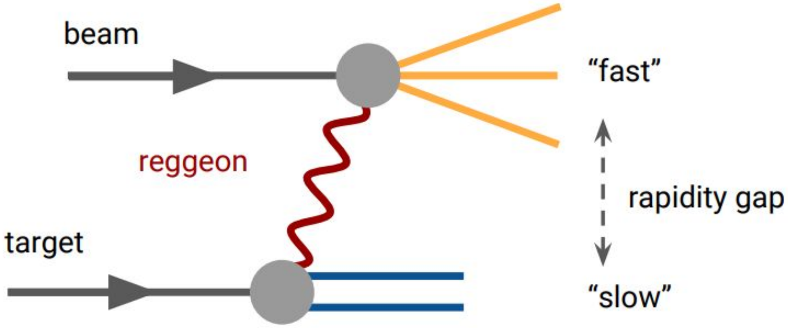
Photoproduction

Powerful tool in spectroscopy

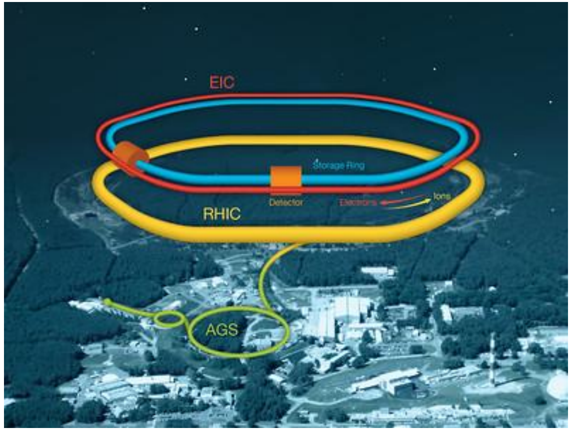
- Can produce any quantum-numbers
- Well understood in terms of diffractive production (**exchange physics**)
- Constrained kinematics means precise probe of production mechanism
- Polarization information gives useful insight into structure
- Minimizes role of rescattering

JPAC [Phys.Rev.D 98 (2018) 3, 034020]



EIC Yellow Report [arXiv:2103.05419]

COMPASS



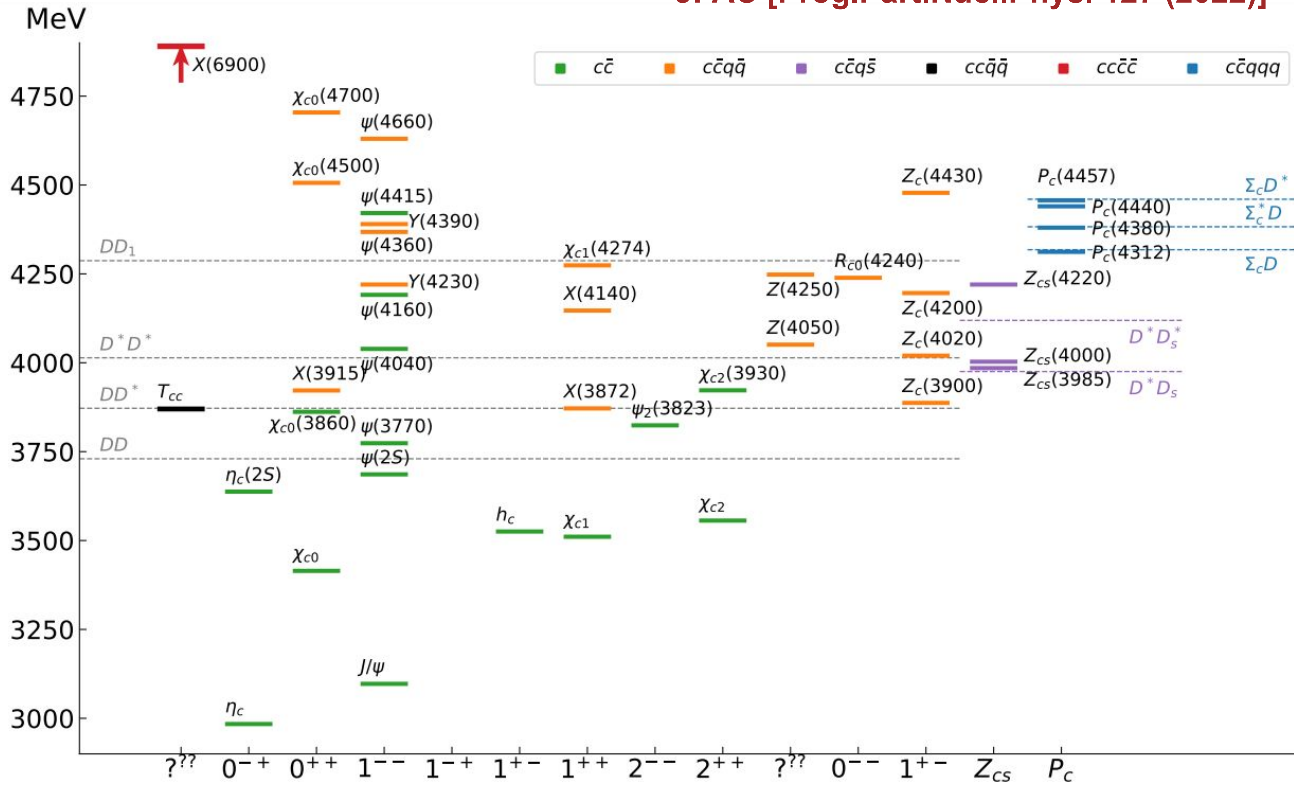
clas GLUEX 007 $^{J/\psi}$

Exotic XYZ states

JPAC [Prog.Part.Nucl.Phys. 127 (2022)]

Rich spectrum of resonance-like signals observed in heavy baryon decays and electron-positron collisions.

Seemingly consistent with structure **beyond $Q\bar{Q}$**.



Exotic XYZ states

See reviews:
JPAC [Prog.Part.Nucl.Phys. 127 (2022)]
Chen et al [Rept. Prog. Phys. 86 (2023) no.2, 026201]
Brambilla et al [Phys.Rept. 873 (2020) 1-154]
Guo et al [Rev.Mod.Phys. 90 (2018) 1, 015004]
Esposito et al [Phys.Rept. 668 (2017) 1-97]

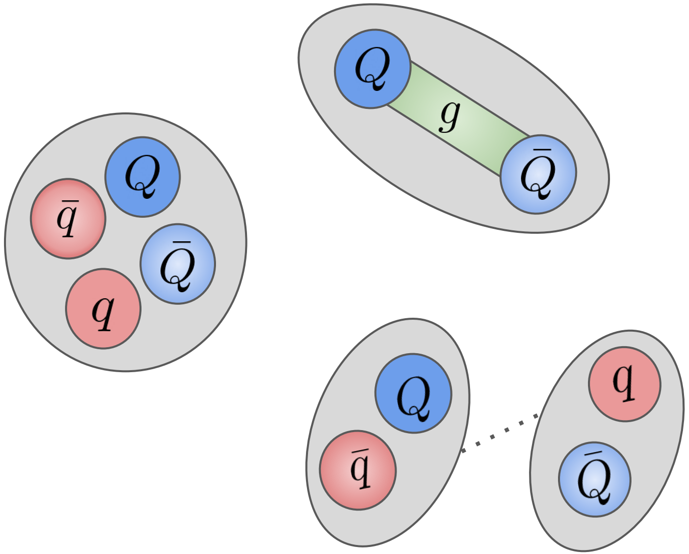
Precise microscopic nature inconclusive, with multiple possible interpretations in terms of QCD degrees of freedom.

Coincidence of nearby multiparticle thresholds may suggest important **multi-channel dynamics**.

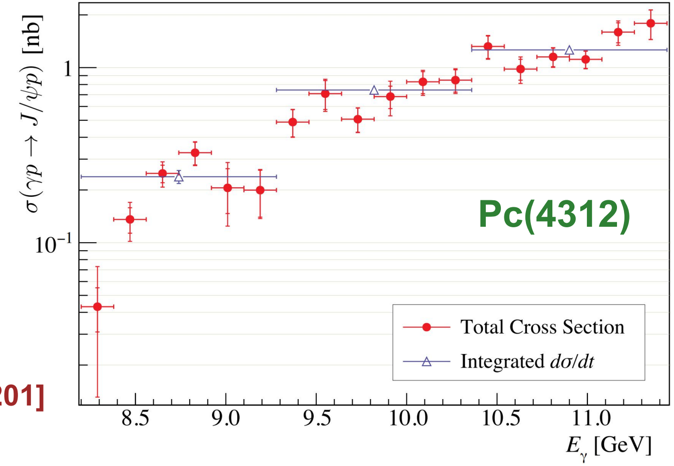
Understanding of many as shallow bound states with prominent molecular component from open-charm

$$a = -\frac{2\,X}{1+X}R + \mathcal{O}(m_\pi^{-1}) \qquad r = -\frac{1-X}{X}R + \mathcal{O}(m_\pi^{-1})$$

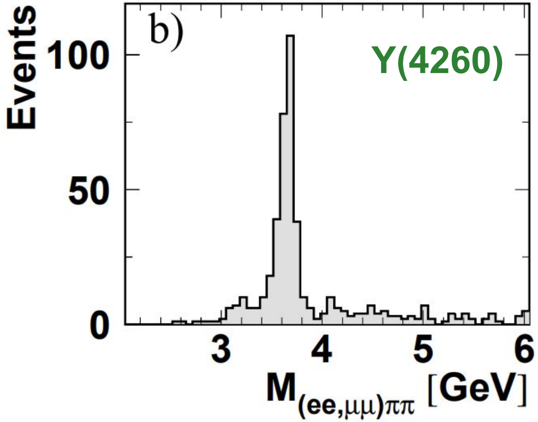
Li et al [arXiv:2110.02766]
Albaladejo and Nieves [arXiv:2203.04864]



Photoproduction searches

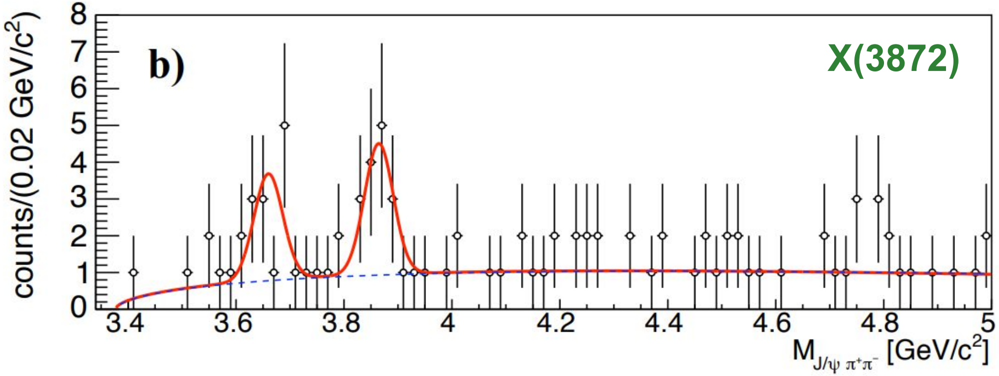


GlueX [Phys.Rev.C 108 (2023) 2, 025201]

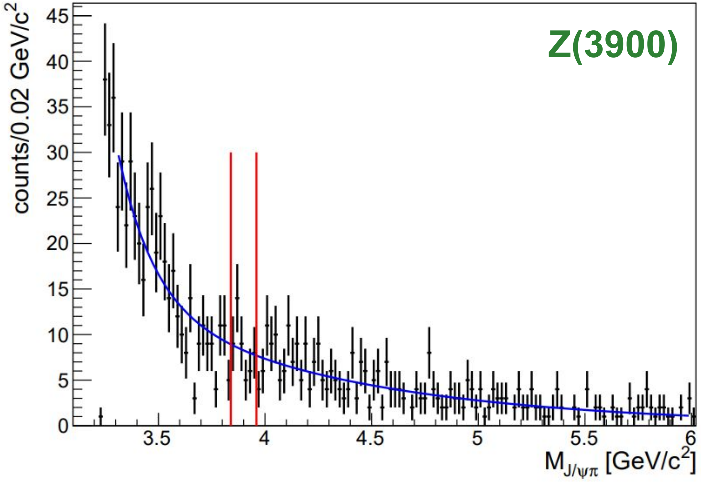


H1 [Phys.Lett.B 541 (2002) 251-264]

COMPASS [Phys.Lett.B 783 (2018) 334-340]



COMPASS [Phys.Lett.B 742 (2015) 330-334]



Proton structure

V.D. Burkert, L. Elouadrhiri, F.X. Girod [arXiv:2310.11568]

Potential probe of gluonic contributions to proton mass by mimicking spin-2 graviton current

- Gravitational form factors

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

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

- Mass radius

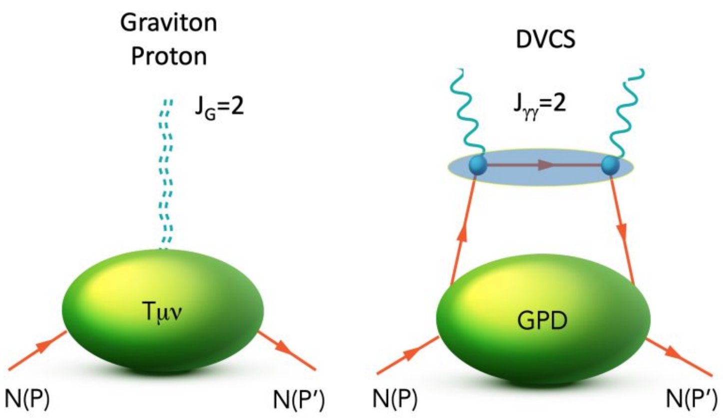
  Kharzeev [Phys. Rev. D 104, 054015 (2021)]

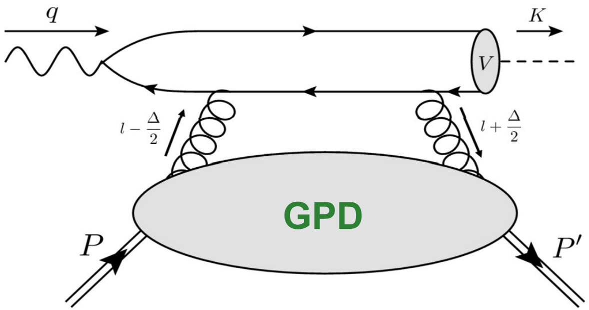
  Mamo & Zahed [Phys. Rev. D 103, 094010 (2021)]

- 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)]





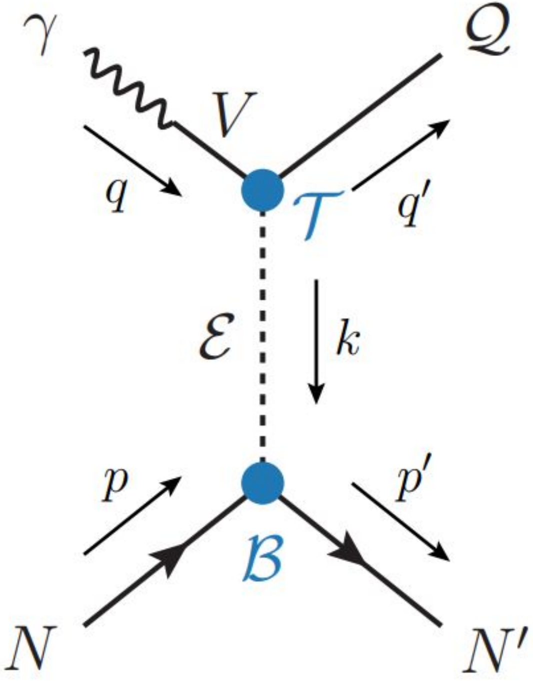
Exclusive photoproduction

Expected dominant production modes relying on measured branching fractions. Minimal assumption on microscopic nature.

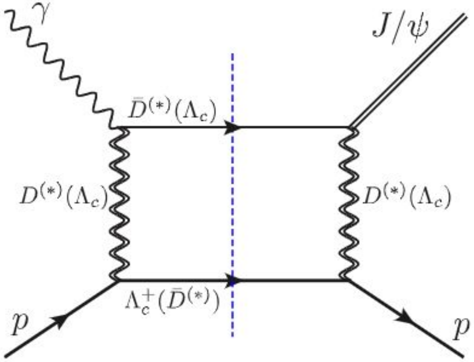
Can consider broad energy range. **Near-threshold** production dominated by meson exchanges while high-energy production proceeds through Reggeon exchanges.

Largest uncertainty comes from use of VMD.

JPAC [Phys. Rev. D 102, 114010 (2020)]



Xu et al [Eur.Phys.J.C 81 (2021) 10, 895]



Ignores possible more complicated production modes which may contribute

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

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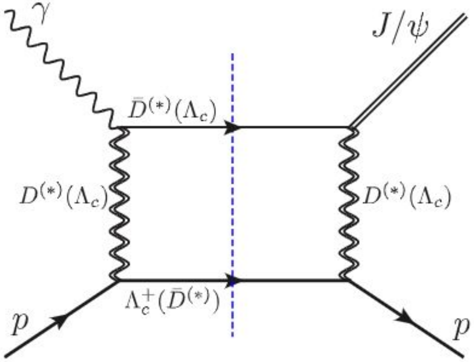
Largest un

Baseline for production by assuming phenomenology the same as in light sectors.

Xu et al [Eur.Phys.J.C 81 (2021) 10, 895]



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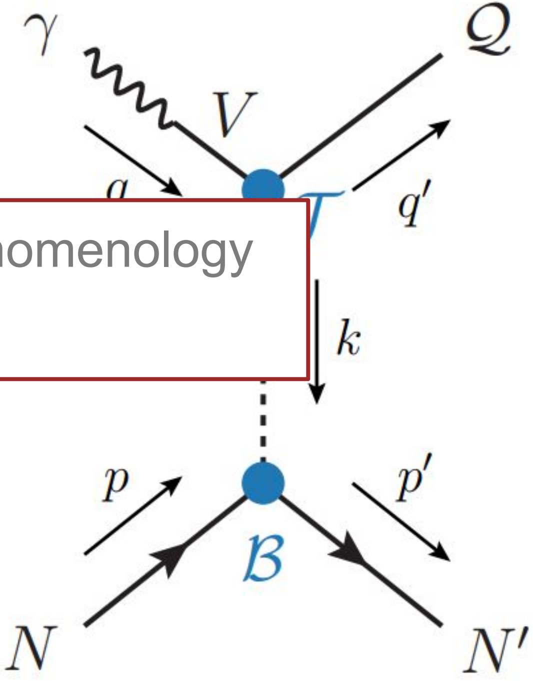
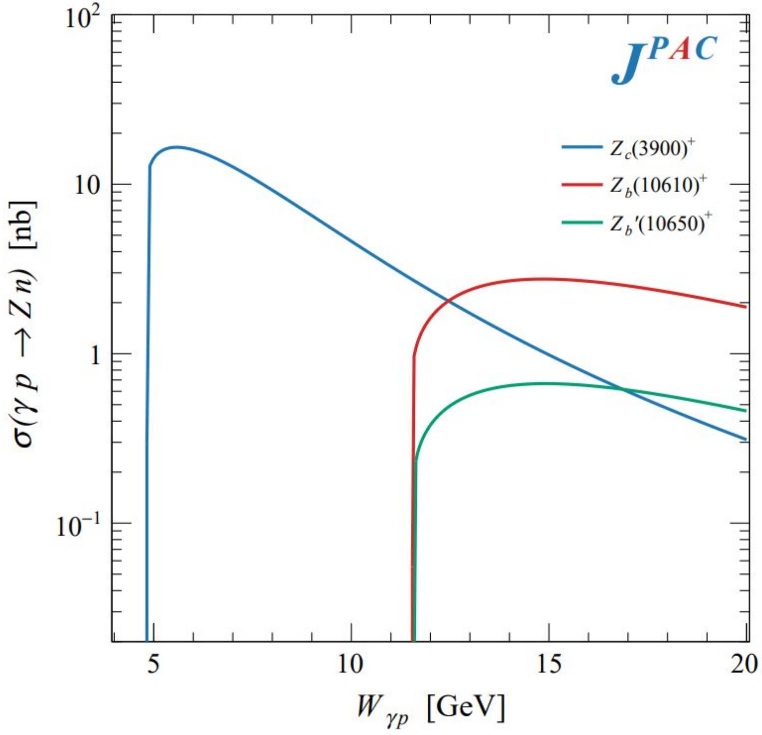
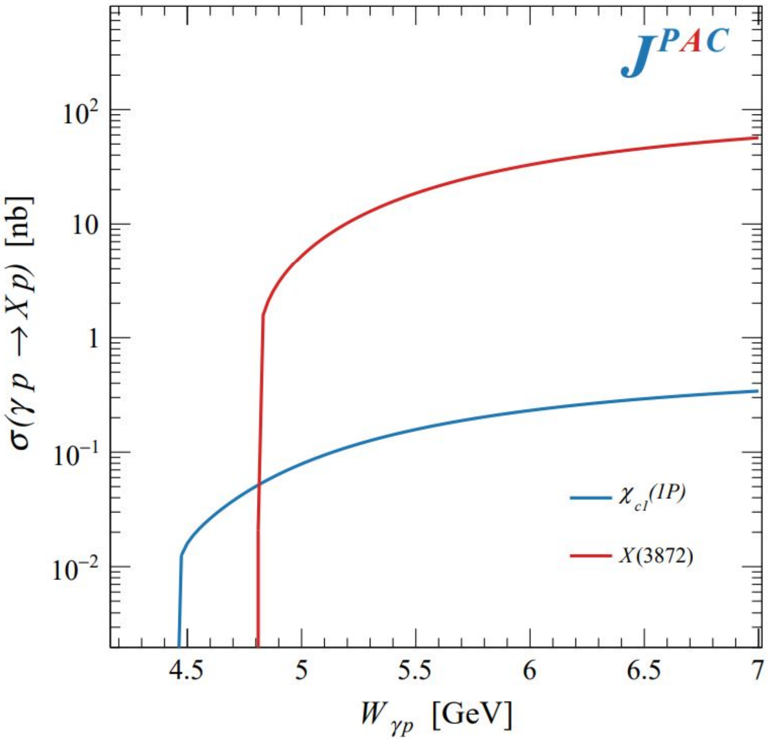


JPAC [Phys. Rev. D 102, 114010 (2020)]

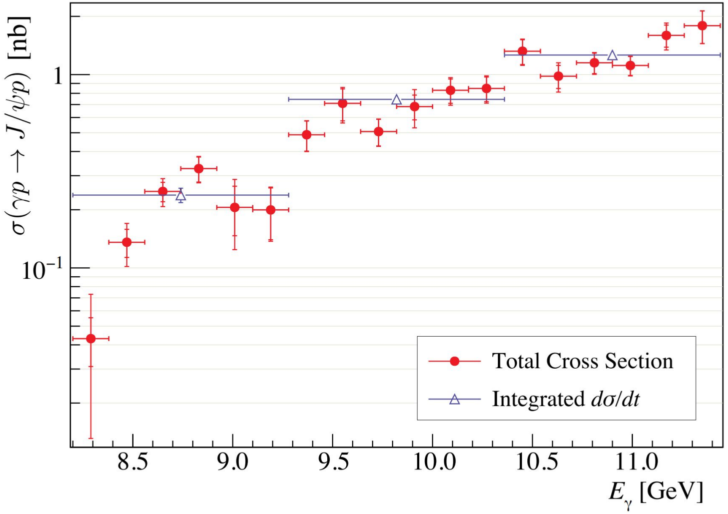
Exclusive photoproduction

Near-threshold production seems very promising for X(3872) and Z states



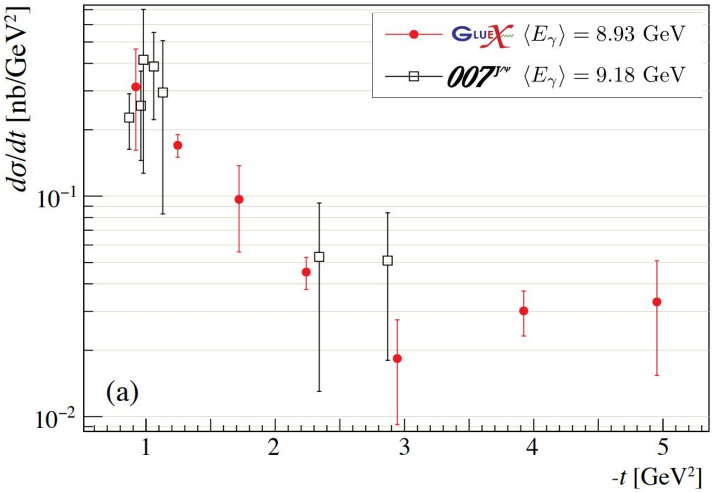


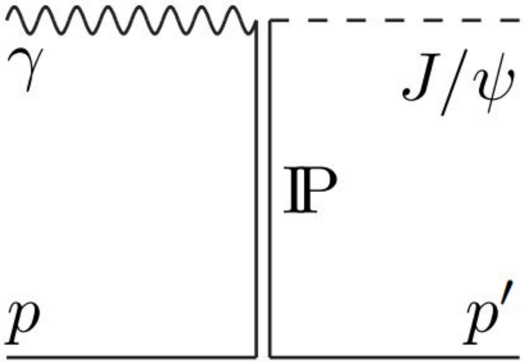
J/ψ at GlueX



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

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



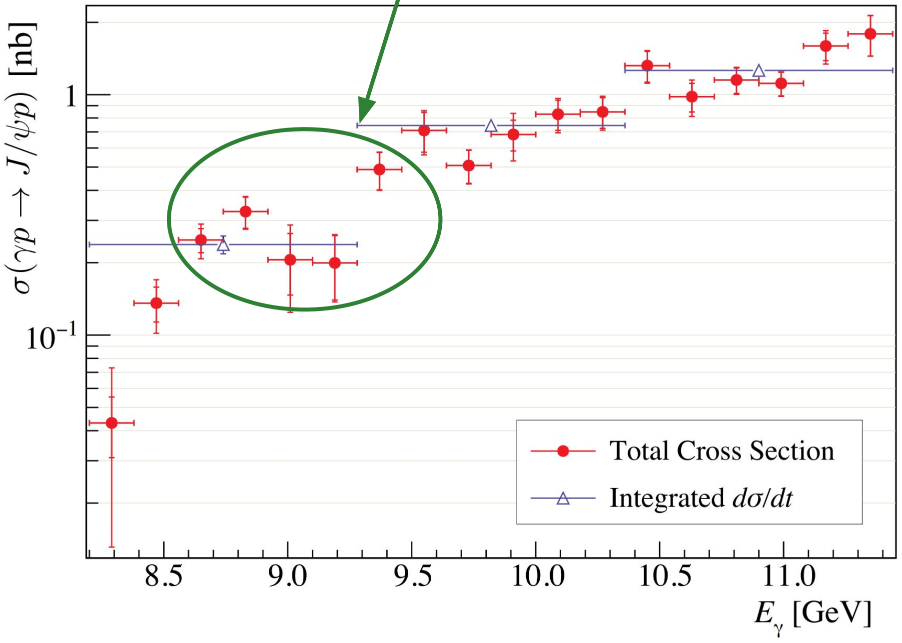


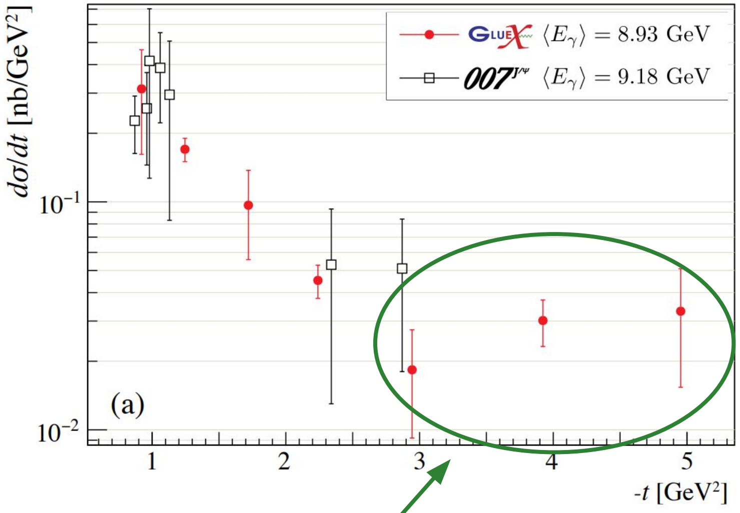
Much larger data set available, incorporating both integrated and differential cross sections.

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

J/ψ at GlueX

"Dip" now established at ~2.6σ compared to a smooth fit





Flattening of t-distribution at large momentum transfer also at ~2.3σ compared to a dipole

Coupled-channels? Pentaquarks?

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

K-matrix analysis

Larger data set allows more comprehensive analysis in terms of **s-channel partial waves**.

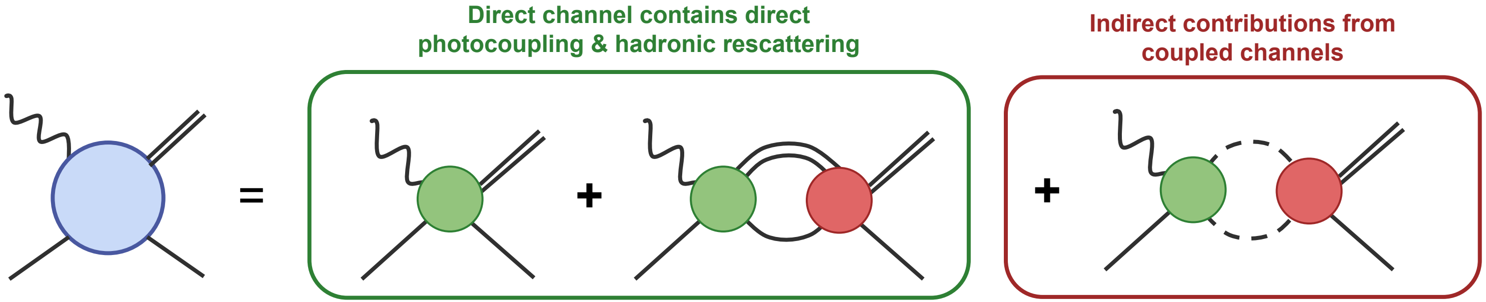
Expansion close to threshold, allows us to use finitely many partial waves, consistent with **coupled-channel unitarity**

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

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

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

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



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

K-matrix analysis

~~Limitations:~~ Advantages:

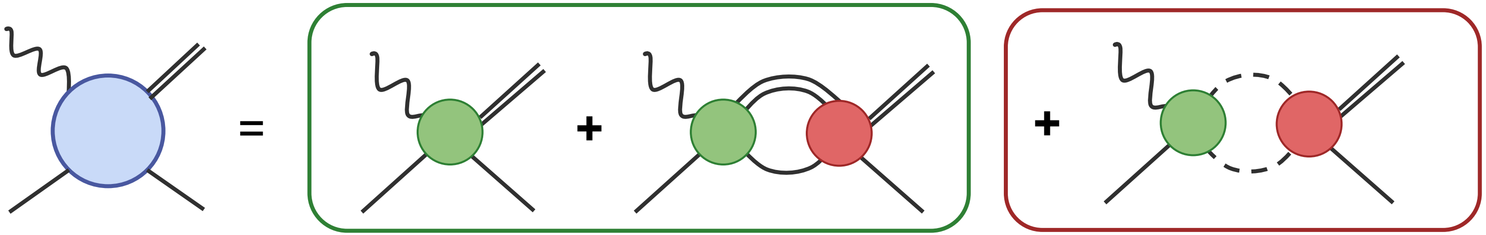
- **Not a microscopic model**
  We don't incur model uncertainty from having to assume dynamics. Model fully analytic and describes entire kinematic range. Depends only on # of terms in PWE and in NTE.

Systematics testable a posteriori. L ≲ 3 and effective range work well

- **Each partial wave must be parameterized independently**

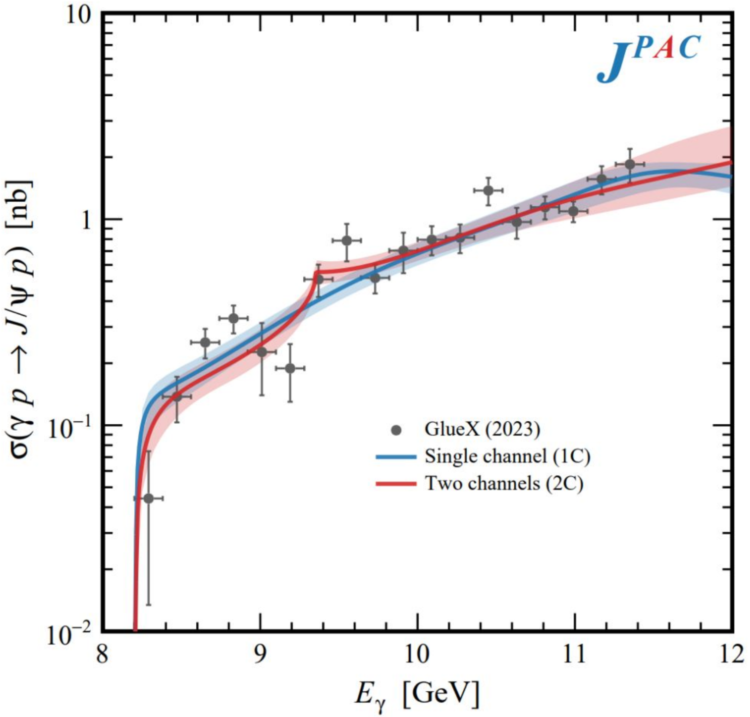
Production and rescattering entirely unconstrained except by unitarity.

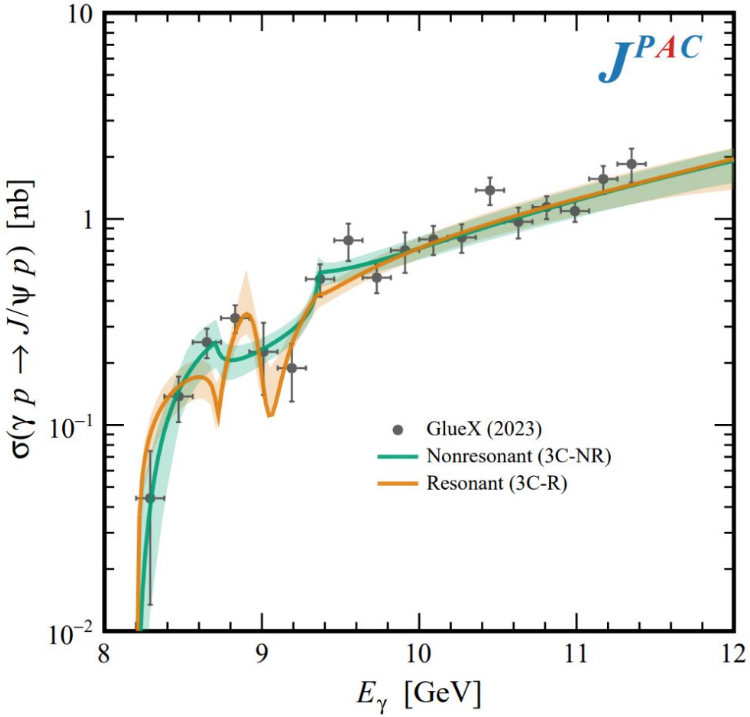
$$K_S^{ij} = \alpha_S^{ij} + \beta_S^i \, q_i^2 \, \delta_{ij} \qquad f_\ell = (pq)^\ell \, n_\ell$$



Integrated cross section

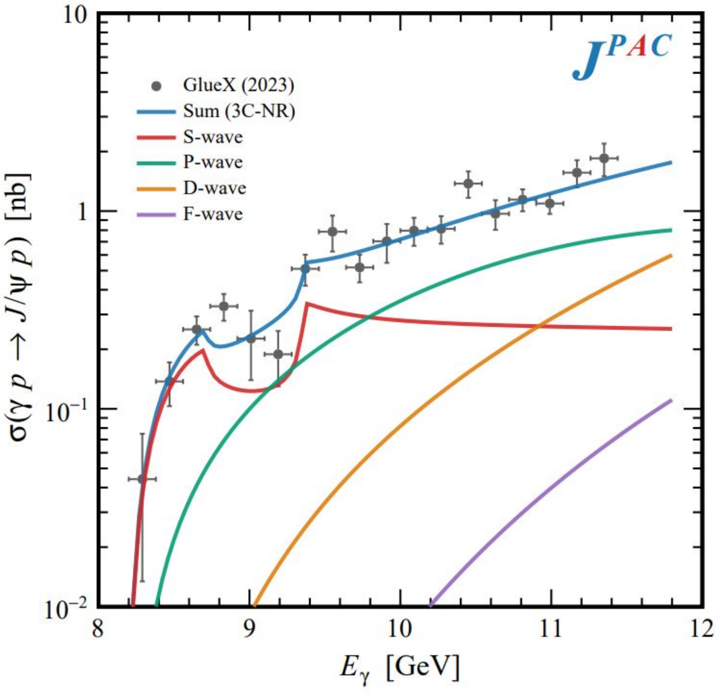
Four solutions with different dynamical pictures found to be consistent with full data with similar statistical significance.

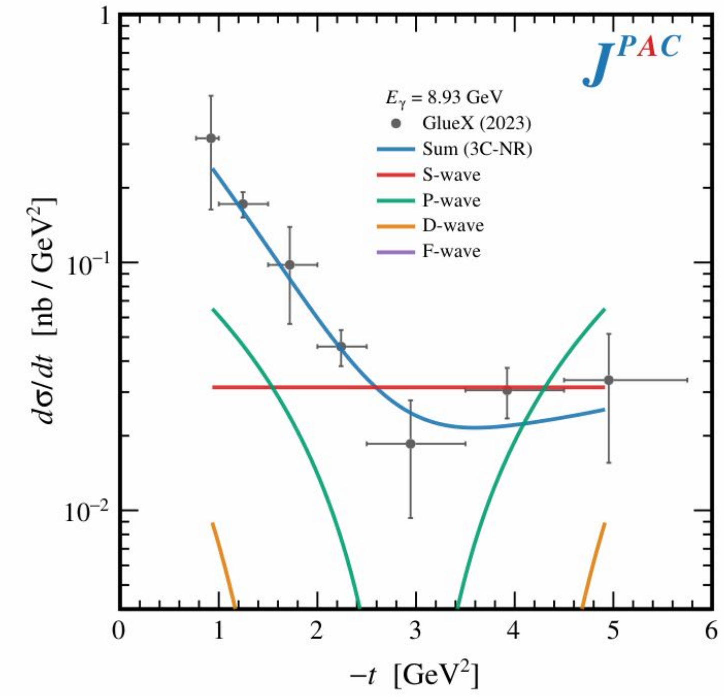




Differential cross section

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





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

Extract dynamics

Unitary amplitude allows us to extract quantities that characterize the interaction with minimal assumption

Elastic scattering length:

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

~ O(1 fm)

Inelasticity:

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

> 25%

Pentaquark poles:

One (3C) solution found with a narrow S-wave pole

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

Extract dynamics

Unitary amplitude allows us to extract quantities that characterize the interaction with minimal assumption

Elastic sca

Need predictions and measurements of polarized observables!

Inelasticity:

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

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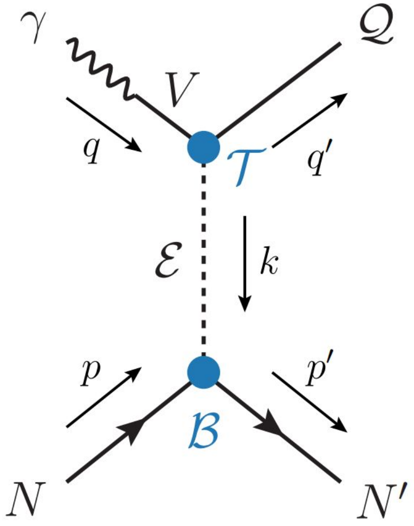
JPAC [Phys.Rev.D 108 (2023) 5, 5]

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:

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

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]

In defense of VMD

The X(3872) observed in purely hadronic and photonic modes gives us unique clue to efficacy of VMD.

Model both by same Lagrangian (compare apples to apples)

$$\mathcal{L}_{Q\gamma\gamma^*} = \frac{1}{2}\frac{g_{Q\gamma\gamma^*}}{m_Q^2}\,\epsilon_{\alpha\beta\mu\nu}\,F^{\alpha\beta}\,\partial_\sigma\,F^{\sigma\mu}\,Q^{*\nu}$$

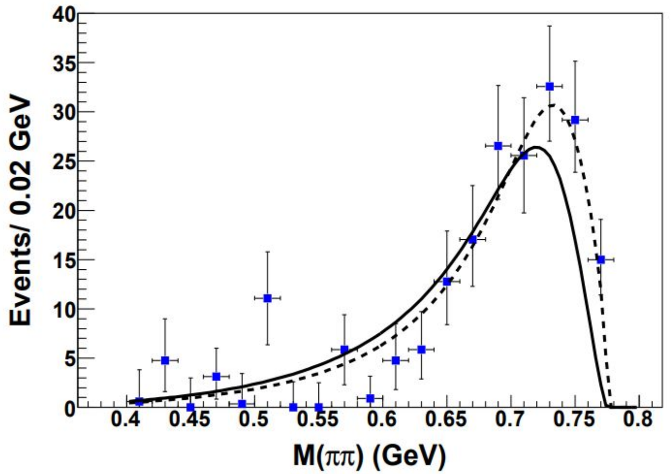
VMD predicts relations between two-photon, radiative, and hadronic couplings

$$g_{Q\gamma\gamma} = \sum_i \frac{g_{Qi\gamma}}{\gamma_i}\,,$$

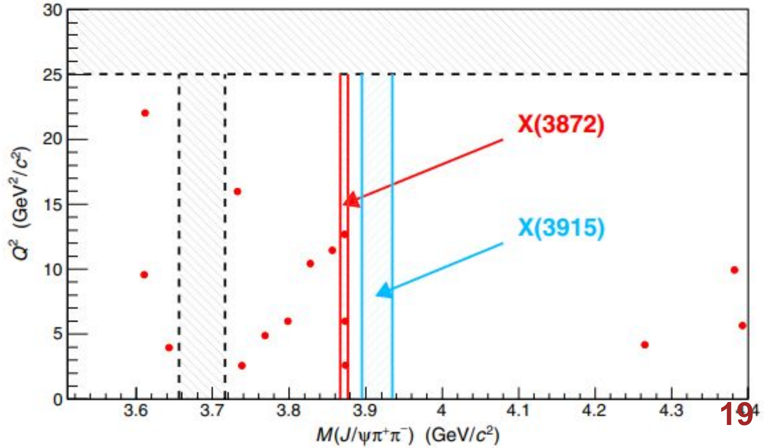
$$g_{Q\gamma\mathcal{E}} = \sum_V \frac{g_{QV\mathcal{E}}}{\gamma_V}\,,$$

$$g_{\gamma NN} = \sum_{\mathcal{E}} \frac{g_{\mathcal{E}NN}}{\gamma_{\mathcal{E}}}\,,$$

	$\|g_{X\gamma\rho}\|$	$\|g_{X\gamma\omega}\|$
VMD 1	0.088	0.199
VMD 2	0.058	0.199
VMD 3	0.088	0.303



Belle [Phys.Rev.D 84 (2011) 052004,
Phys.Rev.Lett. 126 (2021) 12, 122001]

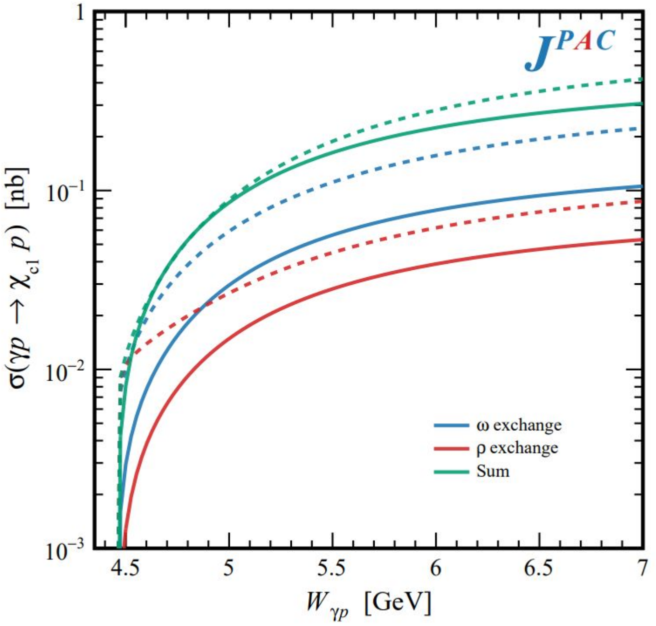


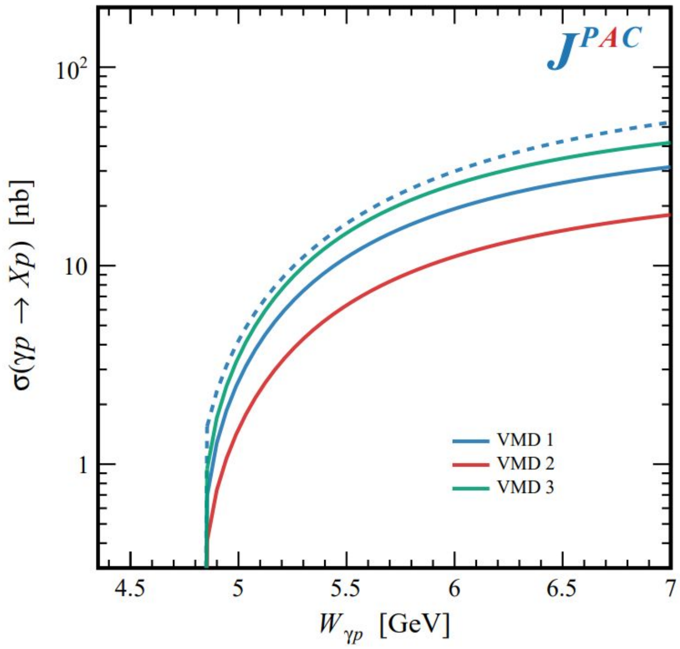
JPAC [arxiv:2404.05326]

In defense of VMD

Alternatively go the other way, use the fully determined photon exchange amplitude to re-predict the hadronic exchange.

$$\langle \lambda_\gamma, \lambda_N | T_\mathcal{E} | \lambda_Q, \lambda_{N'} \rangle = \mathcal{T}^\mu_{\lambda_\gamma, \lambda_{\gamma^*}=\lambda_Q} \, \eta_\mathcal{E} \left[\frac{-g_{\mu\nu}}{t - m_\mathcal{E}^2} \right] \eta_\mathcal{E} \, \beta_\mathcal{E}(t') \, \mathcal{B}^\nu_{\lambda_N, \lambda_{N'}}$$





Rescaling electromagnetic form factors of the with VMD consistent with our original prediction without any knowledge of the X(3872) hadronic coupling

Why does VMD seem to work okay in some sectors but not others? Are there other processes we can look at to test VMD in charm?

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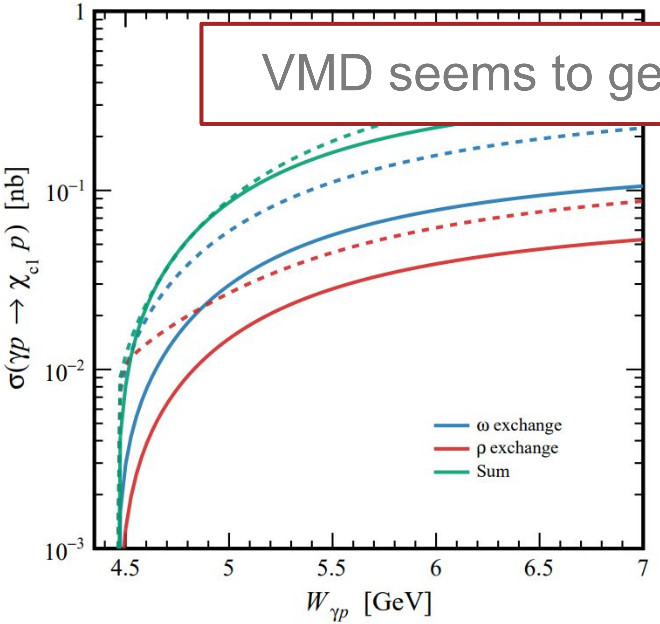

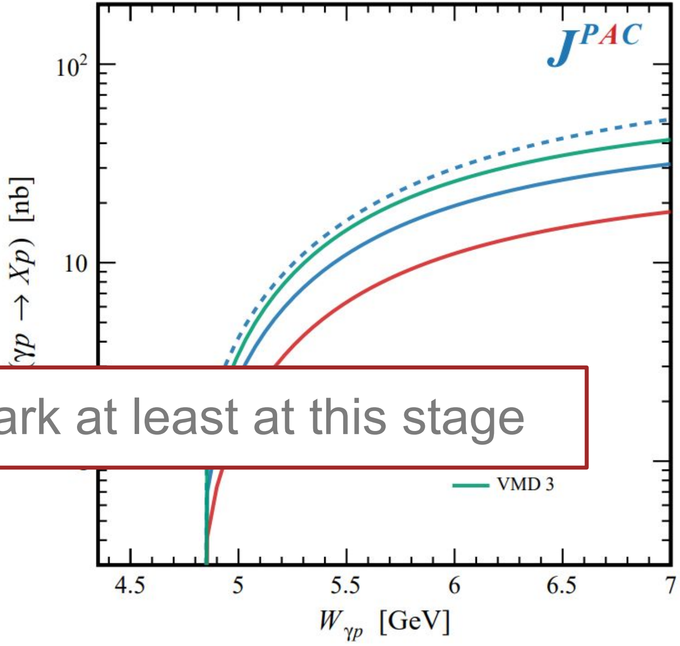

VMD seems to get us in the ballpark at least at this stage

Rescaling electromagnetic form factors of the with VMD consistent with our original prediction without any knowledge of the X(3872) hadronic coupling

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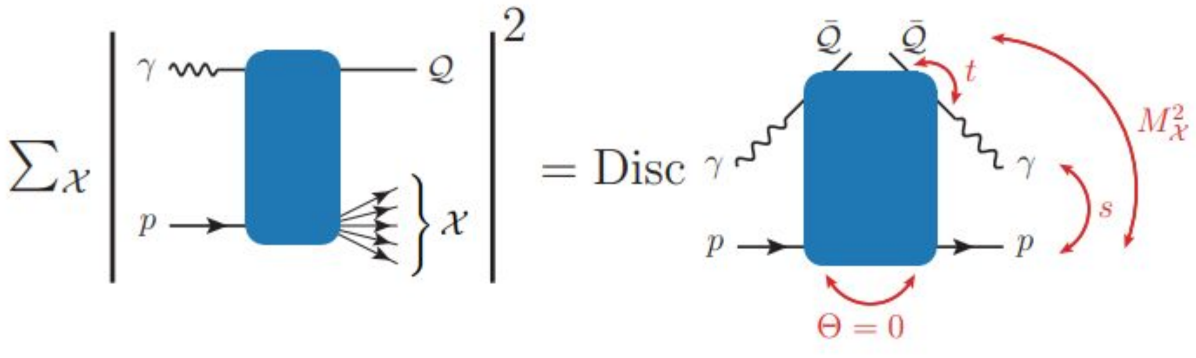
Semi-inclusive production

Expected larger cross-sections, potentially useful for **first observation**.

Exclusive exchange reactions extendable to semi-inclusive final states via generalized optical theorem.



phase-space factors

pion propagator

total hadronic cross-section

$$E_Q \frac{d^3\sigma}{d^3 q_f} = \frac{K}{16\pi^3}\,\frac{1}{2}\sum_{\lambda_\gamma \lambda_Q} |\mathcal{T}_{\lambda_\gamma \lambda_Q}|^2\, \mathcal{P}_\pi^2\, \sigma_{\text{tot}}^{\pi^* N}$$

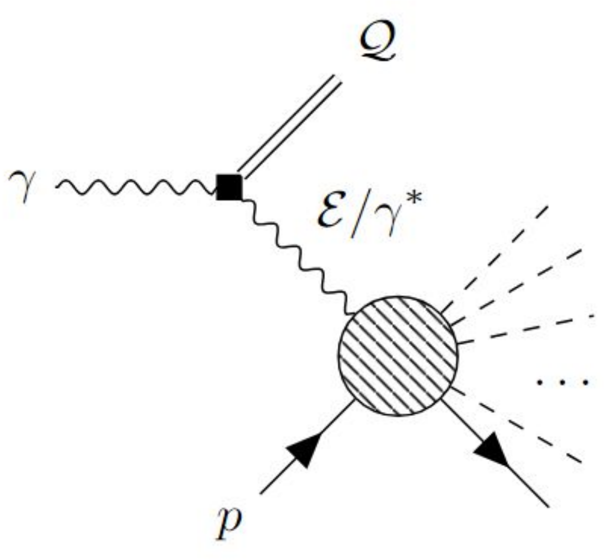
$\pi\gamma$Q coupling

Spineless π exchange factorizes to very simple form in terms of πN total cross section!

Semi-inclusive production (with spin)

Spin-exchange processes like ω exchange require knowledge of ***polarized* ωN cross sections**…

Potential solution is using the apparent success of rescaling electromagnetic form factors to relate to semi-inclusive structure functions!



scalar propagator

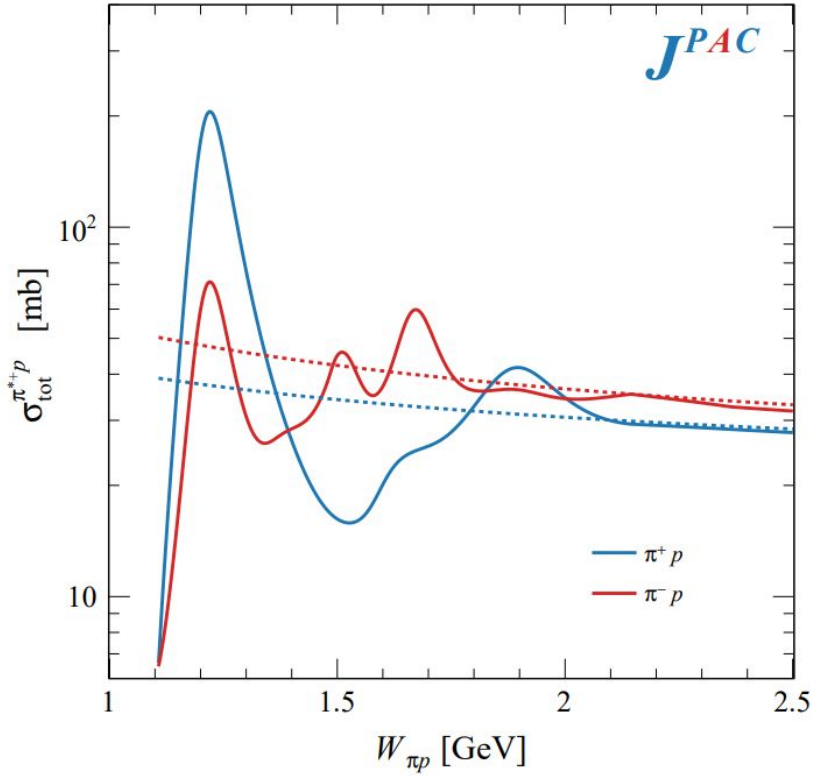
VMD

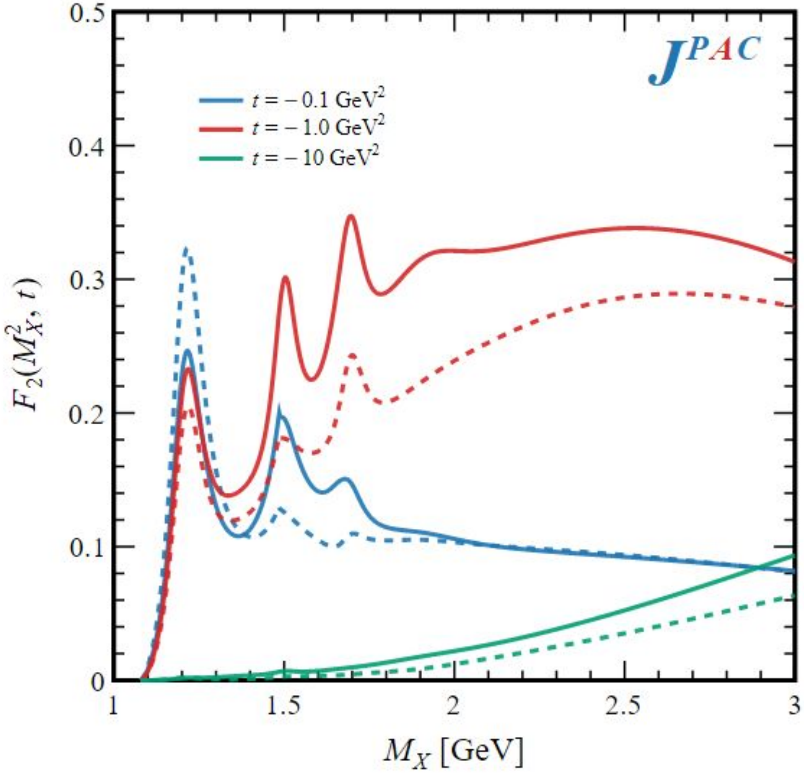
$$\frac{d^2\sigma}{dt\, dM^2_{\mathcal{X}}} = \sum_{\mathcal{E}} \frac{\alpha\, \eta^4_{\mathcal{E}}}{2\,(2\sqrt{s}\, E_\gamma)^2}\, \mathcal{T}^{\mu\nu}_{\gamma\bar{\mathcal{Q}}}\, |\beta_{\mathcal{E}}\, \mathcal{P}_{\mathcal{E}}|^2\, W_{\mu\nu}$$

VγX coupling

Inclusive structure functions

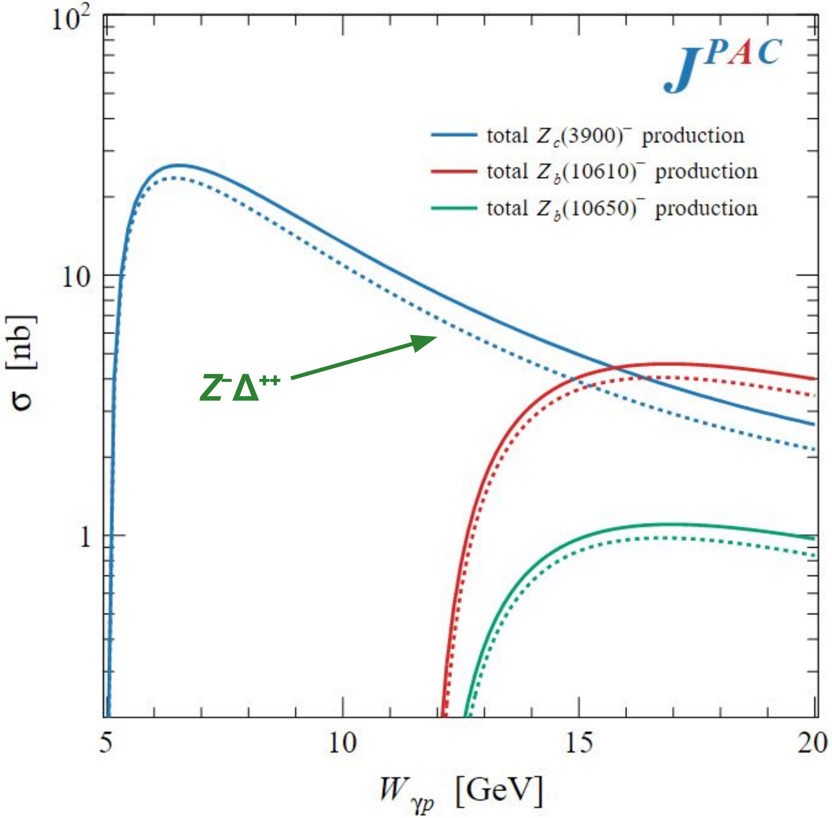
Missing mass in resonance region

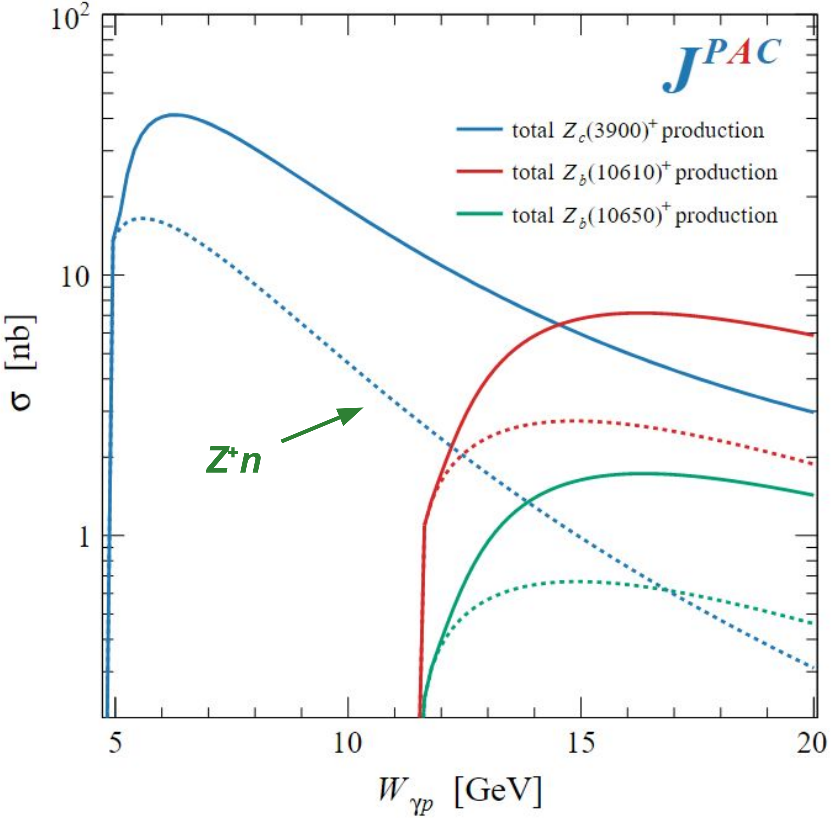




JPAC [Phys.Rev.D 106 (2022) 9, 09]

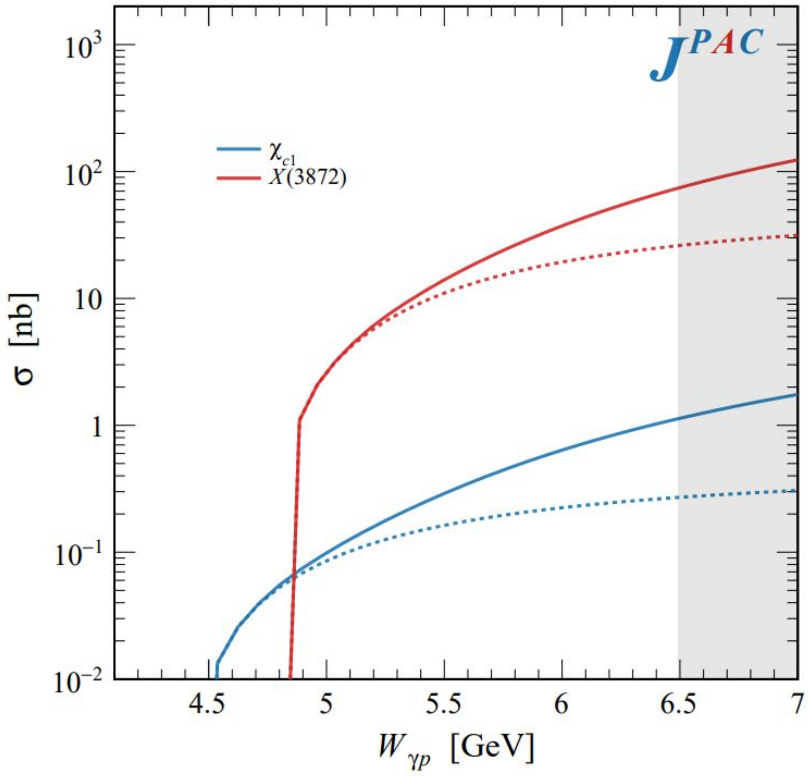
Charged Z production

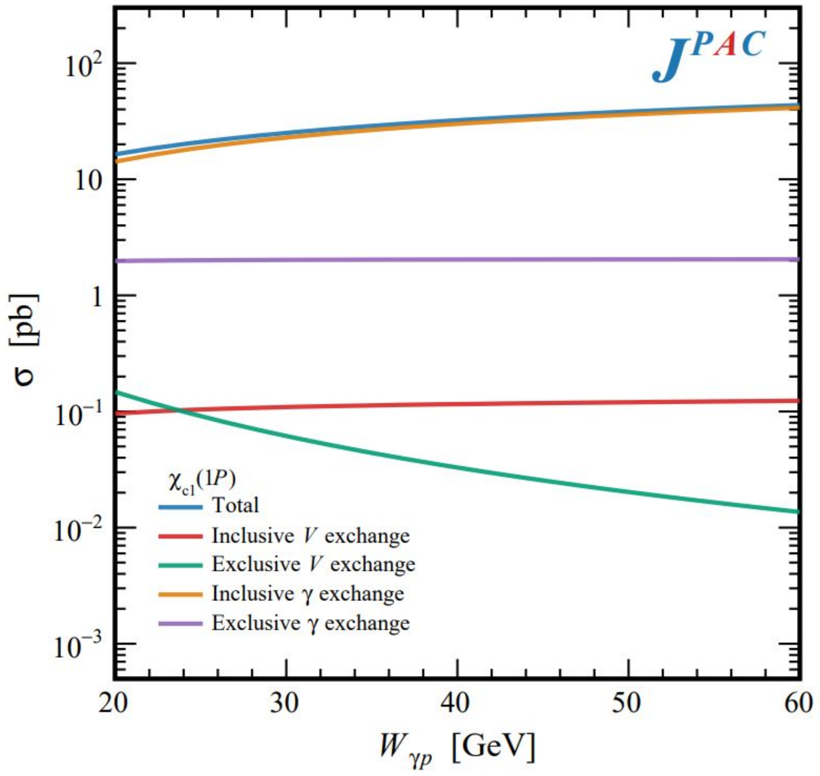




JPAC [arxiv:2404.05326]

X(3872) production





jpacPhoto

Unified code bank for all JPAC photoproduction models.

[1] Double Polarization Observables in Pentaquark Photoproduction [Phys. Rev. D 100, 034019 (2019)]
[2] XYZ spectroscopy at electron-hadron facilities: Exclusive processes [Phys. Rev. D 102, 114010 (2020)]
[3] XYZ spectroscopy at electron-hadron facilities II: [Phys. Rev. D 106 (2022) 09, 094009]
[4] XYZ spectroscopy at electron-hadron facilities III [arXiv:2404.05326]
[5] Dynamics in near-threshold J/ψ photoproduction [Phys. Rev. D 108 (2023) 5, 054018]
[6] Features of πΔ Photoproduction at High Energies [Phys.Lett.B 779 (2018) 77-81]
[7] Vector Meson Photoproduction with a Linearly Polarized Beam [Phys. Rev. D 97, 094003 (2018)]
[8] Exclusive Tensor Meson Photoproduction [Phys. Rev. D 102, 014003 (2020)]

For experimentalists: easier integration of theory models into existing workflows

Broad range of (polarized) observables calculable.

Incorporated into elSpectro
Interfaceable with AmpTools

For theorists: suite of tools for effective model testing, data analysis, reproducibility, etc.

To extend to two meson photoproduction reactions

$$\gamma^5 \left[(\not{q} + \not{p} + m) \right] \epsilon^\mu(q, \lambda)$$

```
lorentz_tensor<dirac_matrix, 1> projector = gamma_5() * (slash(q + p) + M_PROTON) * eps;
```

https://github.com/JointPhysicsAnalysisCenter/jpacPhoto

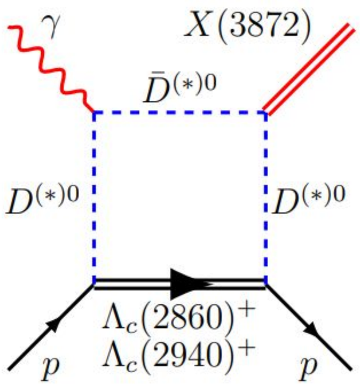
Summary

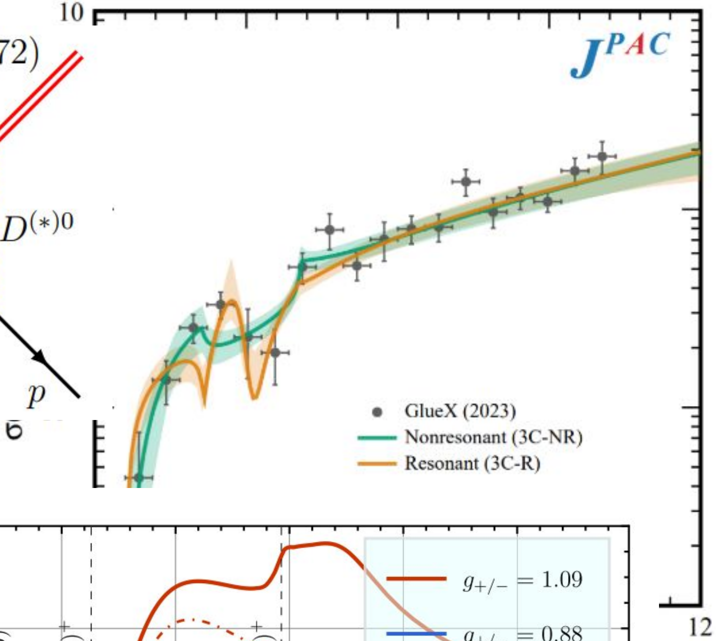
Next generation experiments will extend photoproduction programs to heavy sectors.

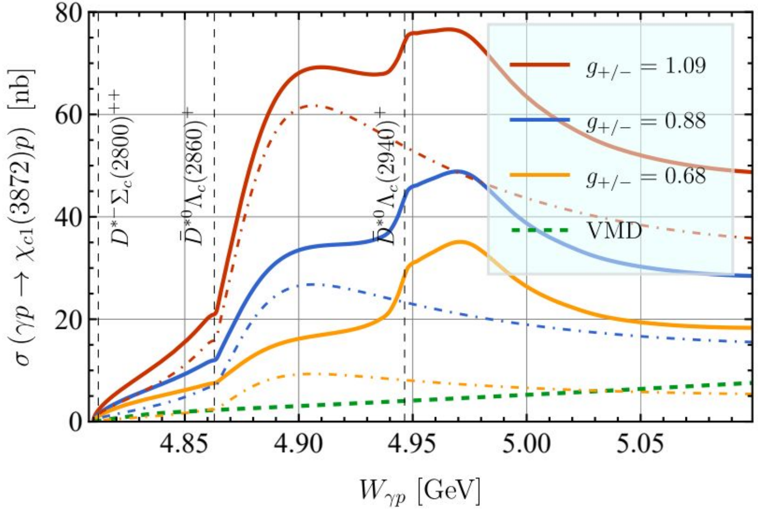
Lot of work needed to motivate potential **exotic signals** and interesting processes to look at.

Aim to use established phenomenology and measured quantities to estimate production rates.

Once data is available, amplitude analysis can extract meaningful quantities to surmise the underlying dynamics.







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

Thank you :)

BACKUPS

Production mechanisms

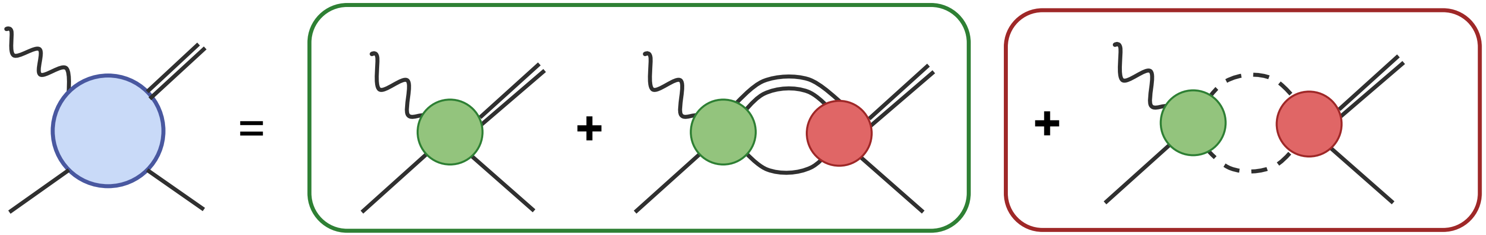
Define the ratio of direct J/ψ photocoupling to all other intermediate channels. Figure of merit measuring the **“directness”** the total production occurs at threshold.

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

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]



Winney et al. [Phys.Rev.D 108 (2023) 5, 5]

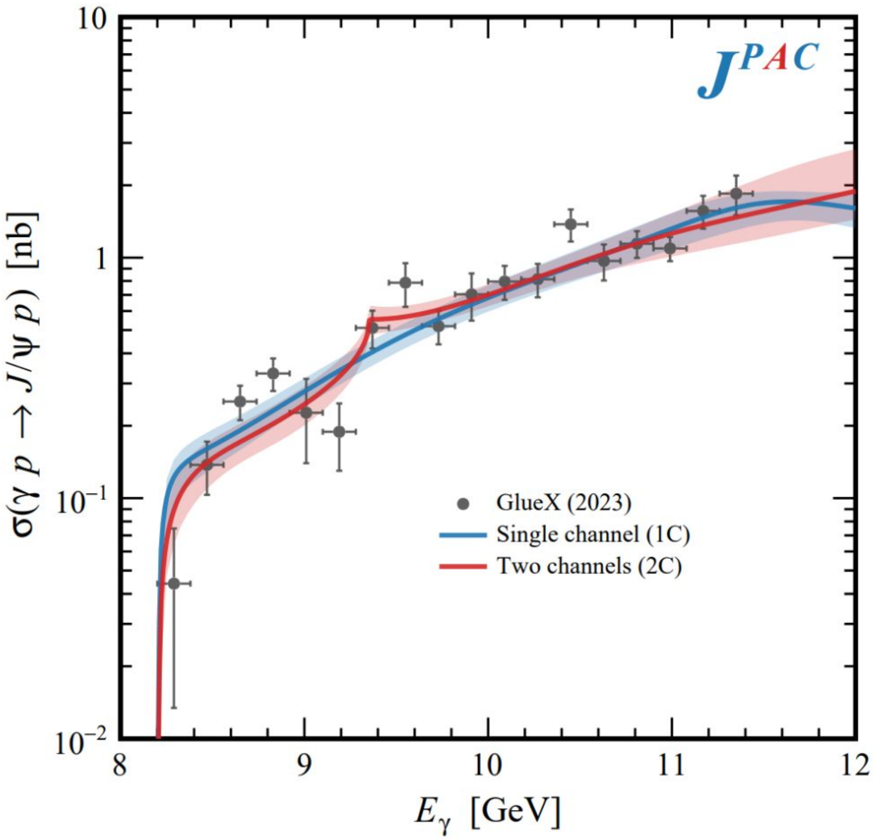
Production mechanisms

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!

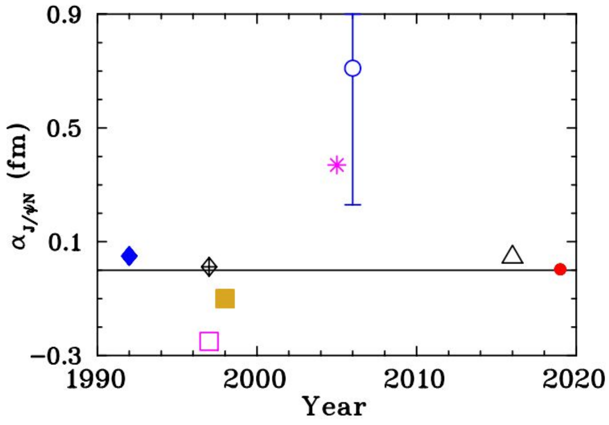


Winney et al. [Phys.Rev.D 108 (2023) 5, 5]

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!

Winney et al. [Phys.Rev.D 108 (2023) 5, 5]

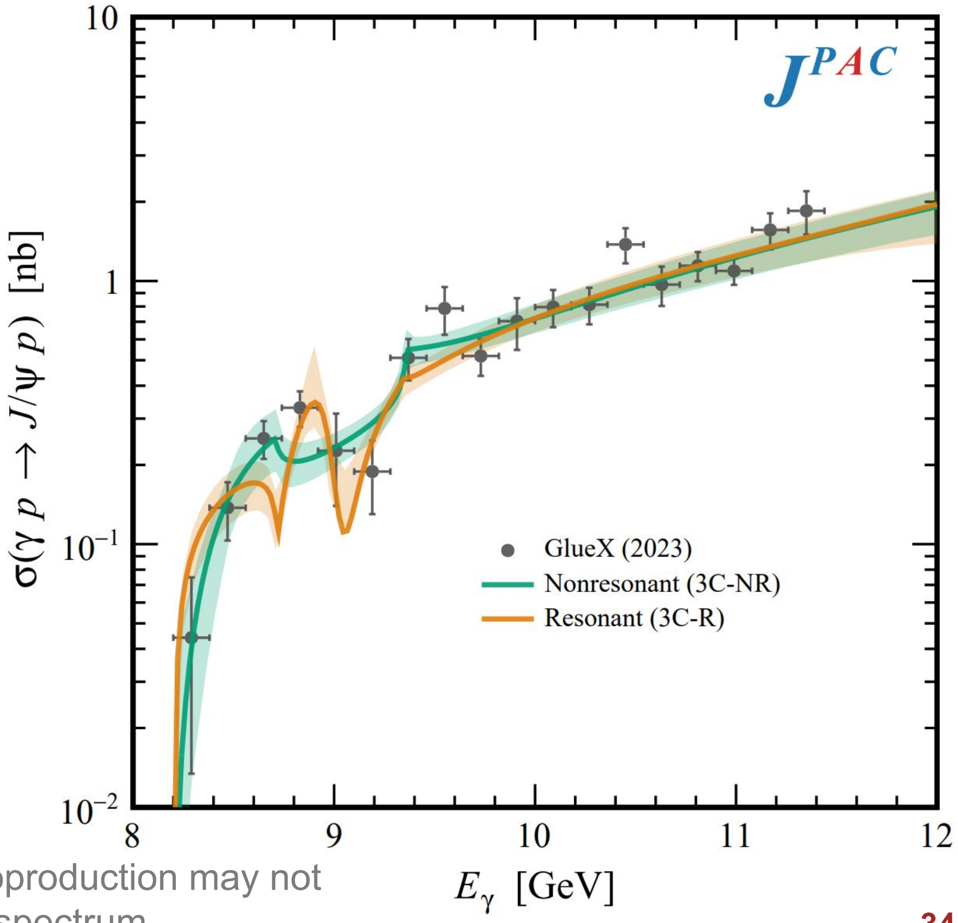
Pentaquark poles

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**!



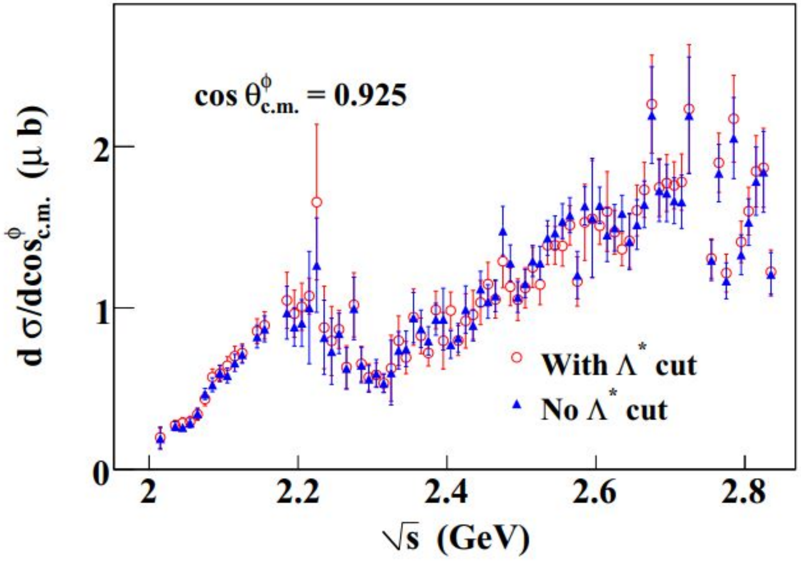
VMD result also indicates nonobservation in photoproduction may not immediately kill possibility of pentaquarks in $J/\psi p$ spectrum

ϕ Photoproduction

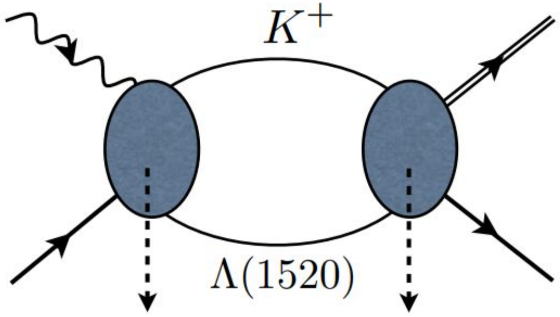
Completely analogous system to charmonium.

Significant structures seen within 1-2 GeV of threshold. Coincides with **open flavor thresholds**.

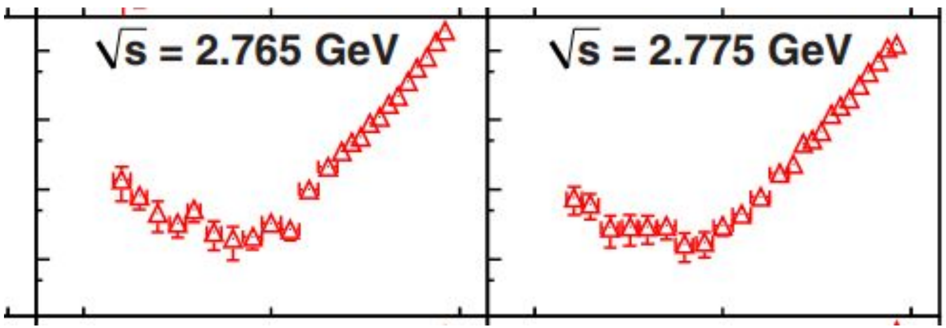
Possibility of hidden strange bound states



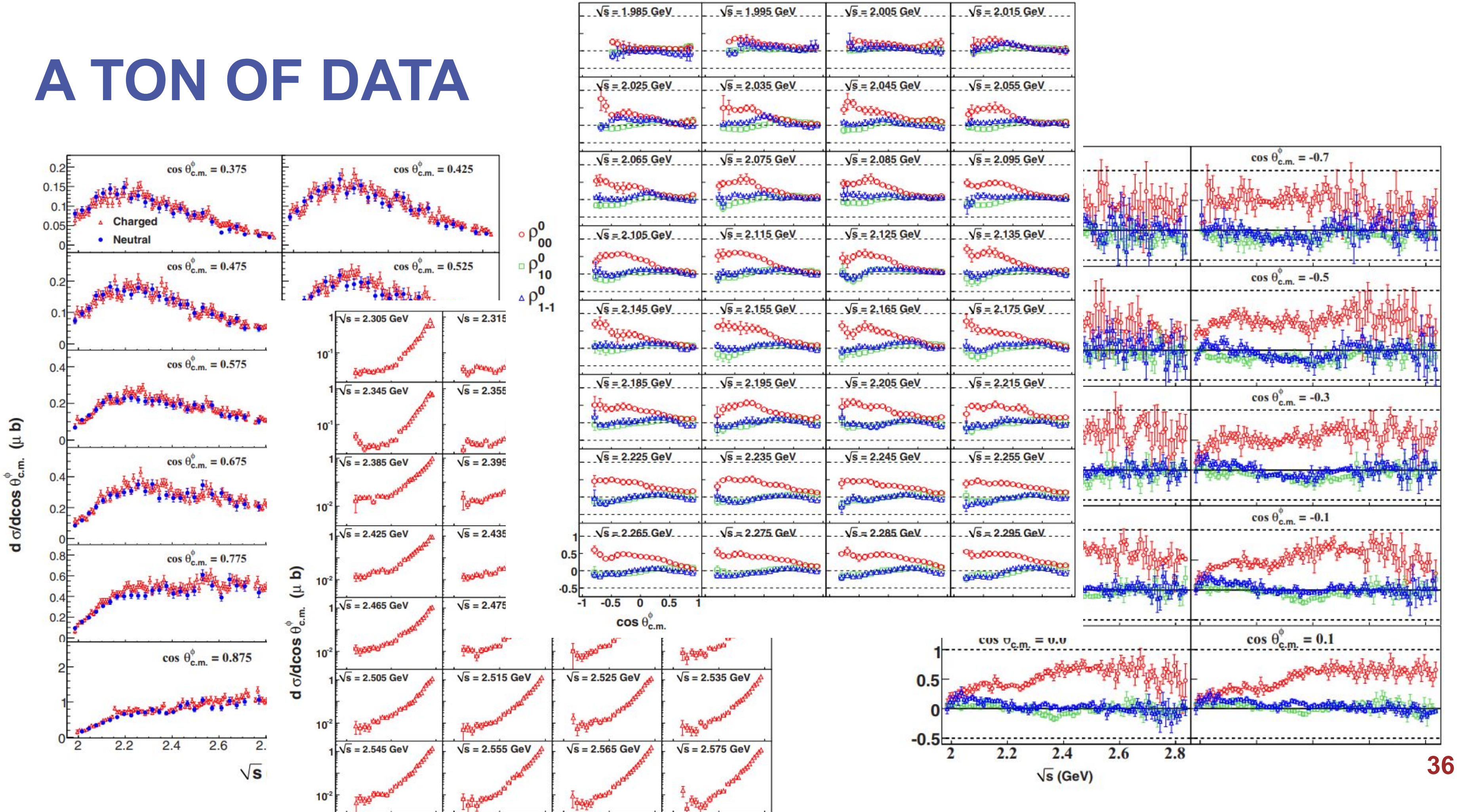
CLAS [Phys.Rev.C 89 (2014) 5, 055208]



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



A TON OF DATA



Charged
Neutral
cos θ^φ_c.m. = 0.375
cos θ^φ_c.m. = 0.425
cos θ^φ_c.m. = 0.475
cos θ^φ_c.m. = 0.525
cos θ^φ_c.m. = 0.575
cos θ^φ_c.m. = 0.675
cos θ^φ_c.m. = 0.775
cos θ^φ_c.m. = 0.875
d σ/dcos θ^φ_c.m. (μ b)
√s
√s = 2.305 GeV
√s = 2.345 GeV
√s = 2.385 GeV
√s = 2.425 GeV
√s = 2.465 GeV
√s = 2.505 GeV
√s = 2.515 GeV
√s = 2.525 GeV
√s = 2.535 GeV
√s = 2.545 GeV
√s = 2.555 GeV
√s = 2.565 GeV
√s = 2.575 GeV
ρ^0_00
ρ^0_10
ρ^0_1-1
√s = 1.985 GeV
√s = 1.995 GeV
√s = 2.005 GeV
√s = 2.015 GeV
√s = 2.025 GeV
√s = 2.035 GeV
√s = 2.045 GeV
√s = 2.055 GeV
√s = 2.065 GeV
√s = 2.075 GeV
√s = 2.085 GeV
√s = 2.095 GeV
√s = 2.105 GeV
√s = 2.115 GeV
√s = 2.125 GeV
√s = 2.135 GeV
√s = 2.145 GeV
√s = 2.155 GeV
√s = 2.165 GeV
√s = 2.175 GeV
√s = 2.185 GeV
√s = 2.195 GeV
√s = 2.205 GeV
√s = 2.215 GeV
√s = 2.225 GeV
√s = 2.235 GeV
√s = 2.245 GeV
√s = 2.255 GeV
√s = 2.265 GeV
√s = 2.275 GeV
√s = 2.285 GeV
√s = 2.295 GeV
cos θ^φ_c.m.
cos θ^φ_c.m. = -0.7
cos θ^φ_c.m. = -0.5
cos θ^φ_c.m. = -0.3
cos θ^φ_c.m. = -0.1
cos θ^φ_c.m. = 0.1
√s (GeV)

Full K-matrix analysis

Possibility to study coupled channels, nearby bound states, etc in considering all spins and helicity dependence.

On going but very preliminary, still trying to understand gauge-invariance structure…

$$l_1^{\mu\nu} = P^\mu \left[(P \cdot q)\, k^\nu - (k \cdot q)\, P^\nu \right] \;, \qquad l_7^{\mu\nu} = q^\mu \gamma^\nu \not{q} \;,$$

$$l_2^{\mu\nu} = (k \cdot q)\, g^{\mu\nu} - q^\mu k^\nu \;, \qquad l_8^{\mu\nu} = P^\mu \gamma^\nu \not{q} \;,$$

$$l_3^{\mu\nu} = (P \cdot q)\, g^{\mu\nu} - q^\mu P^\nu \;, \qquad l_9^{\mu\nu} = \gamma^\mu \left[(P \cdot q)\, k^\nu - (k \cdot q)\, P^\nu \right]$$

$$l_4^{\mu\nu} = g^{\mu\nu} \not{q} - q^\mu \gamma^\nu \;, \qquad l_{10}^{\mu\nu} = \gamma^\mu \left[(k \cdot q)\, \gamma^\nu - k^\nu \not{q} \right] \;,$$

$$l_5^{\mu\nu} = \left[(q \cdot P)\, g^{\mu\nu} - q^\mu P^\nu \right] \not{q} \;, \qquad l_{11}^{\mu\nu} = \gamma^\mu \left[(P \cdot q)\, \gamma^\nu - P^\nu \not{q} \right]$$

$$l_6^{\mu\nu} = P^\mu \left[P^\nu \not{q} - (q \cdot P)\, \gamma^\nu \right] \qquad l_{12}^{\mu\nu} = \gamma^\mu \gamma^\nu \not{q} \;,$$

Hope to have some cool results in the coming months

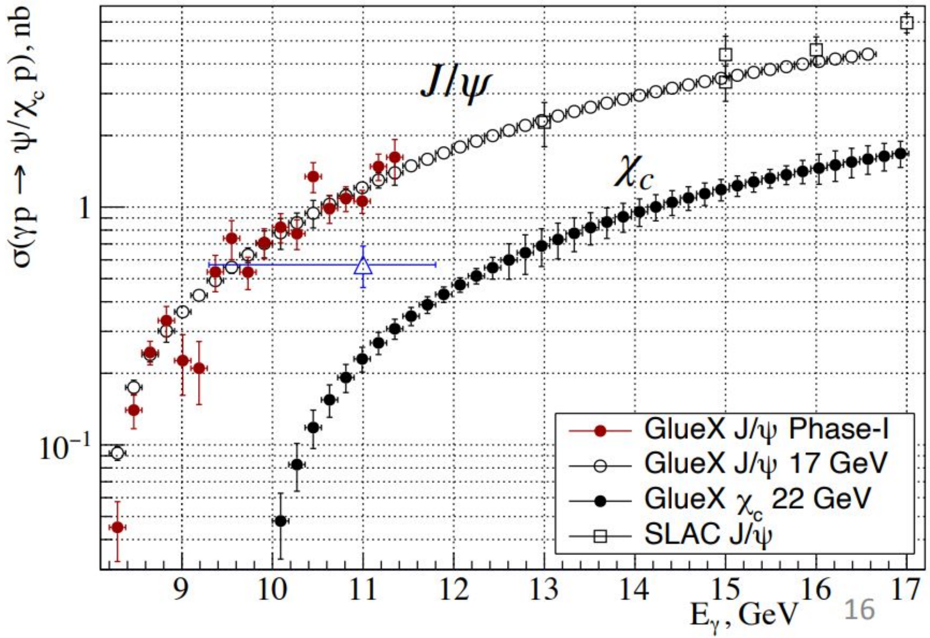
χc1 at GlueX?

From Lubomir's talk at "J/psi and Beyond" Workshop at JLab Aug 2022

Radiative couplings measured (no need for VMD) so vector exchange is in principle a known amplitude.

Observation in GlueX about a factor 10 enhanced compared to prediction (~0.02 nb at 11 GeV)

Other production mechanism? C-odd glue exchange, open charm box? Something else?



- We have used the measured χ_c yields and MC simulations (efficiency ~10%) to scale the JPAC calculations for χ_{c1} photoproduction cross section and make projections for GlueX with 22 GeV beam: