Heavy (Exotic) Spectroscopy in Photoproduction: A Theoretical Overview

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Science at the Luminosity Frontier: Jefferson Lab at 22 GeV
INFN - LNF
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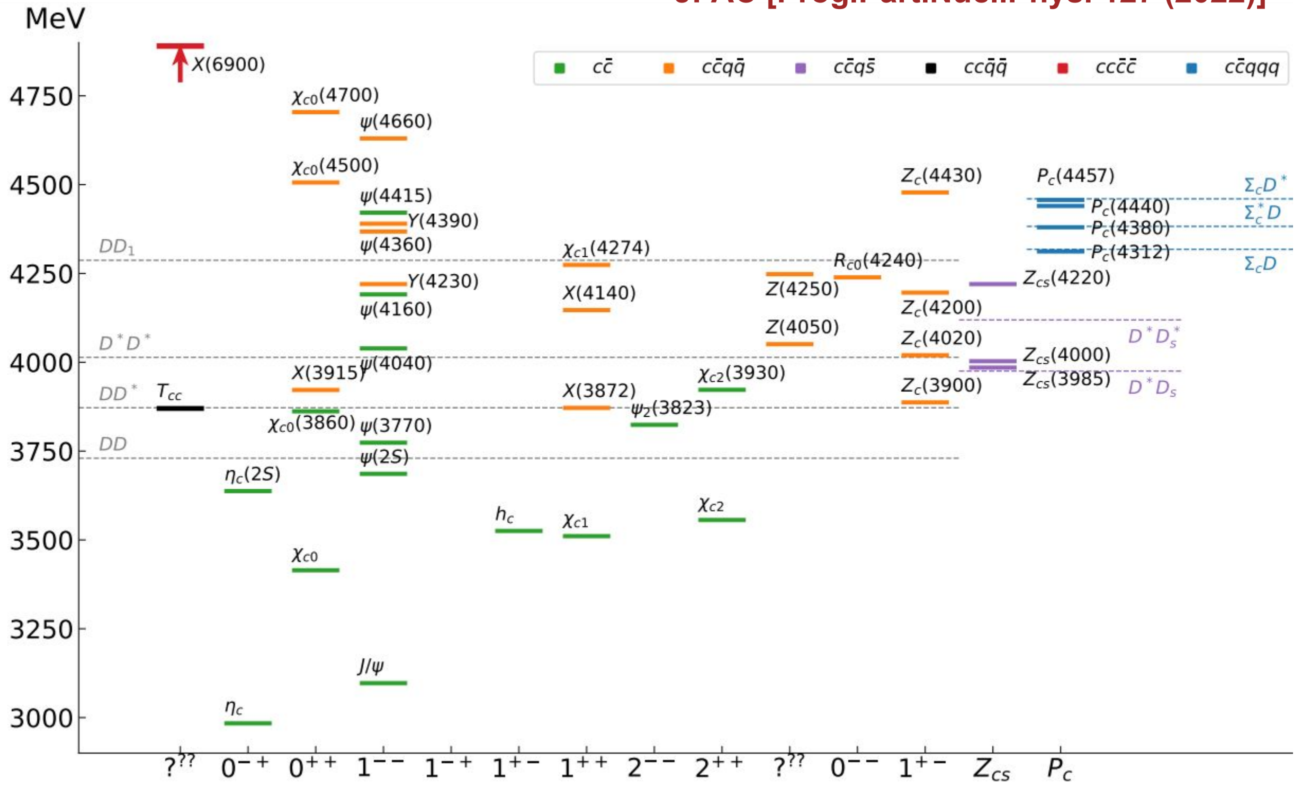
Heavy Exotica

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

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



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

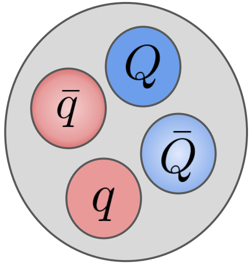
Heavy Exotica

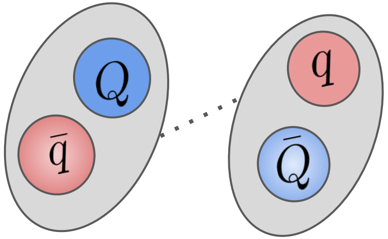
See reviews:
JPAC [Prog.Part.Nucl.Phys. 127 (2022)]
Chen et al [Rept. Prog. Phys. 86 (2023) no.2, 026201]
Brambilla et al [Phys.Rept. 873 (2020) 1-154]
Guo et al [Rev.Mod.Phys. 90 (2018) 1, 015004]
Esposito et al [Phys.Rept. 668 (2017) 1-97]

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

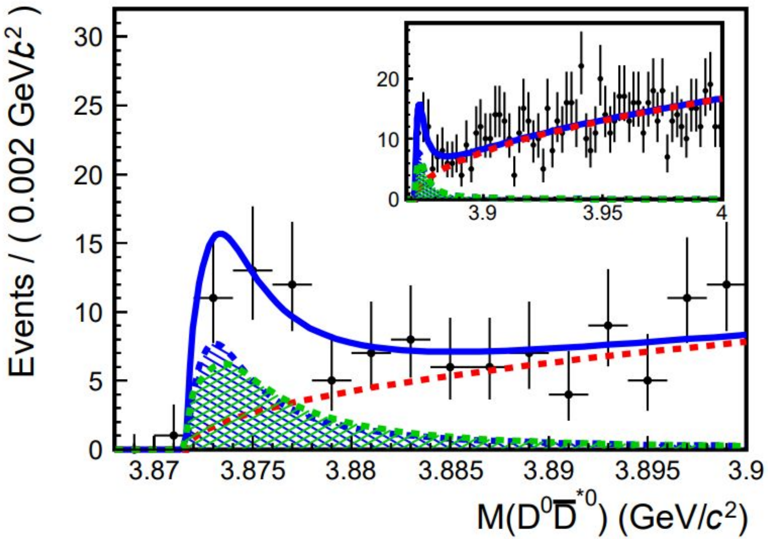
Coincidence of nearby multiparticle thresholds may suggest important **multi-channel dynamics**.

Proposed explanation as shallow bound states with prominently **molecular component** from open-charm channels.





$$m_{D^0} + m_{D^{*0}} - m_{X(3872)} = (0.00 \pm 0.18)\ \mathrm{MeV}$$



Belle [Phys.Rev.D 107 (2023) 11, 112011]

Why photoproduction?

Already an established tool for spectroscopy

- Can produce any quantum-numbers
- Minimizes role of rescattering (**no triangle singularities**)

Szczepaniak [Phys.Lett.B 747 (2015) 410-416]
Guo, Liu, Sakai [Prog.Part.Nucl.Phys. 112 (2020) 103757

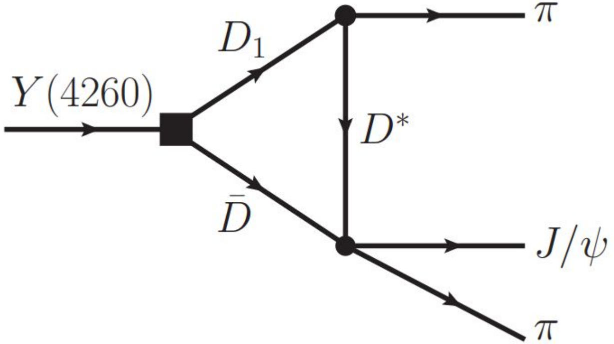
- Can access polarization information (**determine quantum numbers**)

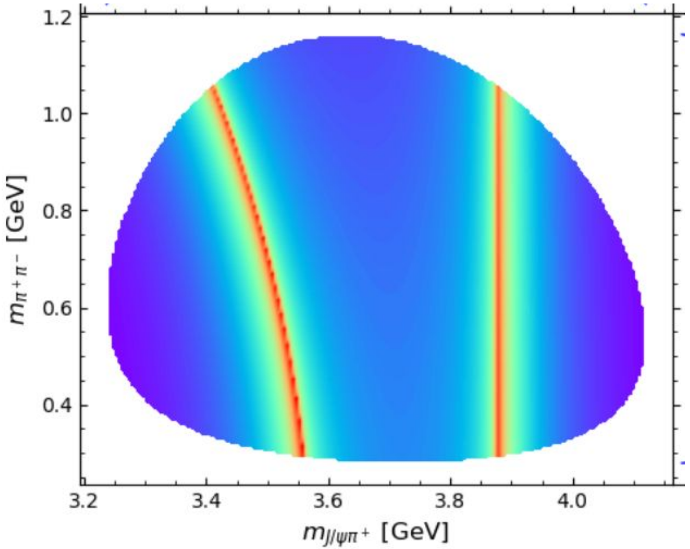
JPAC [Phys.Rev.D 100 (2019) 3, 034019]

- Probe internal structure (***Q*² dependence**)

Babiarz et al [Phys.Rev.D 107 (2023) 7, L071503]

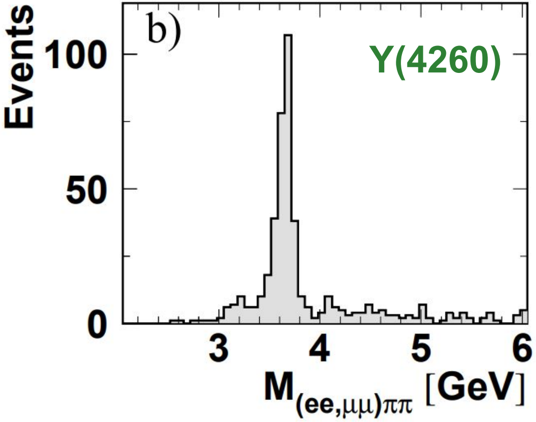
- Constrained kinematics means precise probe of production mechanism (**presence of cusps**)



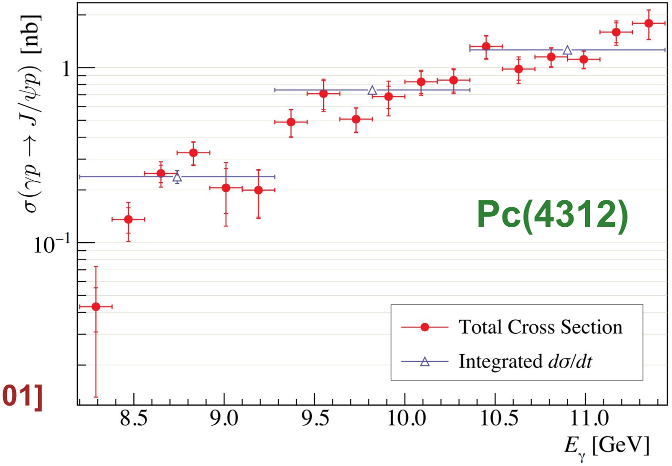


Guo [Nucl.Phys.Rev. 37 (2020) 3, 406-413]

Photoproduction searches

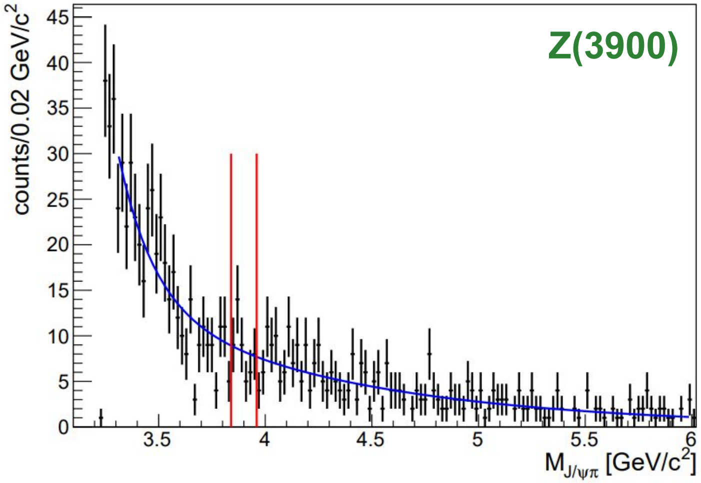


H1 [Phys.Lett.B 541 (2002) 251-264]

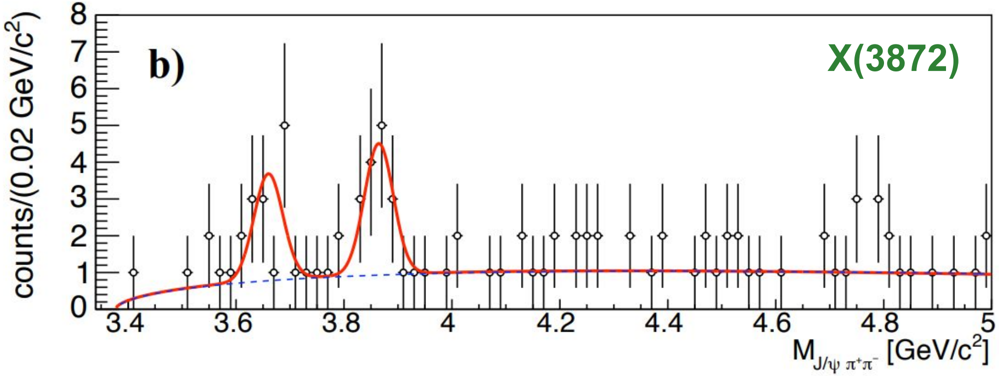


GlueX [Phys.Rev.C 108 (2023) 2, 025201]

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



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



Exclusive production

Expected dominant production modes relying on measured branching fractions. Phenomenologically well established production mechanisms.

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

Largest uncertainty comes from use of VMD, which may not be justified for charmonium.

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

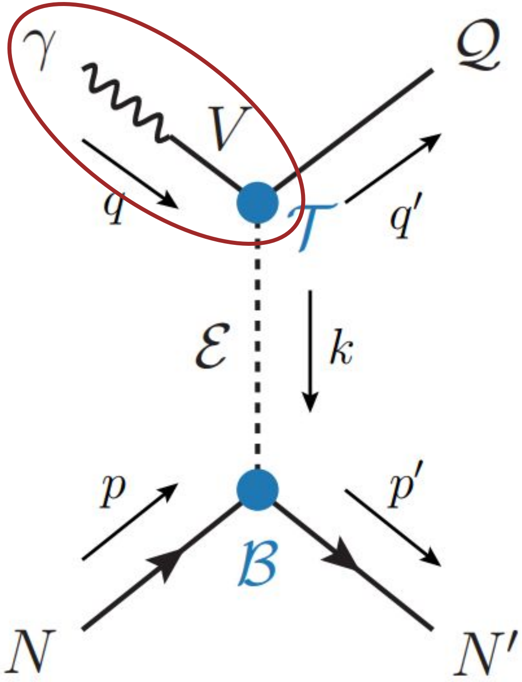
JPAC [Phys.Rev.D 108 (2023) 5, 5]

Hints that VMD might work “fine” in the X(3872) case.

JPAC [Phys.Rev.D 109 (2024) 11, 114035]

Extensions to **semi-inclusive final states** easily possible in forward kinematic region.

JPAC [Phys.Rev.D 106 (2022) 9, 09]
JPAC [Phys.Rev.D 109 (2024) 11, 114035]

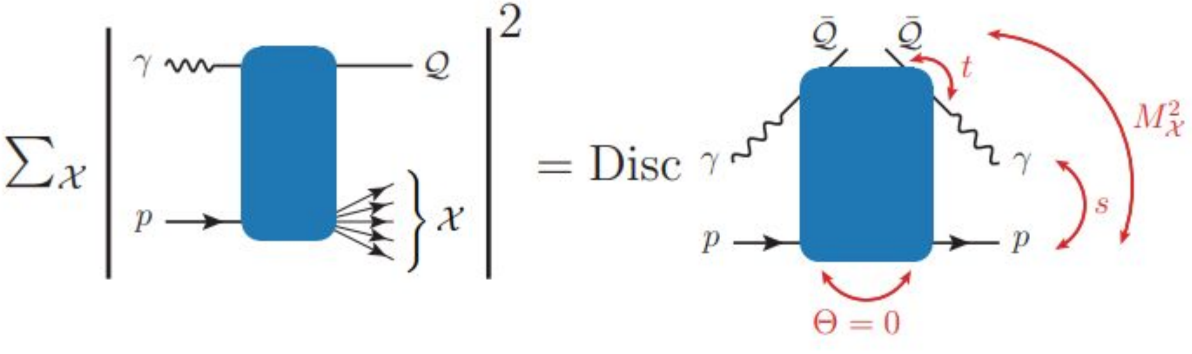


JPAC [Phys.Rev.D 106 (2022) 9, 09]

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

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

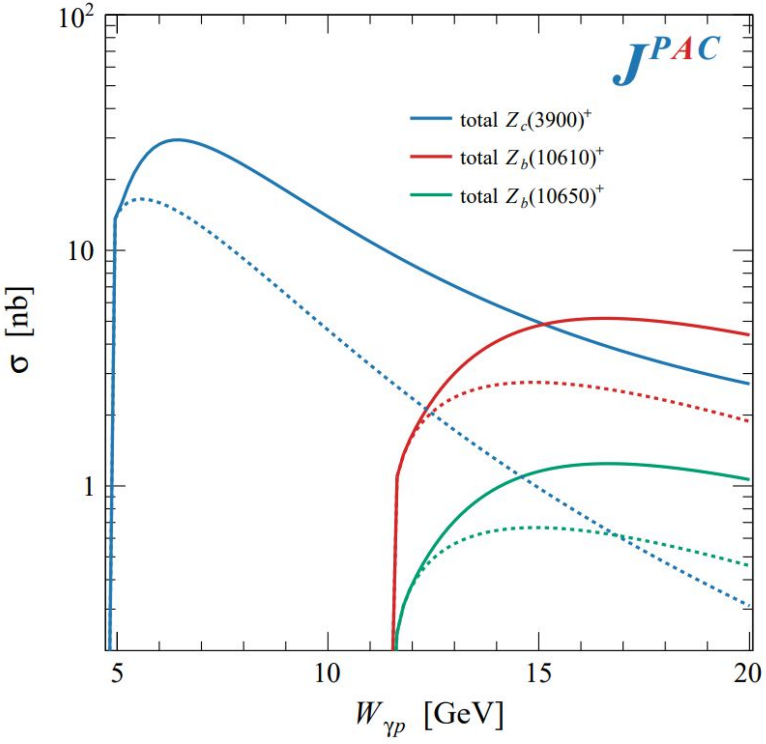
$\pi\gamma$Q coupling

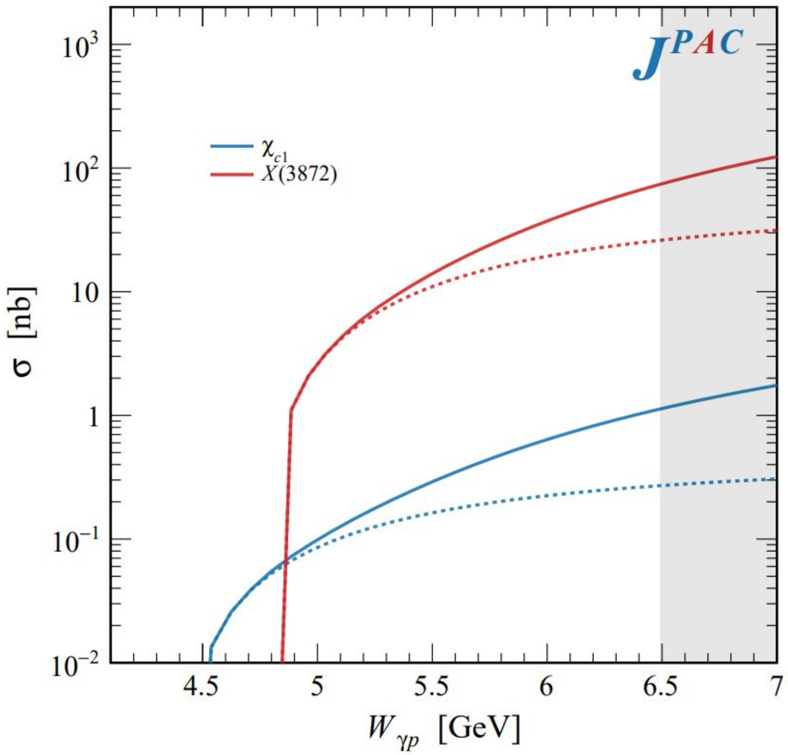
Spinless π exchange factorizes to very simple form in terms of πN total cross section!

JPAC [Phys. Rev. D 102, 114010 (2020)]
JPAC [Phys.Rev.D 106 (2022) 9, 09]
JPAC [Phys.Rev.D 109 (2024) 11, 114035]

Predictions with VMD

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



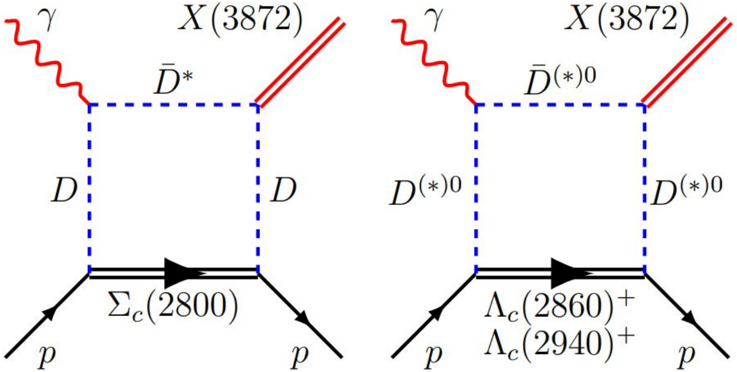


Predictions with Coupled Channels

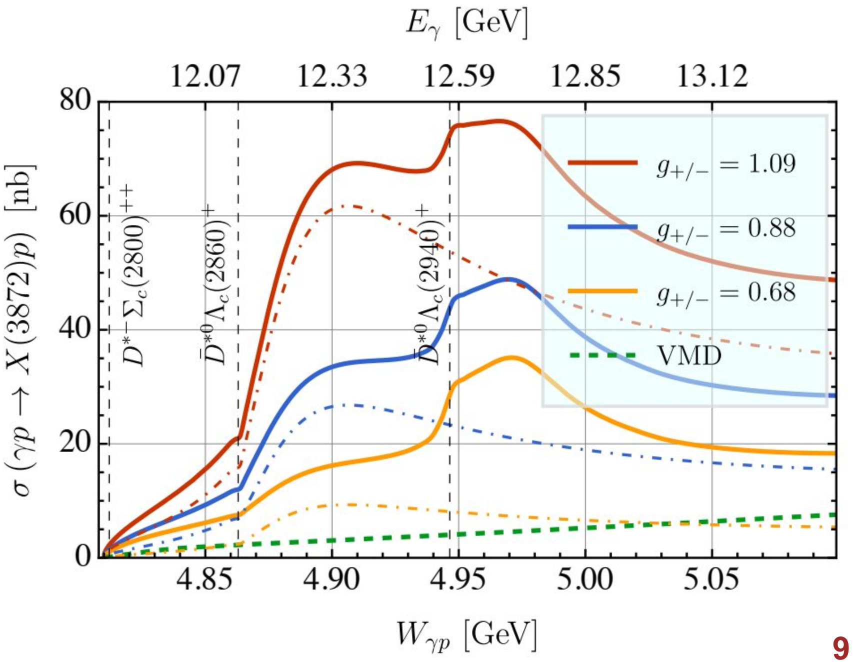
Alternative production mechanism takes advantage of large X(3872) coupling to **open-charm**.

Predicted to be dominant near-threshold enhancements with **prominent cusps**.

No VMD but large uncertainties from poorly determined couplings to excited charmed baryons.



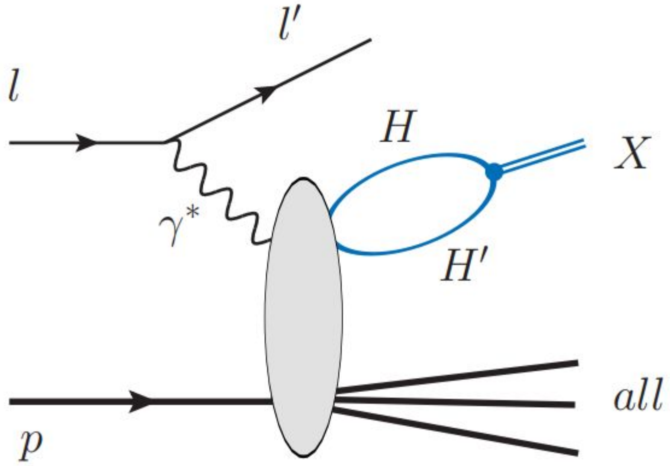
Cao et al [J.Phys.G 51 (2024) 10, 105002]



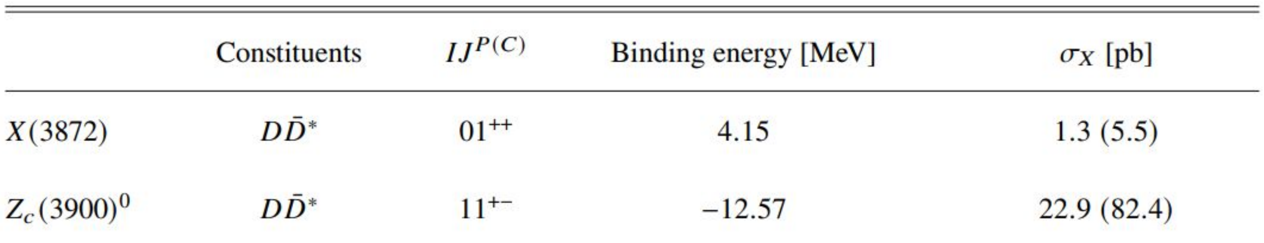
Predictions with Coupled Channels

Semi-inclusive predictions based on production of hadronic molecules through **rescattering of constituents**.

Yang & Guo [Chin.Phys.C 45 (2021) 12, 123101]
Shi, Guo, & Yang [Phys.Rev.D 106 (2022) 11, 114026]



DD* pairs must be produced first via **hard production** and estimated using Pythia then coupled to resonance.



	Constituents	$IJ^{P(C)}$	Binding energy [MeV]	σ_X [pb]
$X(3872)$	$D\bar{D}^*$	01^{++}	4.15	1.3 (5.5)
$Z_c(3900)^0$	$D\bar{D}^*$	11^{+-}	−12.57	22.9 (82.4)

Pentaquarks?

Resonant-like signals in **$J/\psi p$ spectrum** by LHCb. Consistent with five valence quarks but not seen by any other experiment.

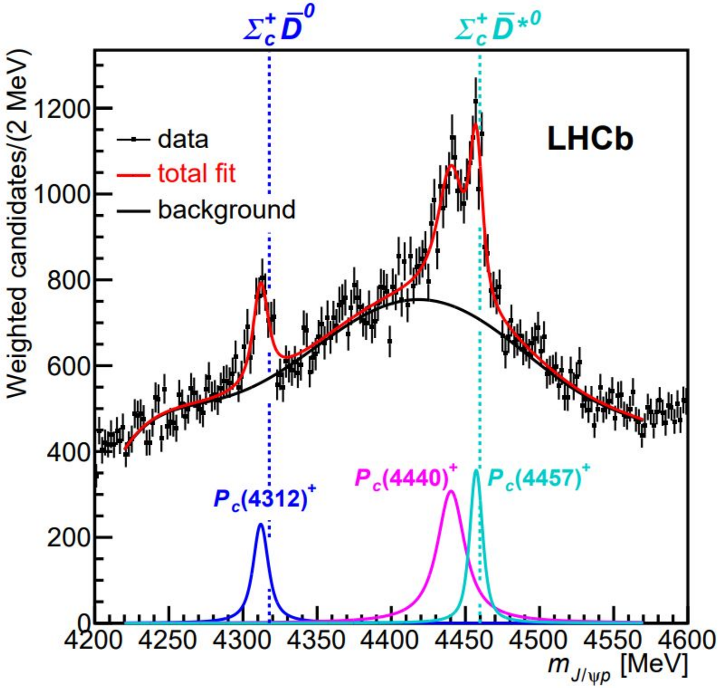
Strange counterparts also seen in ***$J/\psi\Lambda$* spectrum.**

LHCb [Phys.Rev.Lett. 131 (2023) 3, 031901]
LHCb [Sci.Bull. 66 (2021) 1278-1287]

Phenomenology well described by molecular picture

Wu et al [Phys.Rev.C 84 (2011) 015202]
Du et al[JHEP 08 (2021) 157]

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

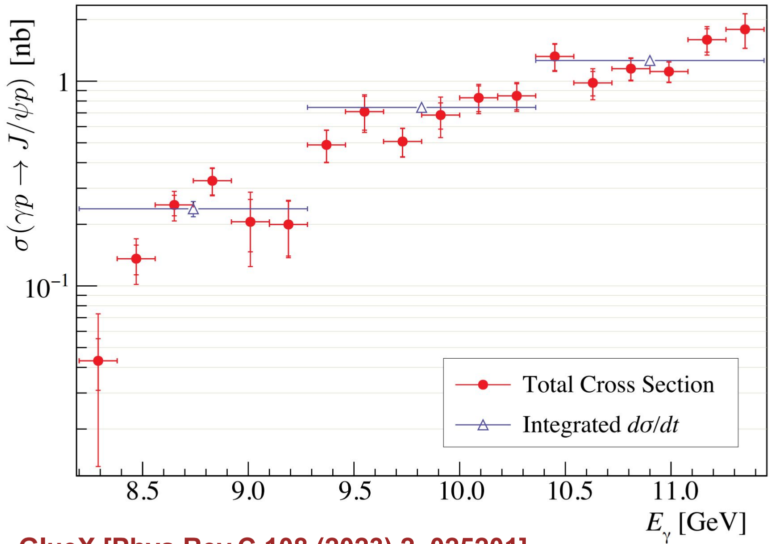


Quantum numbers unknown
Lots of nearby triangle singularities
Mass range accessible by current experiments

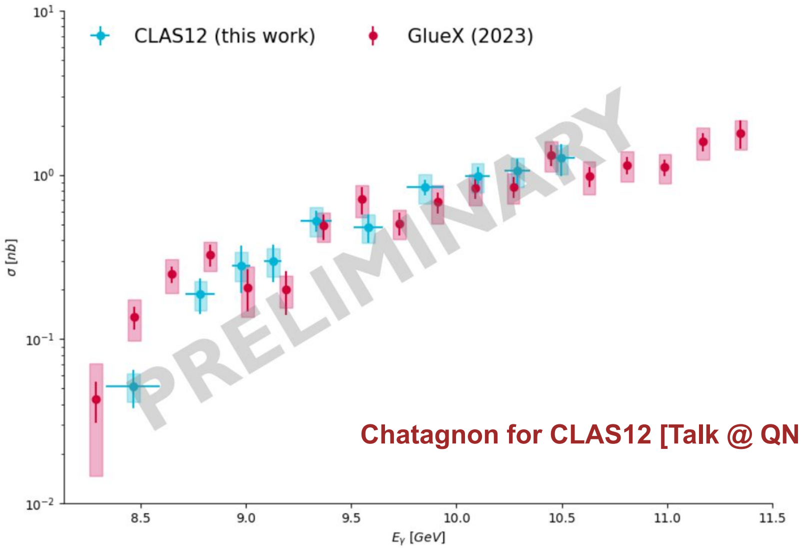
Perfect for photoproduction

Pentaquarks?

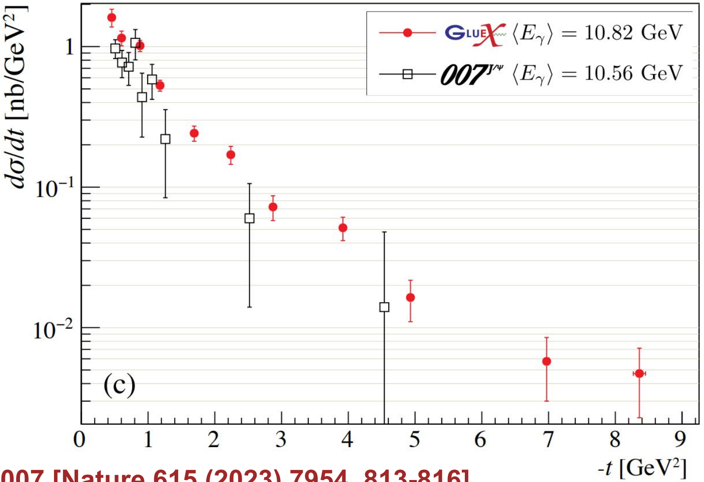
No peaks!



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



Chatagnon for CLAS12 [Talk @ QNP2014]



Jpsi-007 [Nature 615 (2023) 7954, 813-816]

Pentaquarks?

Two possibilities becoming likely:

- Confirmation of kinematic effects (**non-existence**)
- Genuine resonances but with **highly suppressed radiative couplings**

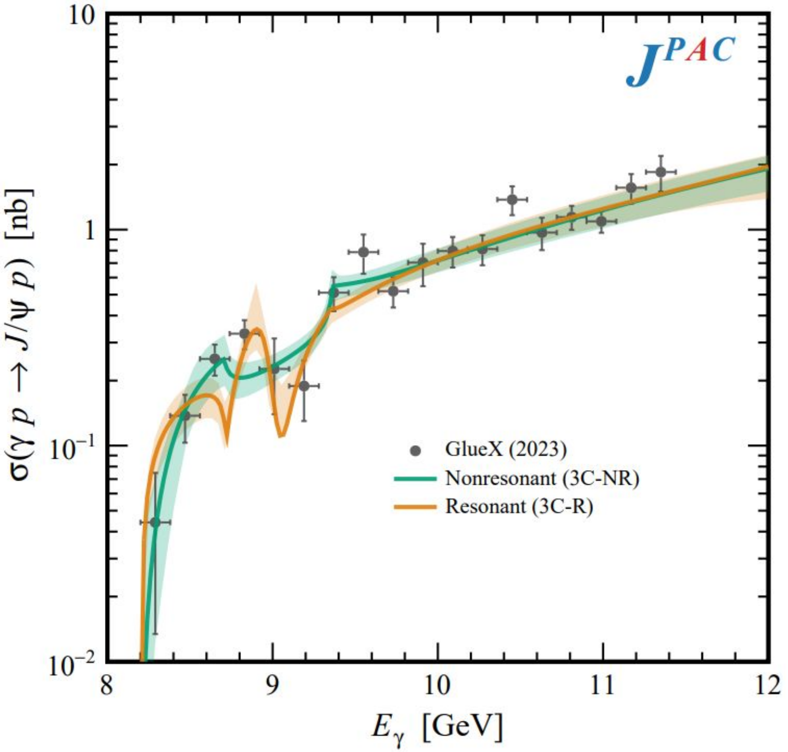
Small γp coupling with **sizeable J/ψp width** consistent with a severe violation of VMD.

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

Possibly further hint at molecular nature, as both γp and J/ψp couplings predicted to be suppressed

Duan et al [arXiv:2409.10364]

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

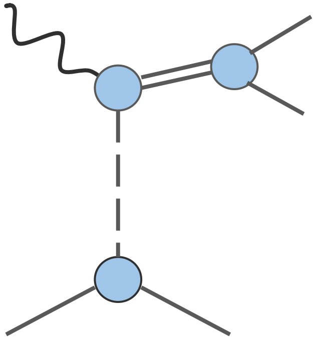


If true, production should be enhanced in open charm photoproduction.

Backgrounds

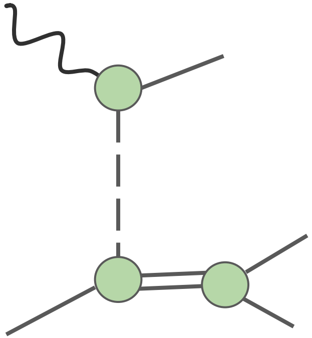
The X(3872) and Zc(3900) predicted to be the most readily accessible exotics. Need to also estimate size and shape of expected background processes to **$\gamma p \rightarrow J/\psi \pi p$** and **$\gamma p \rightarrow J/\psi \varrho p$**.

Other nearby mesons?



Nothing nearby for the exotic channels

Baryon resonances?



Possible misidentification of π or ϱ from N* or Δ but these are kinematically separable from meson resonances in the top vertex

Backgrounds

Only non-trivial background comes from **non-resonant production** of final state.

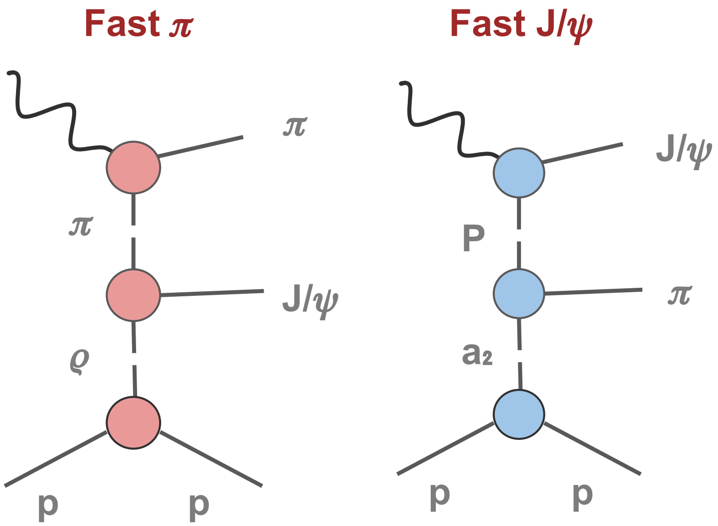
Analogous to ongoing studies on $\eta\pi$ studies with COMPASS.

JPAC [Eur. Phys. J. C 81, 647 (2021)]

Appeal to **double Regge phenomenology** but still a lot of modeling possible involving the spin structure of vertices and couplings.

Shimada, Martin & Irving [Nucl.Phys.B 142 (1978) 344-364]

Studies are ongoing!



Summary

Lots of theory work has been done to explore spectroscopy possibilities with a 22 GeV JLab!

- X(3872) and Zc(3900) production predicted to be sizeable in both naive VMD and coupled channel mechanisms.
- Both exclusive and semi-inclusive production modes seem promising.
- Non-observation of hidden-charm pentaquarks in photoproduction is another clue not a death sentence. Exploration of open charm channels or hadronic production likely needed.
- Estimating non-resonant backgrounds is tricky business and is ongoing alongside other double Regge studies at JPAC.

Thank you!

BACKUPS

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

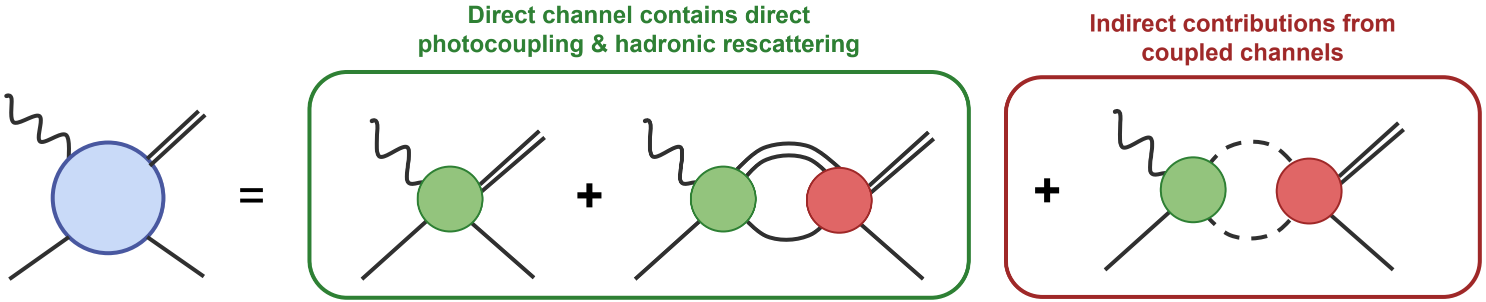
K-matrix analysis

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**

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

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



Direct channel contains direct photocoupling & hadronic rescattering

Indirect contributions from coupled channels

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

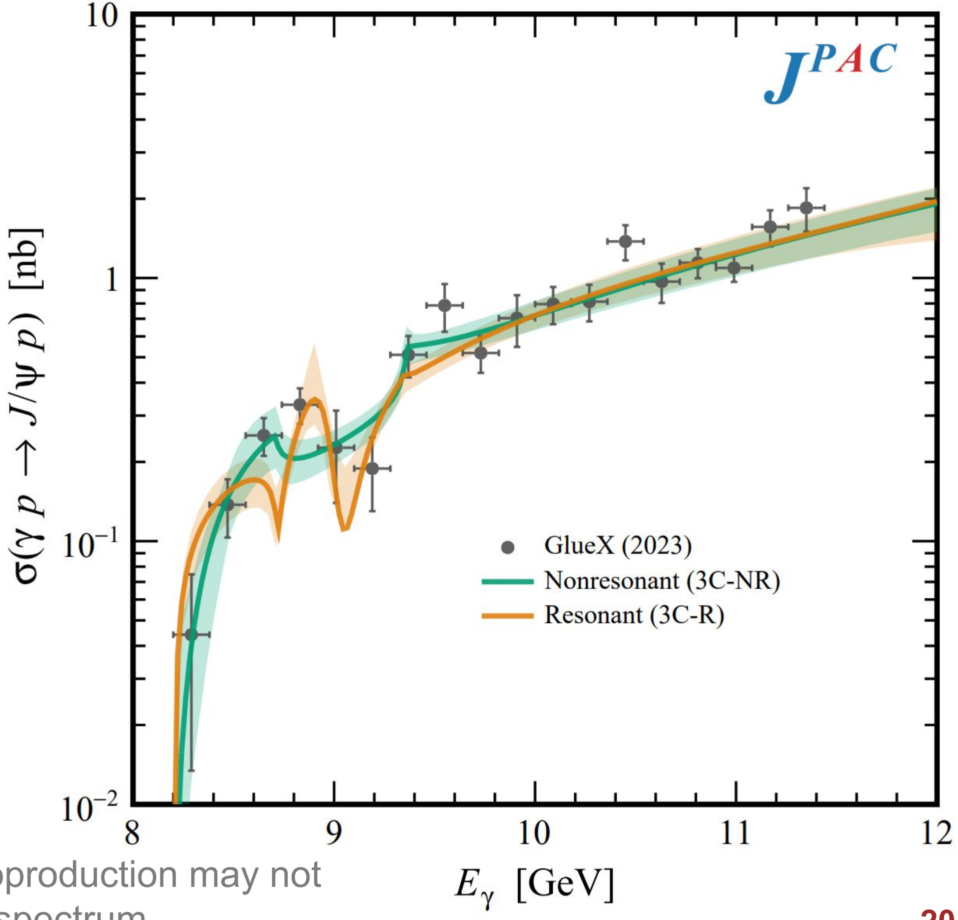
Pentaquark poles

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**!



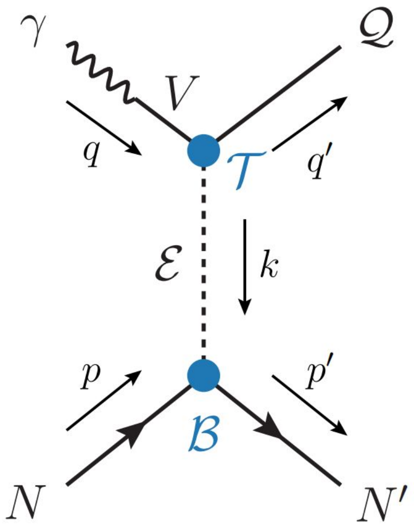
VMD result also indicates nonobservation in photoproduction may not immediately kill possibility of pentaquarks in $J/\psi p$ spectrum

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)

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

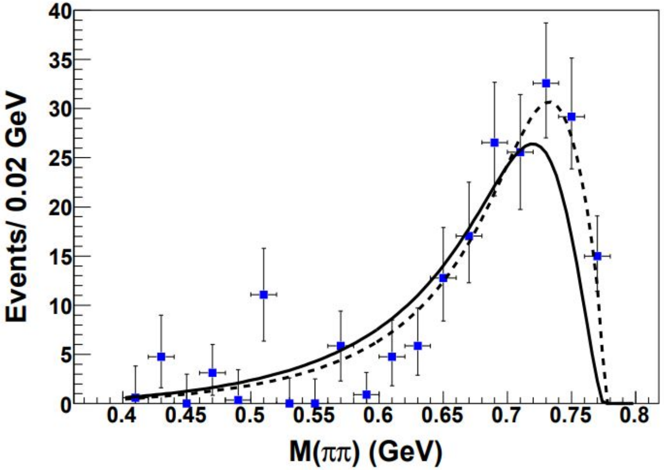
VMD predicts relations between two-photon, radiative, and hadronic couplings

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

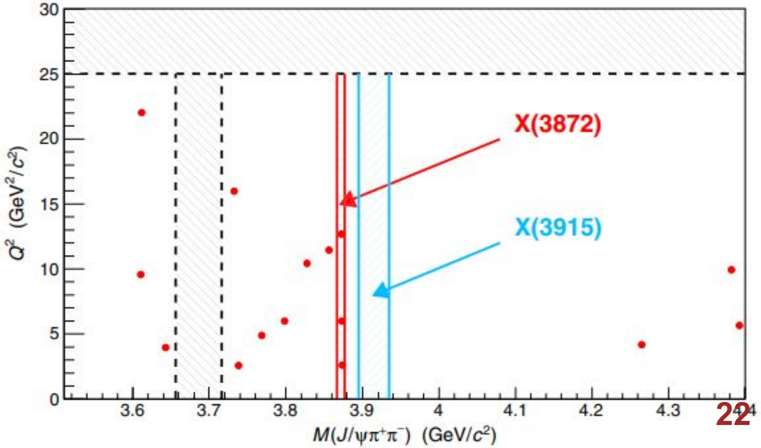
$$g_{Q\gamma\mathcal{E}} = \sum_V \frac{g_{QV\mathcal{E}}}{\gamma_V}\,,$$

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

	$\lvert g_{X\gamma\rho}\rvert$	$\lvert g_{X\gamma\omega}\rvert$
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]

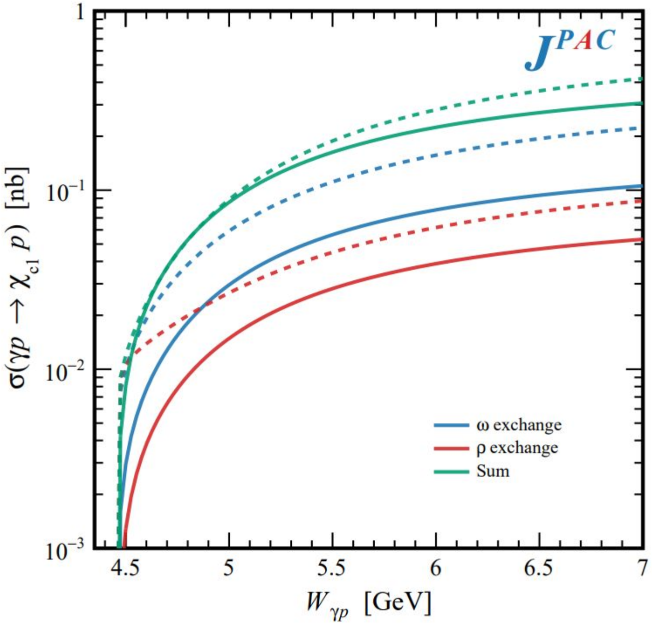


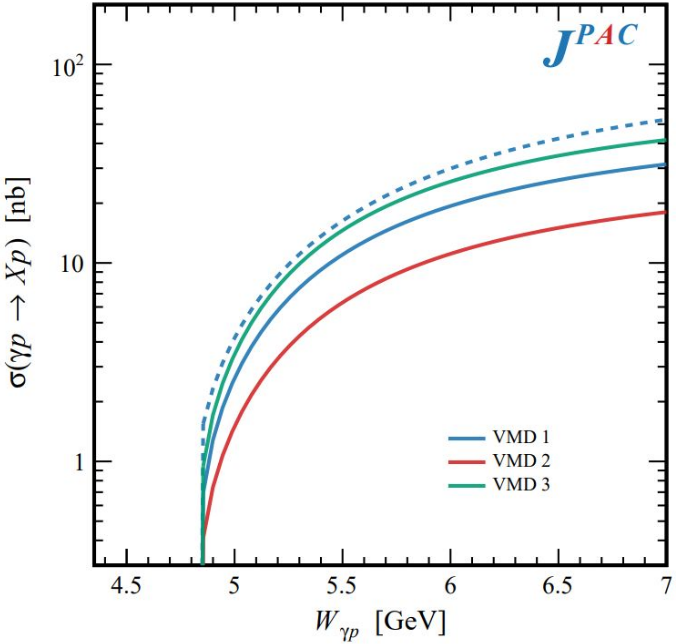
JPAC [arxiv:2404.05326]

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?

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!

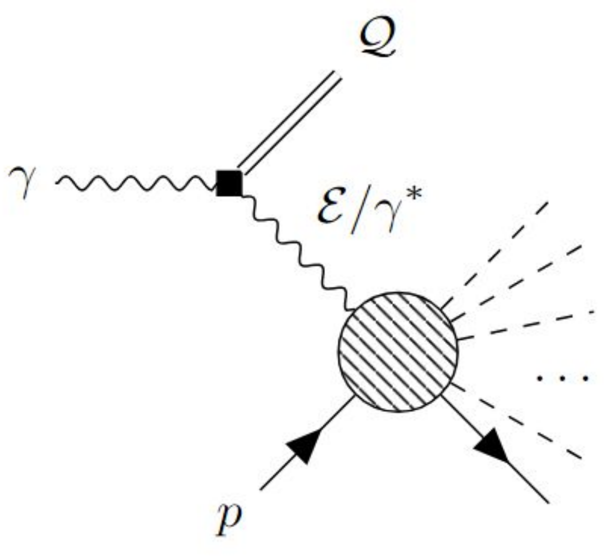
scalar propagator

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