Charmonium (and beyond) in Photoproduction

Daniel Winney
Bonn University - HISKP

Future Directions in Spectroscopy Analysis (FSDA)
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Summary

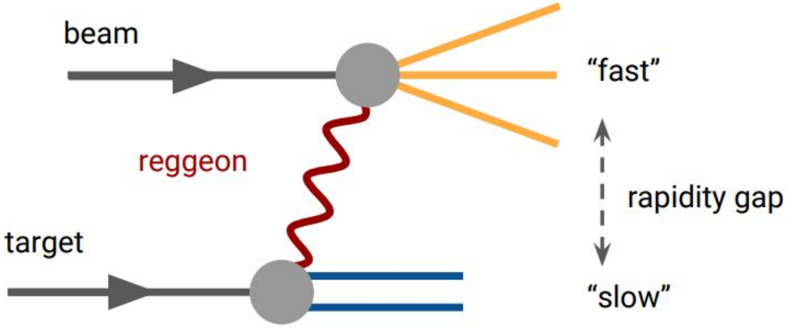
- Introduction
  - Why look at charm sector?
  - Why photoproduction?
- Exclusive reactions:
  - XYZ **[Phys. Rev. D 102, 114010 (2020)]**
  - J/ψ **[Phys. Rev. D 108 (2023) 5, 054018]**
- Semi-inclusive reactions:
  - Zc(3900) **[Phys. Rev. D 106 (2022) 09, 094009]**
  - X(3872) **[finishing soon]**
- and beyond…

Photoproduction

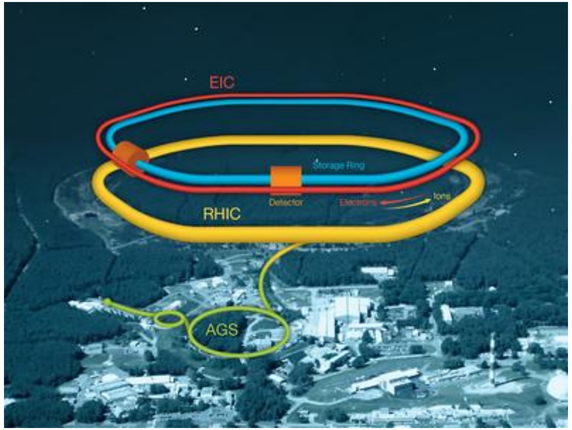
Powerful tool in spectroscopy

- 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]

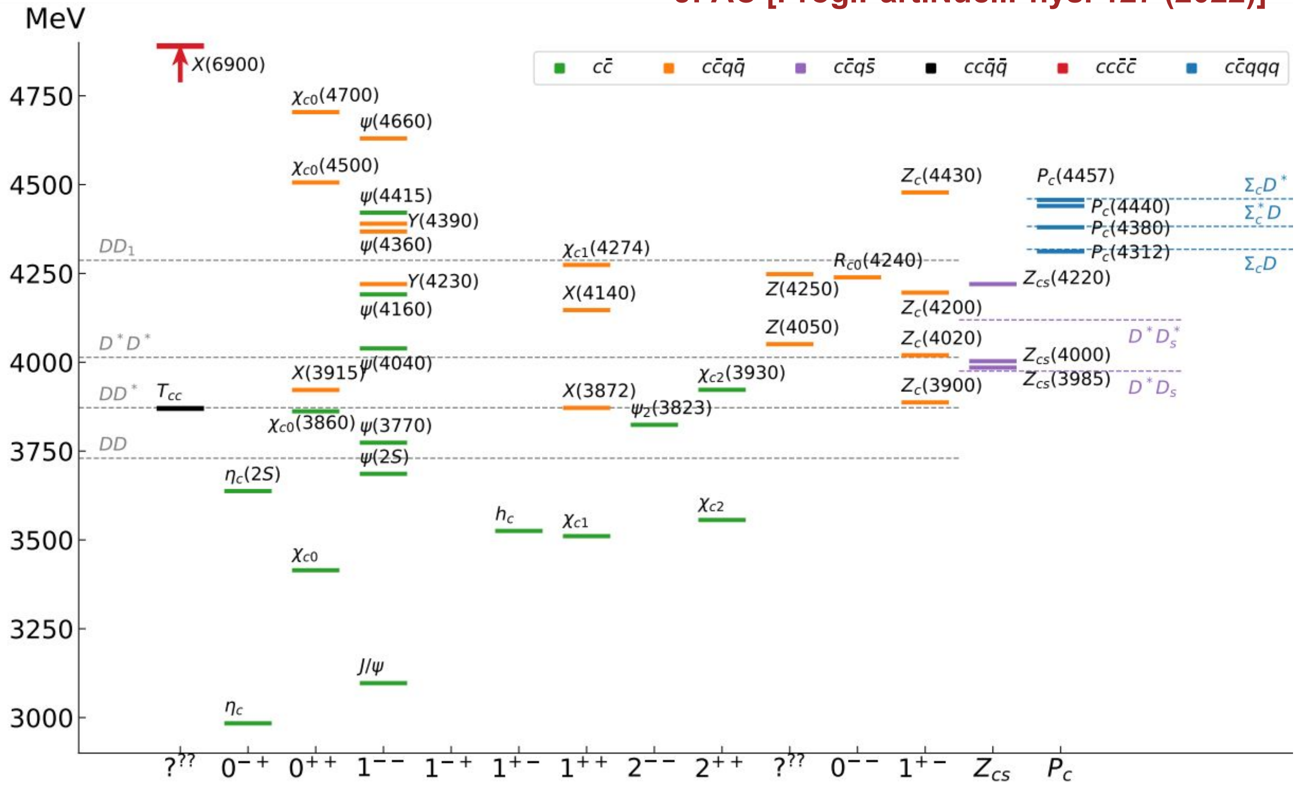


Exotic XYZ states

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)]



Exotic XYZ states

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

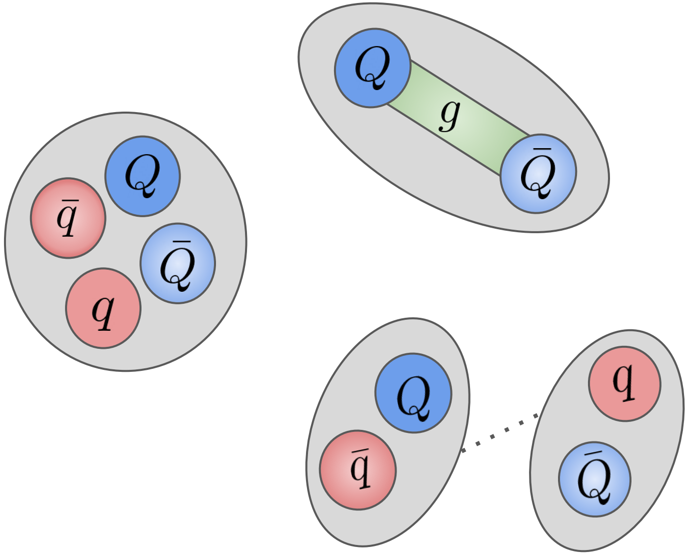
Coincidence of nearby multiparticle thresholds may suggest important **multi-channel dynamics**.

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

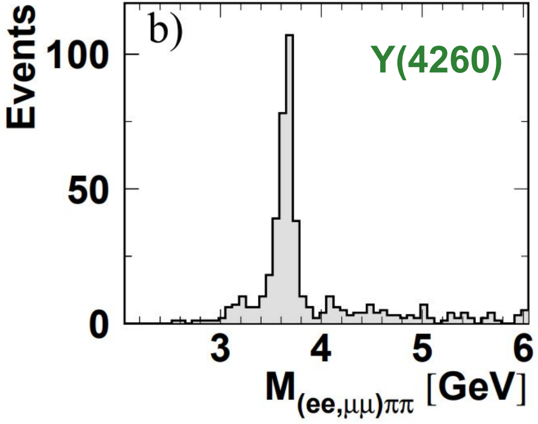
$$a = -\frac{2\,X}{1+X} R + \mathcal{O}(m_\pi^{-1}) \qquad r = -\frac{1-X}{X} R + \mathcal{O}(m_\pi^{-1})$$

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

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]

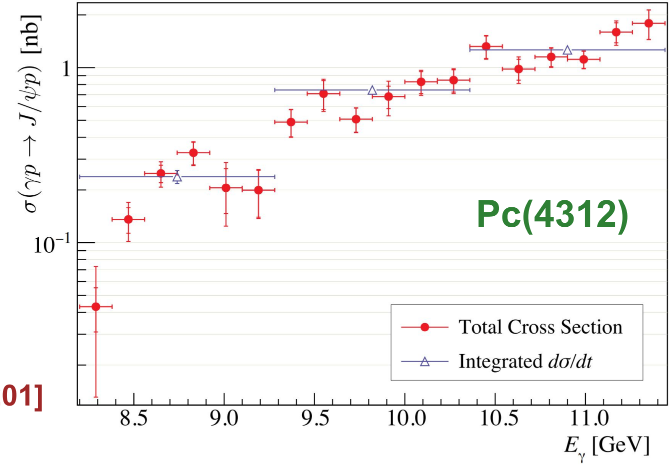


Photoproduction searches

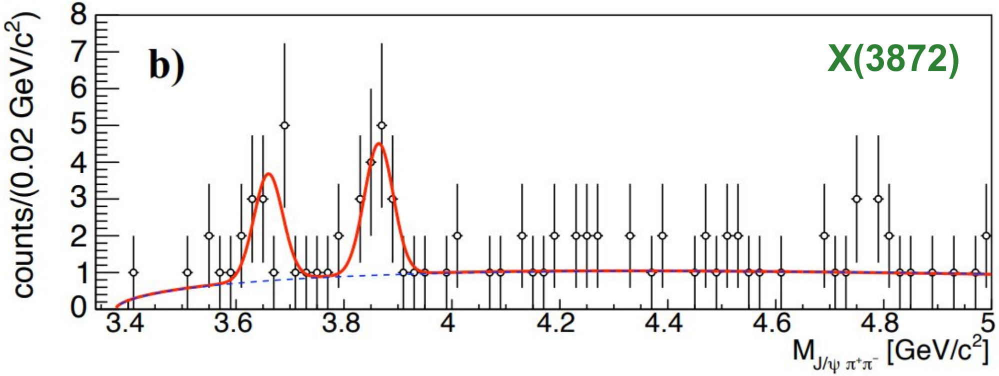


H1 [Phys.Lett.B 541 (2002) 251-264]

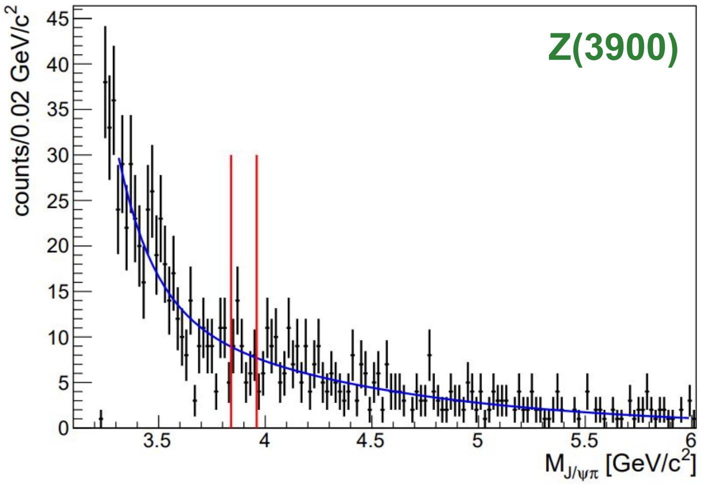
GlueX [Phys.Rev.C 108 (2023) 2, 025201]



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



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



Proton structure

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)]

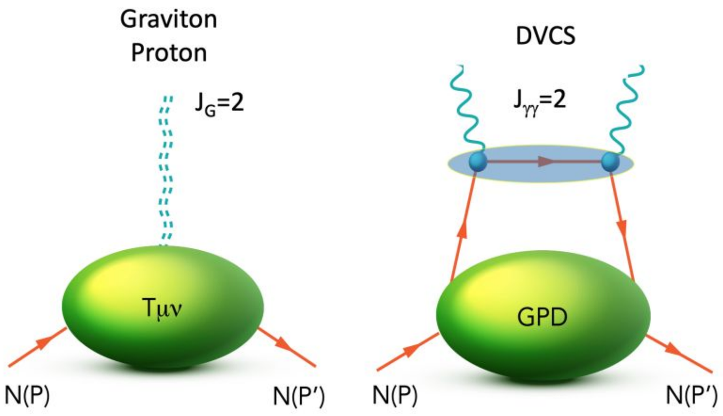
  Mamo & Zahed [Phys. Rev. D 103, 094010 (2021)]

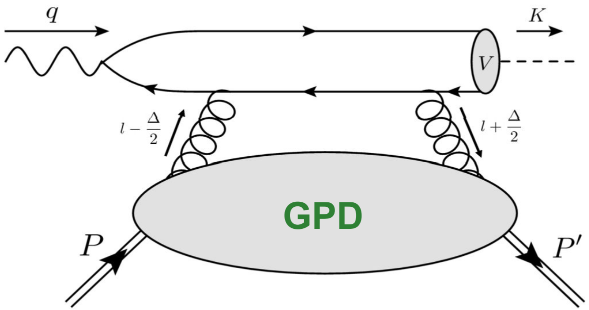
- Trace anomaly contribution to proton mass

  Wang, Chen, & Evslin [Eur.Phys.J.C 80 (2020) 6, 507]

  Hatta & Yang [Phys. Rev. D 98, 074003 (2018)]

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





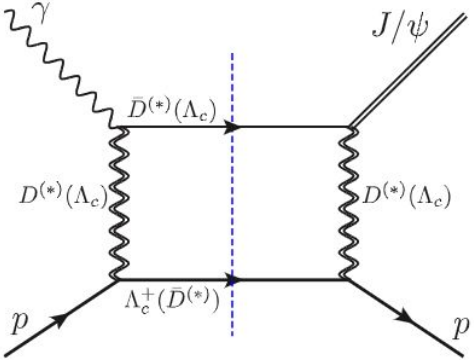
Exclusive photoproduction

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.

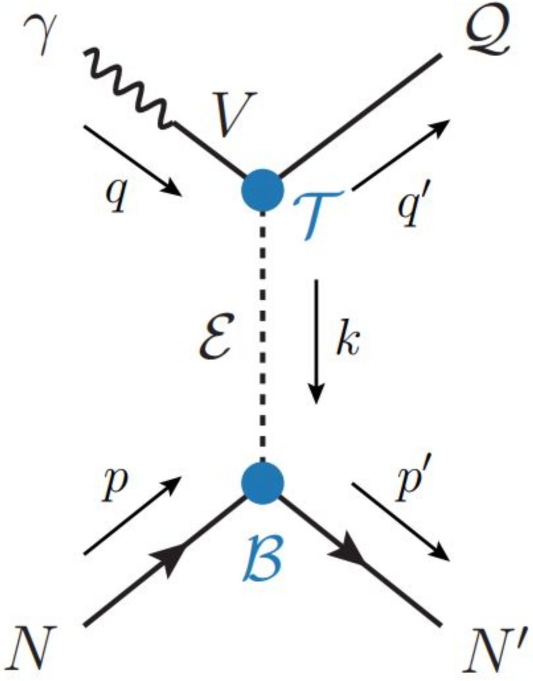
Xu et al [Eur.Phys.J.C 81 (2021) 10, 895]



Ignores possible more complicated production modes which may contribute

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

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



Exclusive photoproduction

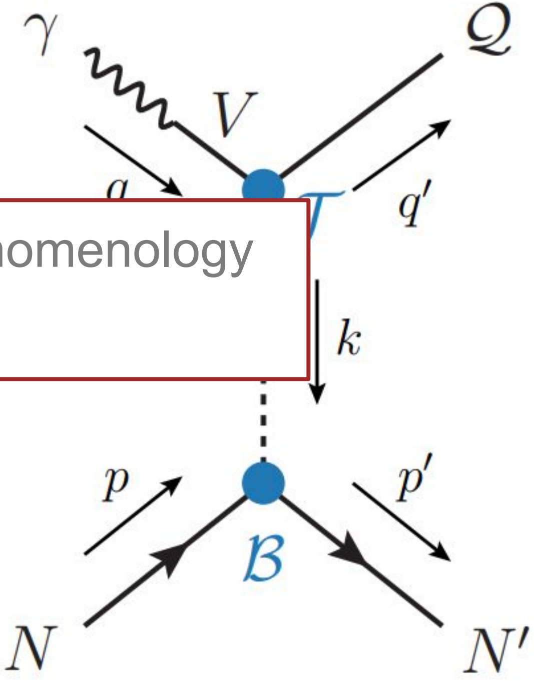
Expected dominant production modes relying on measured branching fractions. Minimal assumption on microscopic nature.

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

Largest un

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

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



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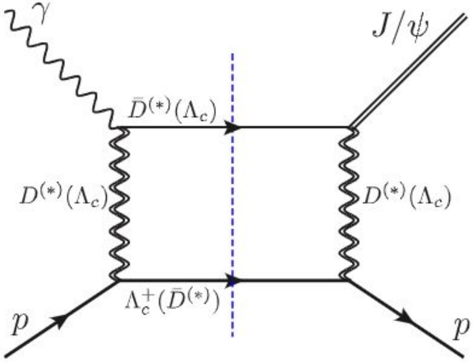


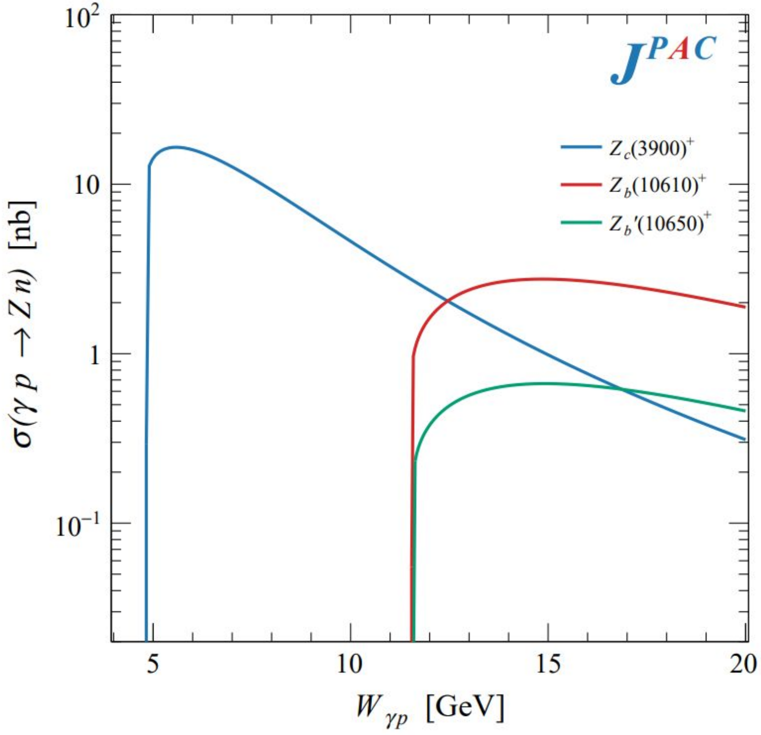
Ignores possible more complicated production modes which may contribute

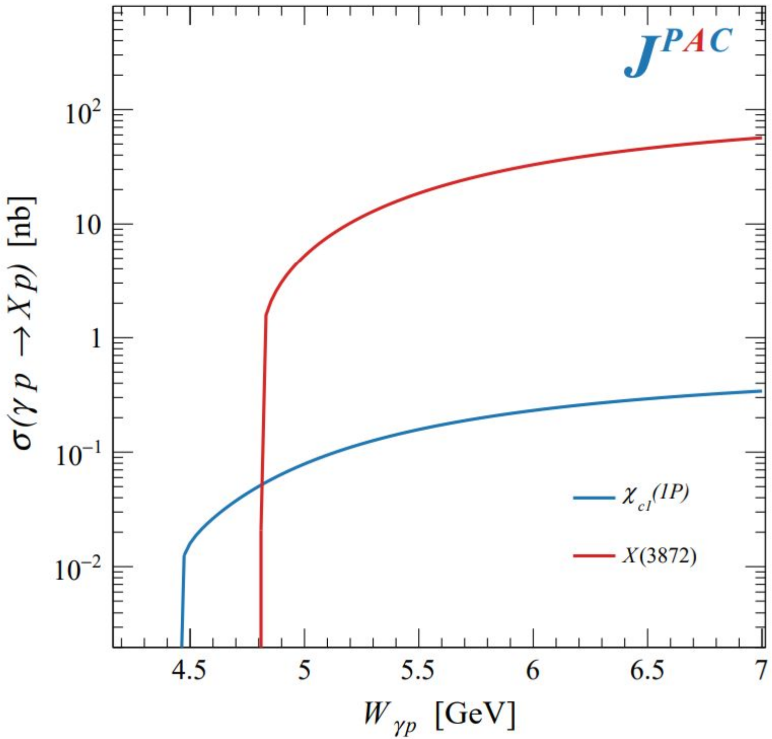
Du et al [Eur.Phys.J.C 80 (2020) 11, 1053]

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

Exclusive photoproduction

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





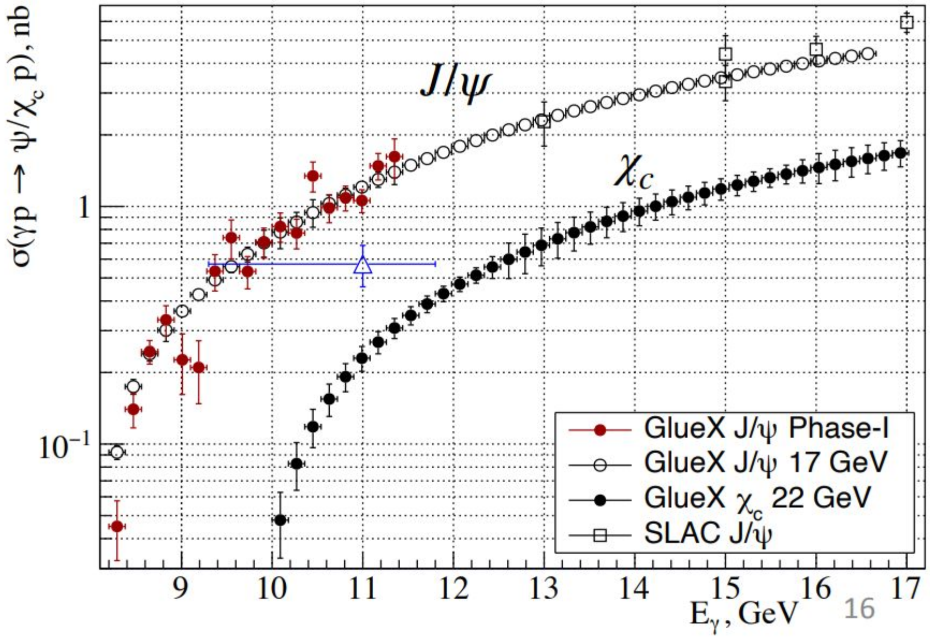
χc1 at GlueX?

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.

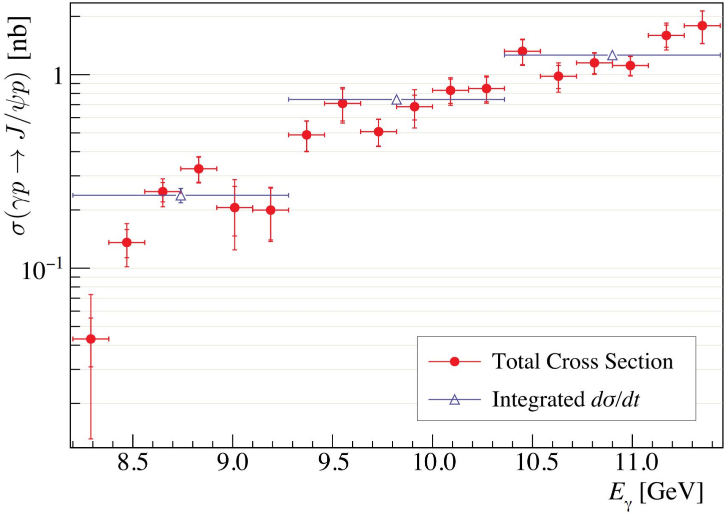
Observation in GlueX about a factor 10 enhanced compared to prediction (~0.02 nb at 11 GeV)

Is observed state the 1P or 2P? Both? Other production mechanism? C-even glue exchange, open charm box? Something else?



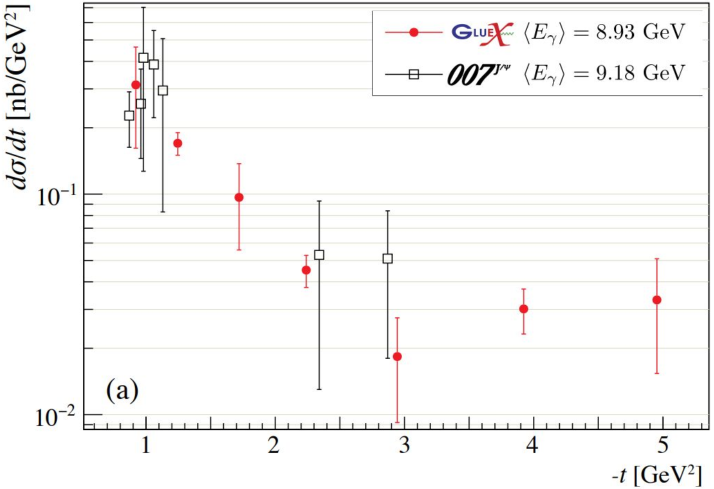
- We have used the measured χ_c yields and MC simulations (efficiency ~10%) to scale the JPAC calculations for χ_{c1} photoproduction cross section and make projections for GlueX with 22 GeV beam:

J/ψ at GlueX



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

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

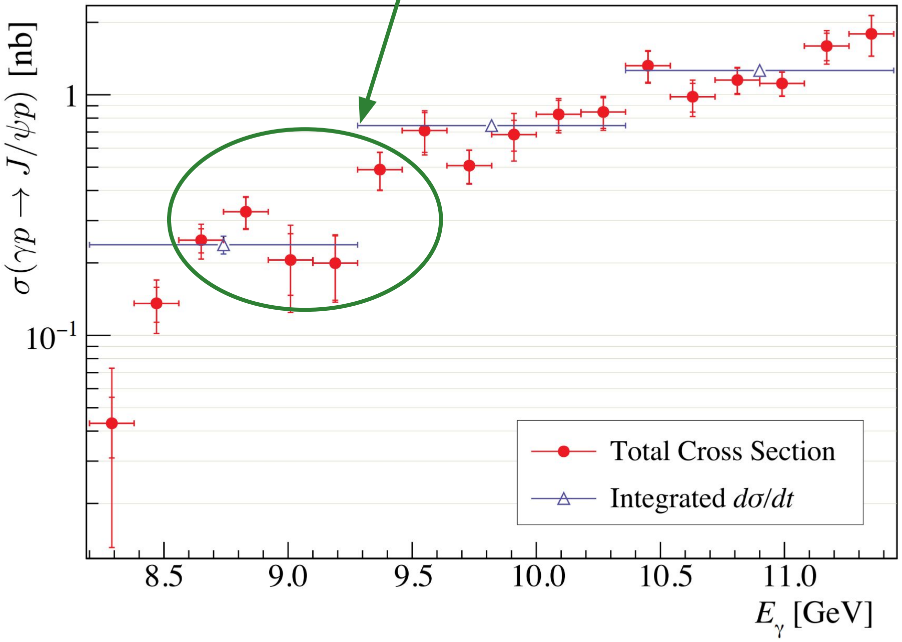


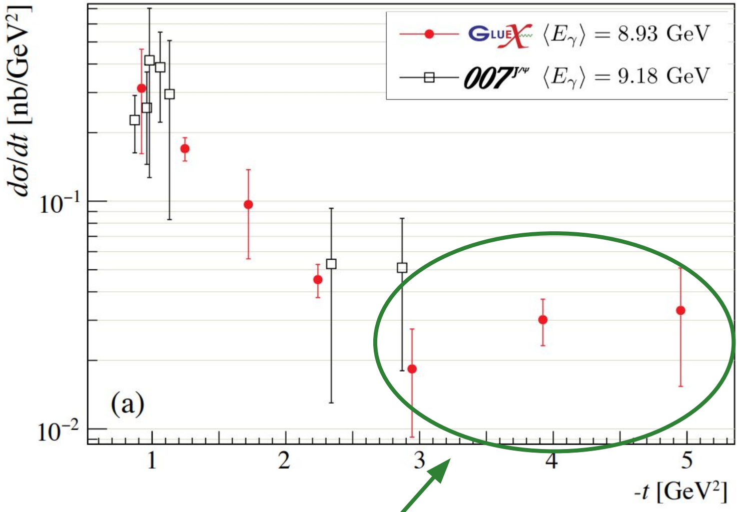
Much larger data set available, incorporating both integrated and differential cross sections.

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]

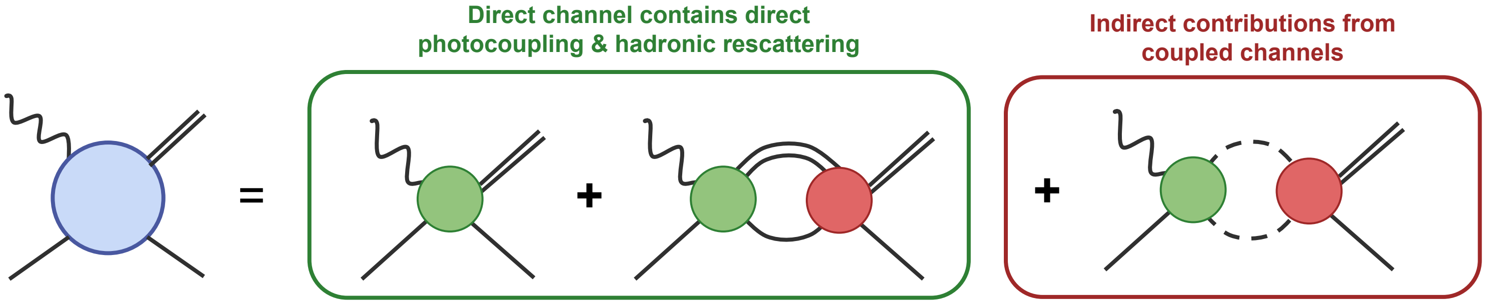
K-matrix analysis

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**

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

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



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

K-matrix analysis

~~Limitations:~~ Advantages:

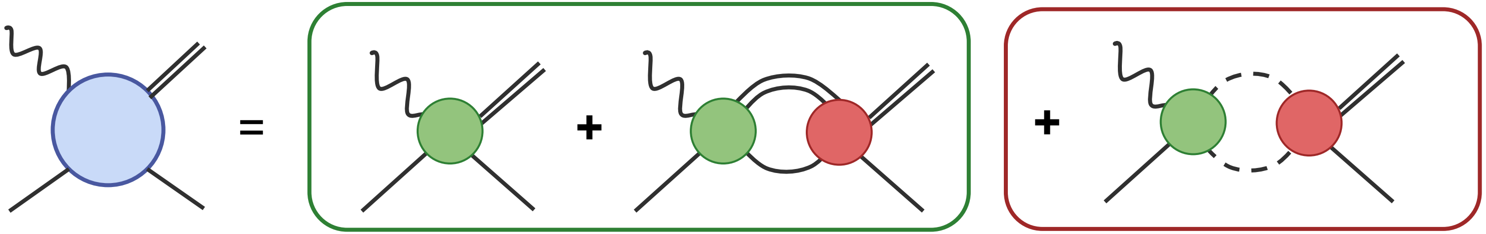
- **Not a microscopic model**
  We don't incur model uncertainty from having to assume dynamics. Model fully analytic and describes entire kinematic range. Depends only on # of terms in PWE and in NTE.

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.

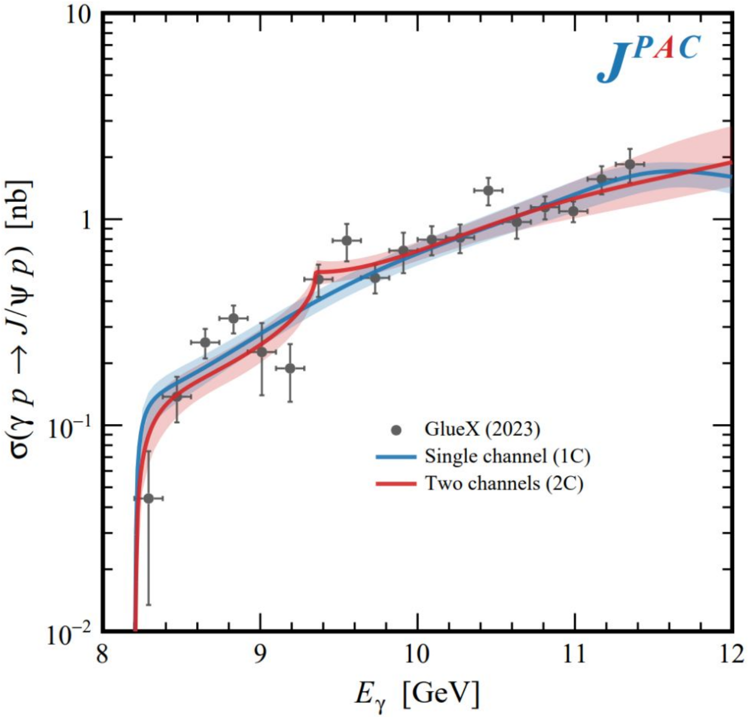
$$K_S^{ij} = \alpha_S^{ij} + \beta_S^i \, q_i^2 \, \delta_{ij} \qquad f_\ell = (pq)^\ell \, n_\ell$$

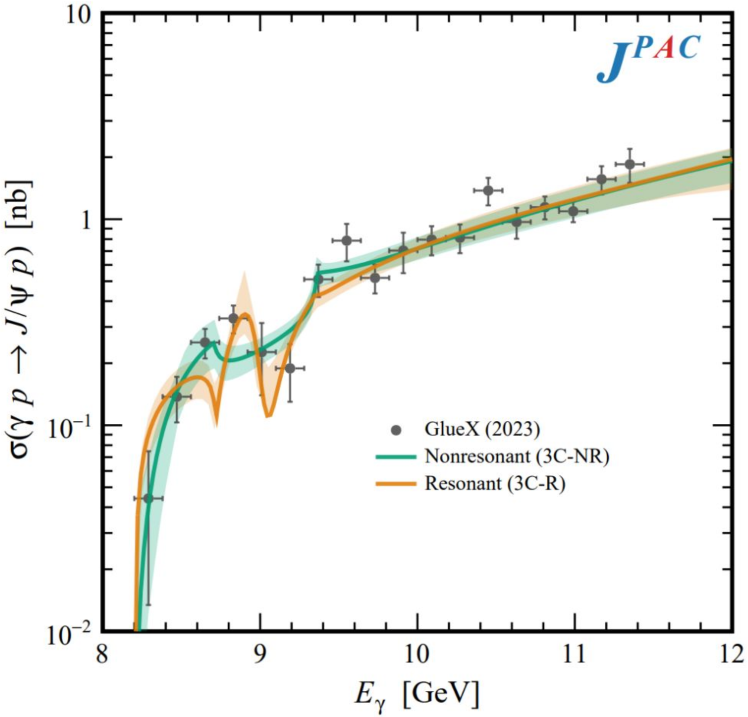


JPAC [Phys.Rev.D 108 (2023) 5, 5]

Integrated cross section

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

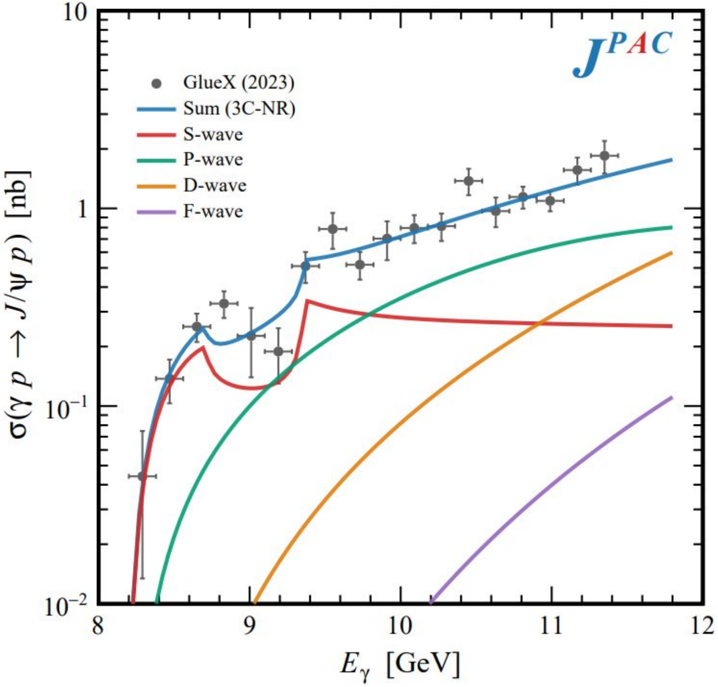


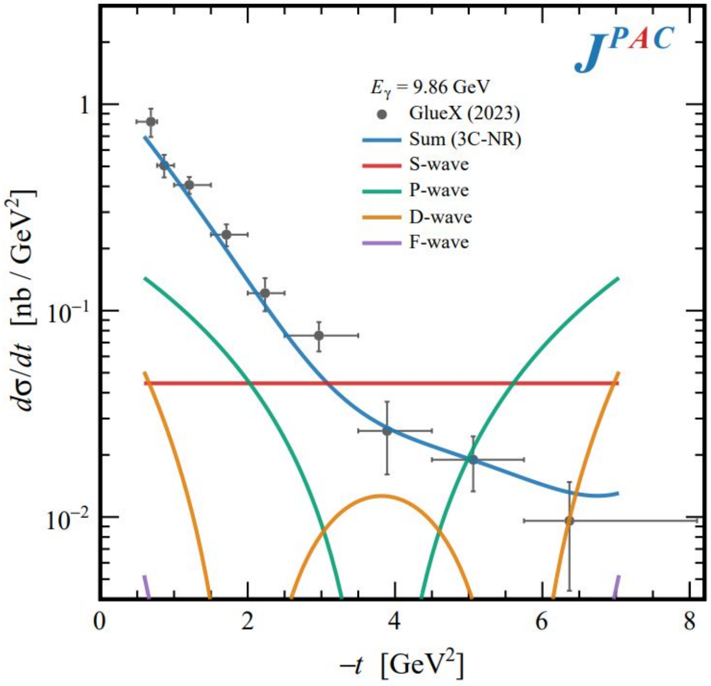


JPAC [Phys.Rev.D 108 (2023) 5, 5]

Differential cross section

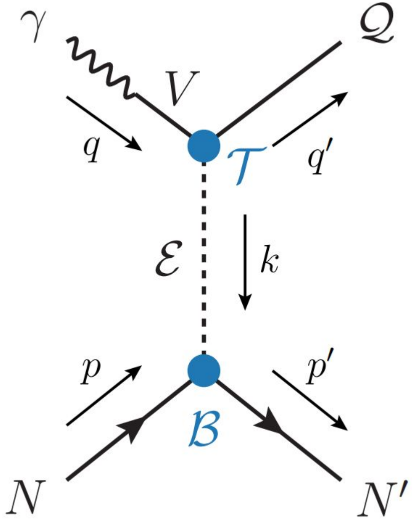
Exponential t behavior captured with only a **few partial waves** (completely analytic is t)





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

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]

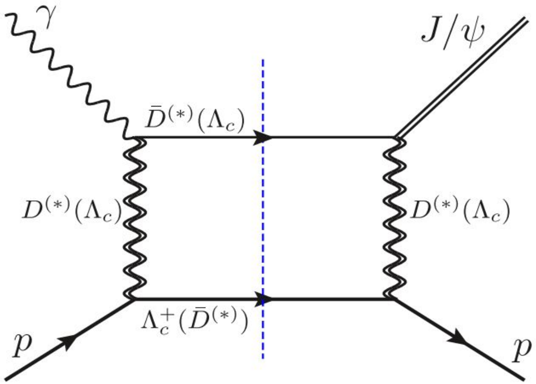
Need better models

K-matrix demonstrates non-negligible contribution from nearby thresholds. Theory should now go back to looking for **microscopic explanation** which incorporates this.

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

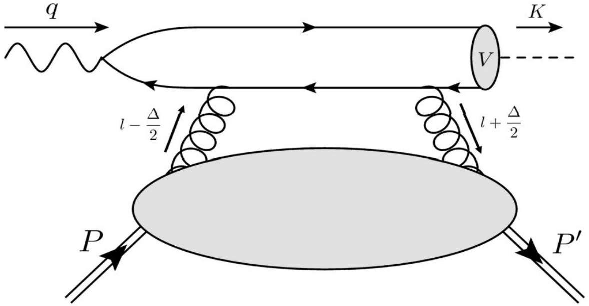
Boxes cannot incorporate glue and completely ignore differential distribution…

Need prediction for helicity dependence



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

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



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)

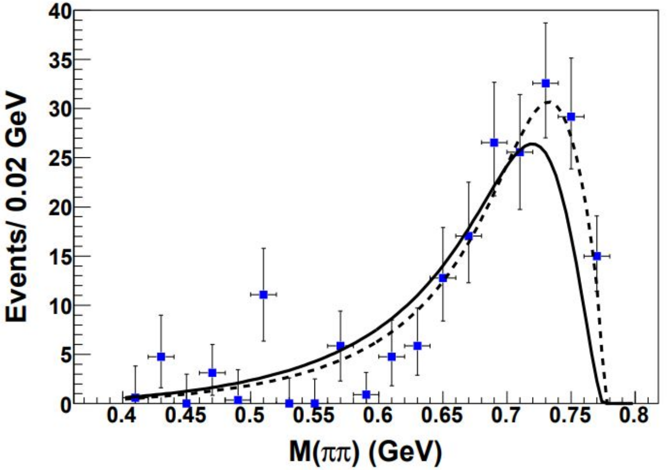
$$\mathcal{L}_{\mathcal{Q}\gamma\gamma^*} = \frac{1}{2}\,\frac{g_{\mathcal{Q}\gamma\gamma^*}}{m_{\mathcal{Q}}^2}\,\epsilon_{\alpha\beta\mu\nu}\,F^{\alpha\beta}\,\partial_\sigma\,F^{\sigma\mu}\,\mathcal{Q}^{*\nu}$$

Use VMD to “predict” the photon coupling from the hadronic one.

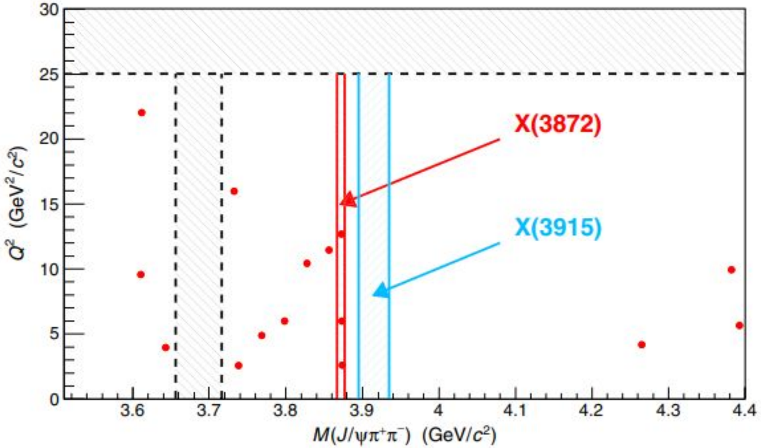
$$g_{\mathcal{Q}\gamma\mathcal{E}} = g_{\mathcal{Q}V\mathcal{E}}/\eta_V = g_{\mathcal{Q}\gamma\gamma^*}\,\eta_{\mathcal{E}}$$

Couplings entirely compatible with naive VMD, dominant ω exchange reproduces the photon coupling within 10%

$\mathcal{Q}$	V	$\mathcal{E}$	$g_{\mathcal{Q}\gamma\gamma^*} \times 10^3$
$X(3872)$	γ	γ^*	3.2
	J/ψ	ρ	5.38
		ω	3.54



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



In defense of VMD

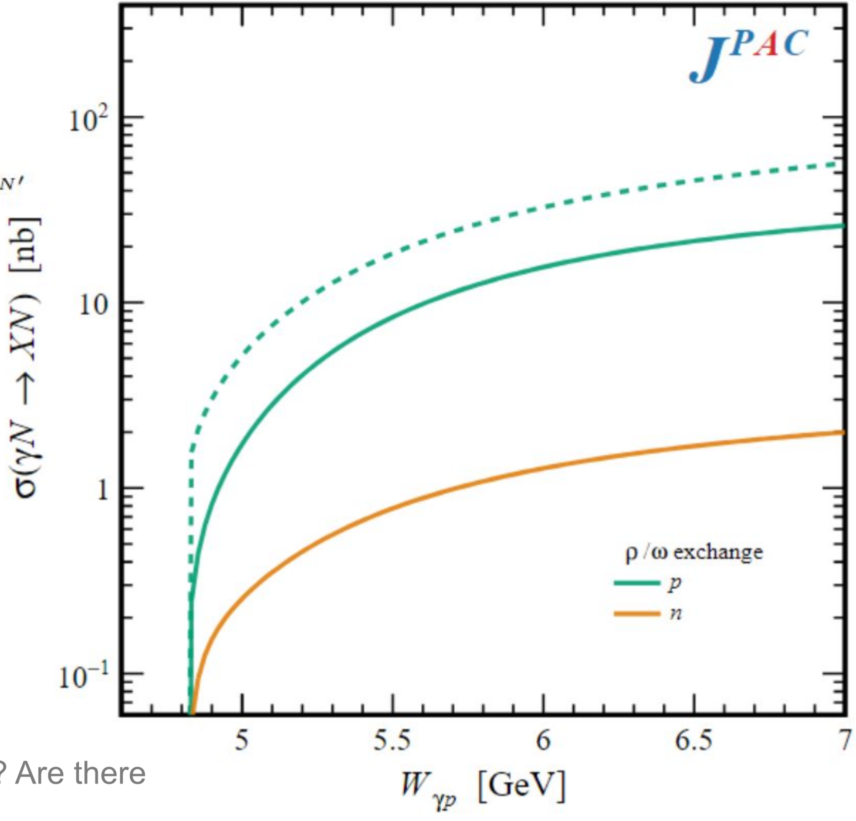
Alternatively go the other way, use the fully determined photon exchange amplitude to re-predict the hadronic exchange.

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

Rescaling electromagnetic form factors of the with VMD consistent with out original prediction up to factor of ~2 without any knowledge of the X(3872) hadronic coupling

$$\mathcal{B}^{\mu}_{\lambda_N \lambda_{N'}} = e \, \bar{u}(p', \lambda_{N'}) \left[F_1(t) \, \gamma^\mu + F_2(t) \, \frac{\sigma^{\mu\nu} \, q_\nu}{2 m_N} \right] u(p, \lambda_N)$$

By no means conclusive but gives us indication enough to not abandon the whole VMD-based program (yet)

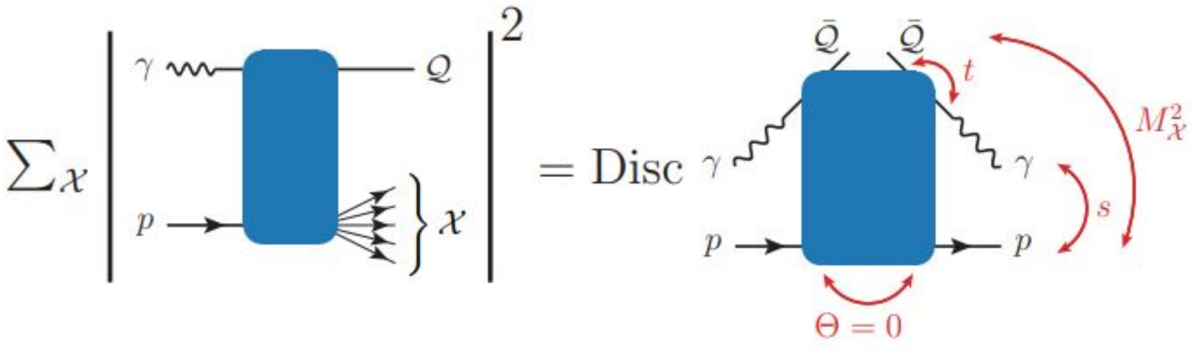


Why does VMD seem to work okay in some sectors but not others? Are there other processes we can look at to test VMD in charm?

Semi-inclusive production

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

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

$\pi\gamma$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!

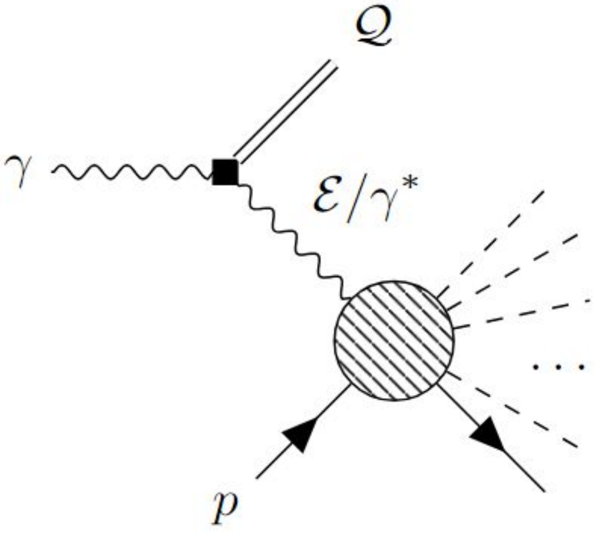
scalar propagator

VMD

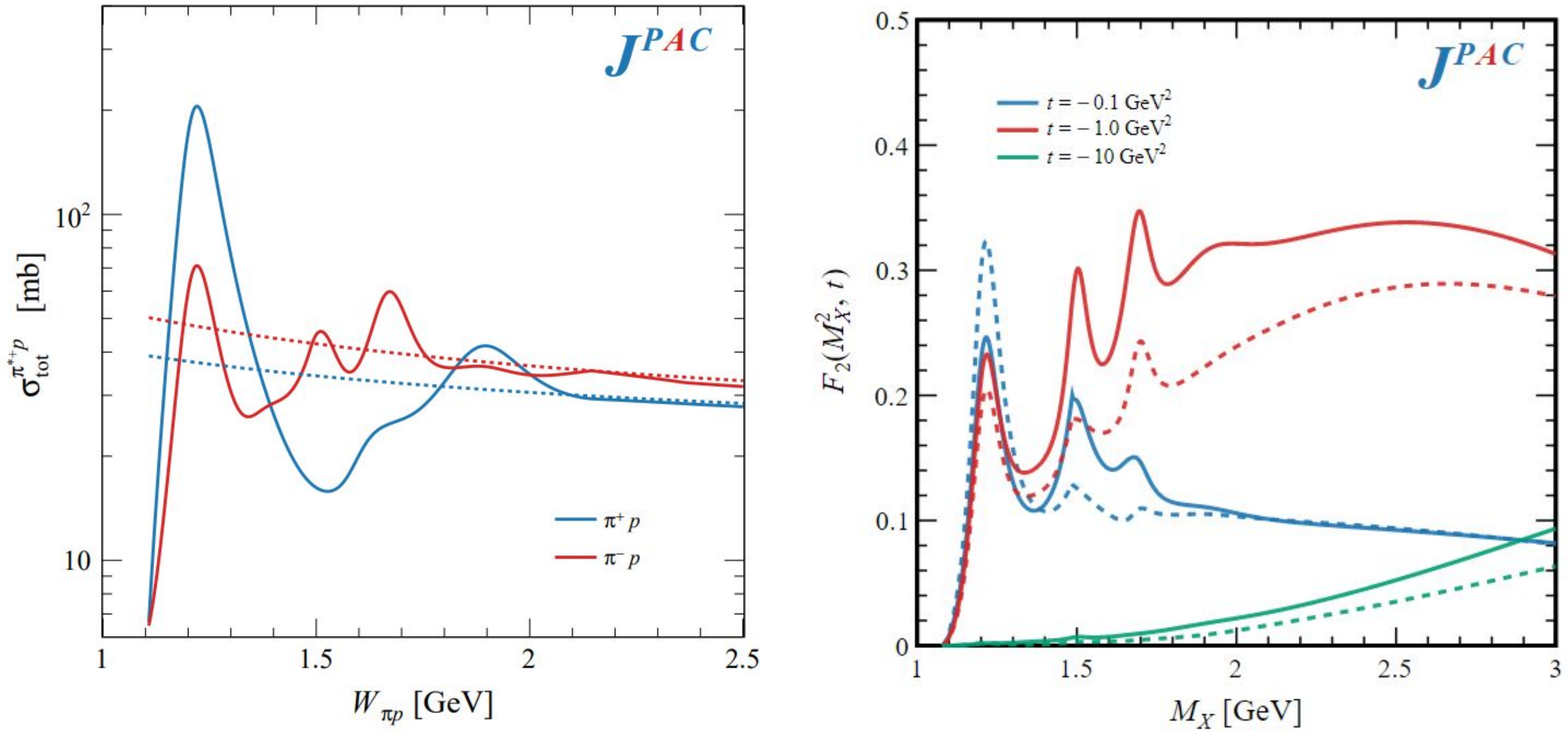
$$\frac{d^2\sigma}{dt\,dM^2_{\mathcal{X}}} = \sum_{\mathcal{E}} \frac{\alpha\,\eta^4_{\mathcal{E}}}{2\,(2\sqrt{s}\,E_\gamma)^2}\, T^{\mu\nu}_{\gamma\bar{\mathcal{Q}}}\, |\beta_{\mathcal{E}}\,\mathcal{P}_{\mathcal{E}}|^2\, W_{\mu\nu}$$

VγX coupling

Inclusive structure functions

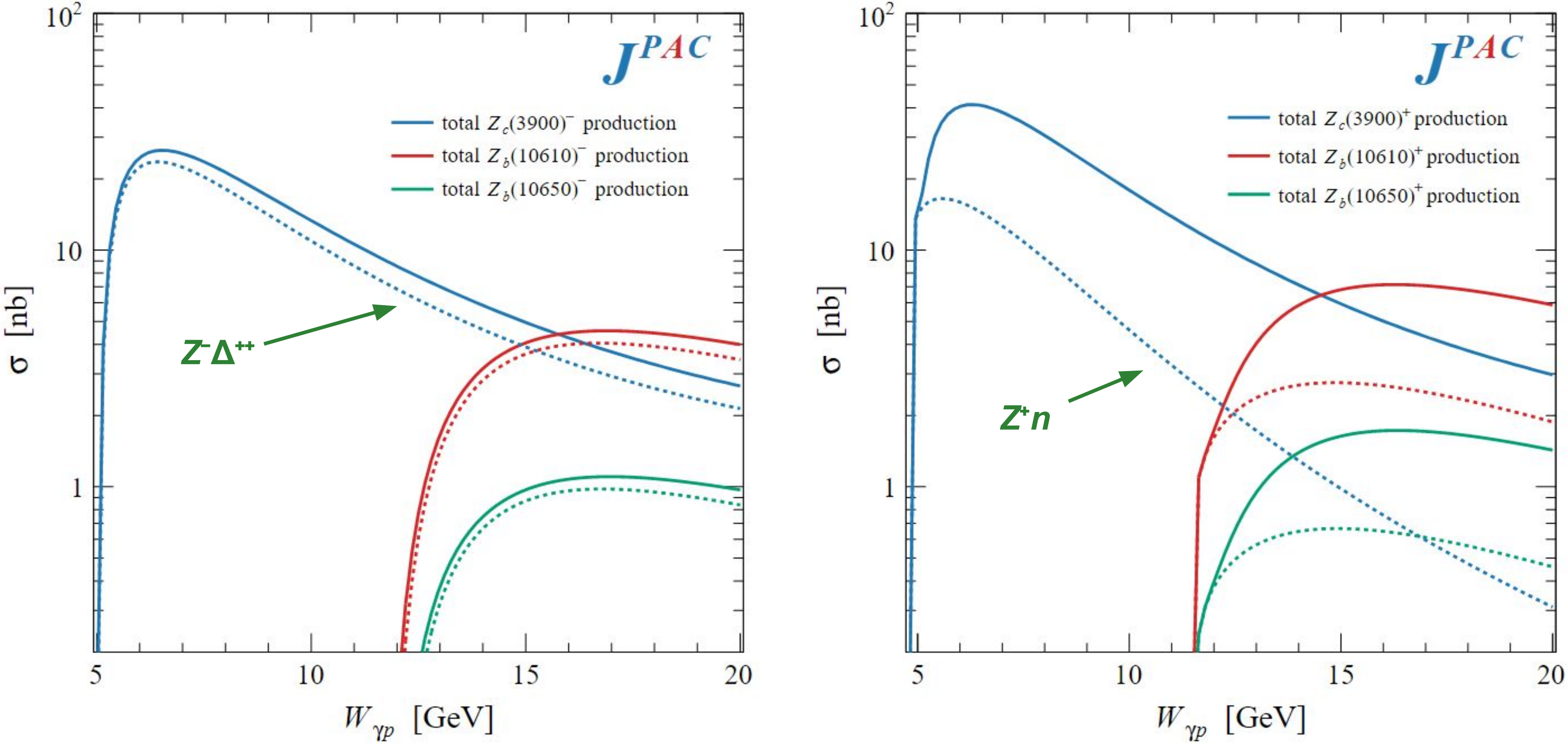


Missing mass in resonance region



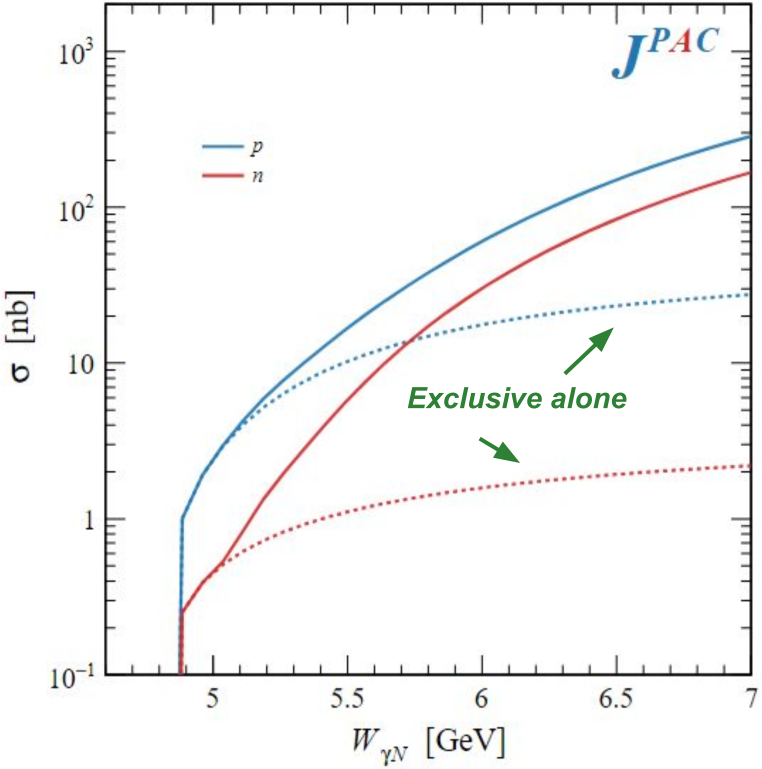
JPAC [Phys.Rev.D 106 (2022) 9, 09]

Charged Z production

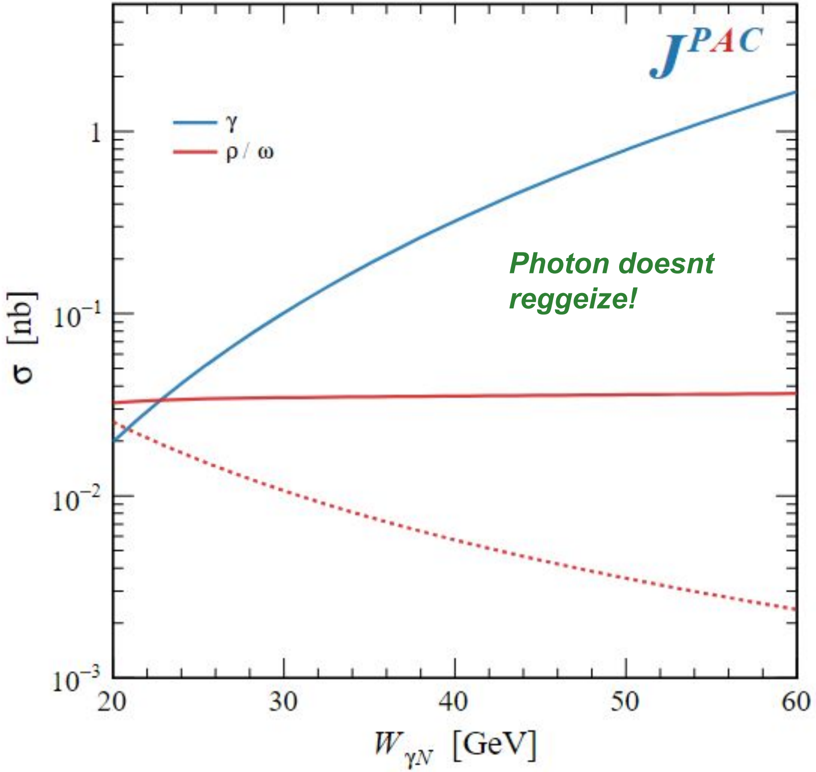


JPAC [in progress]

X(3872) production



Exclusive alone



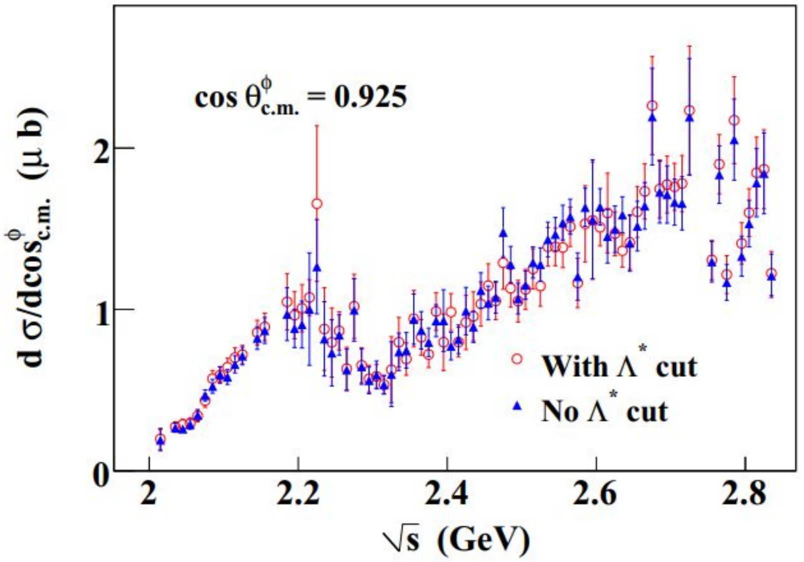
Photon doesnt reggeize!

ϕ Photoproduction

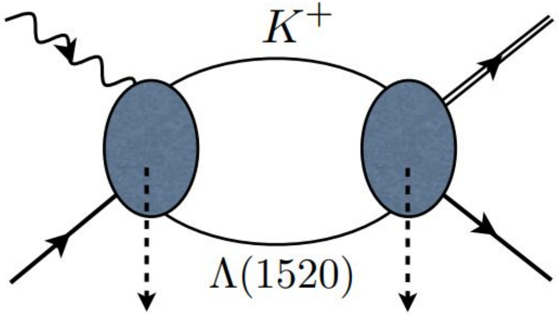
Completely analogous system to charmonium.

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

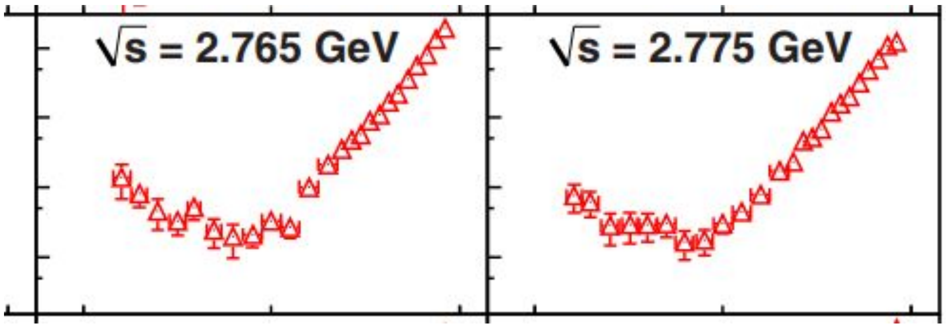
Possibility of hidden strange bound states



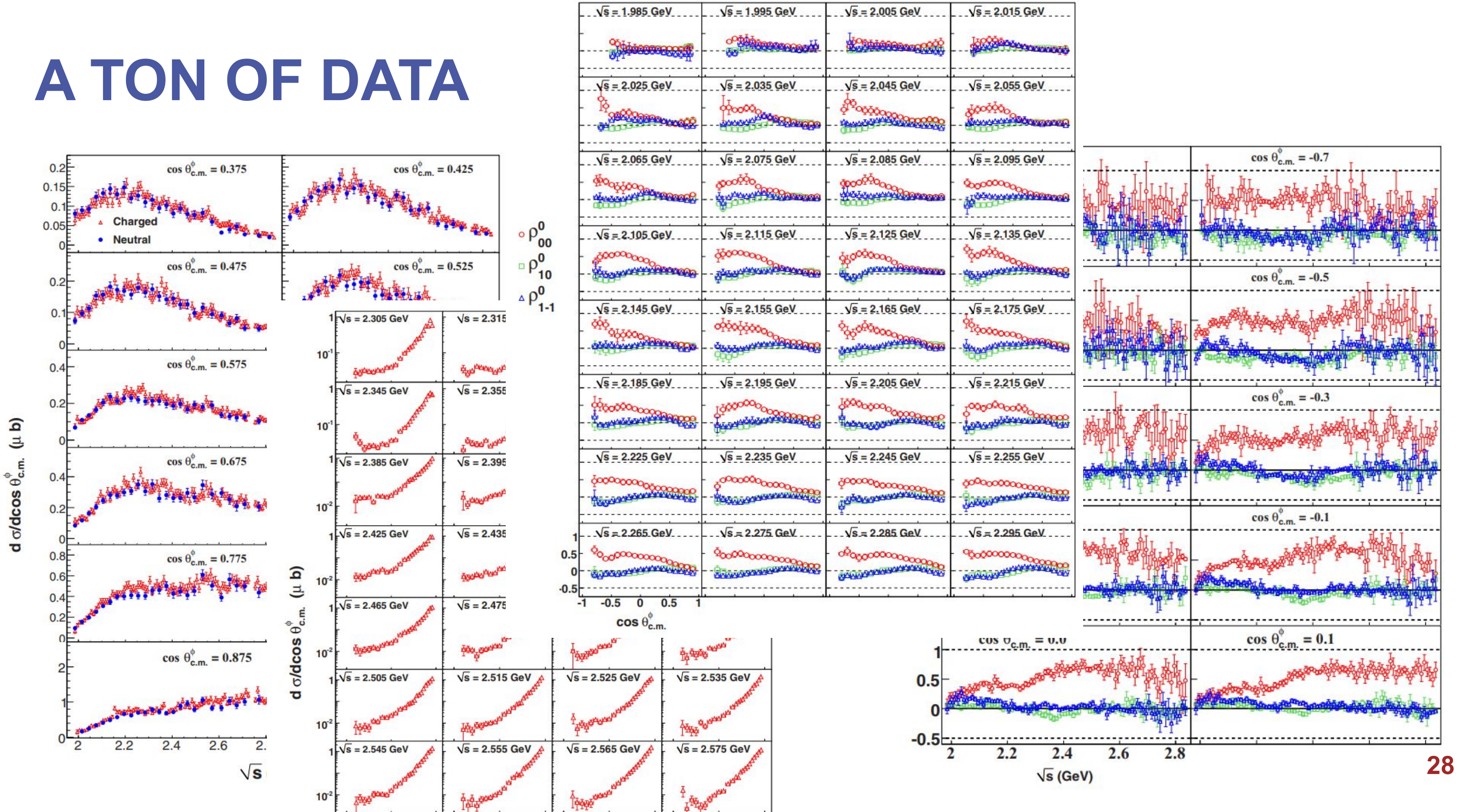
CLAS [Phys.Rev.C 89 (2014) 5, 055208]



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



A TON OF DATA


Charged
Neutral
cos $\theta^{\phi}_{c.m.}$ = 0.375
cos $\theta^{\phi}_{c.m.}$ = 0.425
cos $\theta^{\phi}_{c.m.}$ = 0.475
cos $\theta^{\phi}_{c.m.}$ = 0.525
cos $\theta^{\phi}_{c.m.}$ = 0.575
cos $\theta^{\phi}_{c.m.}$ = 0.675
cos $\theta^{\phi}_{c.m.}$ = 0.775
cos $\theta^{\phi}_{c.m.}$ = 0.875
d σ/dcos $\theta^{\phi}_{c.m.}$ (μ b)
√s
2
2.2
2.4
2.6
$\sqrt{s}$ = 2.305 GeV
$\sqrt{s}$ = 2.345 GeV
$\sqrt{s}$ = 2.385 GeV
$\sqrt{s}$ = 2.425 GeV
$\sqrt{s}$ = 2.465 GeV
$\sqrt{s}$ = 2.505 GeV
$\sqrt{s}$ = 2.515 GeV
$\sqrt{s}$ = 2.525 GeV
$\sqrt{s}$ = 2.535 GeV
$\sqrt{s}$ = 2.545 GeV
$\sqrt{s}$ = 2.555 GeV
$\sqrt{s}$ = 2.565 GeV
$\sqrt{s}$ = 2.575 GeV
○ ρ^0_{00}
□ ρ^0_{10}
△ ρ^0_{1-1}
$\sqrt{s}$ = 1.985 GeV
$\sqrt{s}$ = 1.995 GeV
$\sqrt{s}$ = 2.005 GeV
$\sqrt{s}$ = 2.015 GeV
$\sqrt{s}$ = 2.025 GeV
$\sqrt{s}$ = 2.035 GeV
$\sqrt{s}$ = 2.045 GeV
$\sqrt{s}$ = 2.055 GeV
$\sqrt{s}$ = 2.065 GeV
$\sqrt{s}$ = 2.075 GeV
$\sqrt{s}$ = 2.085 GeV
$\sqrt{s}$ = 2.095 GeV
$\sqrt{s}$ = 2.105 GeV
$\sqrt{s}$ = 2.115 GeV
$\sqrt{s}$ = 2.125 GeV
$\sqrt{s}$ = 2.135 GeV
$\sqrt{s}$ = 2.145 GeV
$\sqrt{s}$ = 2.155 GeV
$\sqrt{s}$ = 2.165 GeV
$\sqrt{s}$ = 2.175 GeV
$\sqrt{s}$ = 2.185 GeV
$\sqrt{s}$ = 2.195 GeV
$\sqrt{s}$ = 2.205 GeV
$\sqrt{s}$ = 2.215 GeV
$\sqrt{s}$ = 2.225 GeV
$\sqrt{s}$ = 2.235 GeV
$\sqrt{s}$ = 2.245 GeV
$\sqrt{s}$ = 2.255 GeV
$\sqrt{s}$ = 2.265 GeV
$\sqrt{s}$ = 2.275 GeV
$\sqrt{s}$ = 2.285 GeV
$\sqrt{s}$ = 2.295 GeV
cos $\theta^{\phi}_{c.m.}$
cos $\theta^{\phi}_{c.m.}$ = -0.7
cos $\theta^{\phi}_{c.m.}$ = -0.5
cos $\theta^{\phi}_{c.m.}$ = -0.3
cos $\theta^{\phi}_{c.m.}$ = -0.1
cos $\theta^{\phi}_{c.m.}$ = 0.0
cos $\theta^{\phi}_{c.m.}$ = 0.1
√s (GeV)
2.8

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…

$$\begin{aligned}
l_1^{\mu\nu} &= P^\mu\,[(P\cdot q)\,k^\nu - (k\cdot q)\,P^\nu]\ , \\
l_2^{\mu\nu} &= (k\cdot q)\,g^{\mu\nu} - q^\mu\,k^\nu\ , \\
l_3^{\mu\nu} &= (P\cdot q)\,g^{\mu\nu} - q^\mu\,P^\nu\ , \\
l_4^{\mu\nu} &= g^{\mu\nu}\not{q} - q^\mu\,\gamma^\nu\ , \\
l_5^{\mu\nu} &= [(q\cdot P)\,g^{\mu\nu} - q^\mu\,P^\nu]\,\not{q}\ , \\
l_6^{\mu\nu} &= P^\mu\,[P^\nu\,\not{q} - (q\cdot P)\,\gamma^\nu]
\end{aligned}$$

$$\begin{aligned}
l_7^{\mu\nu} &= q^\mu\,\gamma^\nu\,\not{q}\ , \\
l_8^{\mu\nu} &= P^\mu\,\gamma^\nu\,\not{q}\ , \\
l_9^{\mu\nu} &= \gamma^\mu\,[(P\cdot q)\,k^\nu - (k\cdot q)\,P^\nu] \\
l_{10}^{\mu\nu} &= \gamma^\mu\,[(k\cdot q)\,\gamma^\nu - k^\nu\,\not{q}]\ , \\
l_{11}^{\mu\nu} &= \gamma^\mu\,[(P\cdot q)\,\gamma^\nu - P^\nu\,\not{q}] \\
l_{12}^{\mu\nu} &= \gamma^\mu\,\gamma^\nu\,\not{q}\ ,
\end{aligned}$$

Hope to have some cool results in the coming months

Thank you :)