Deciphering the mechanism of near-threshold J/ψ photoproduction

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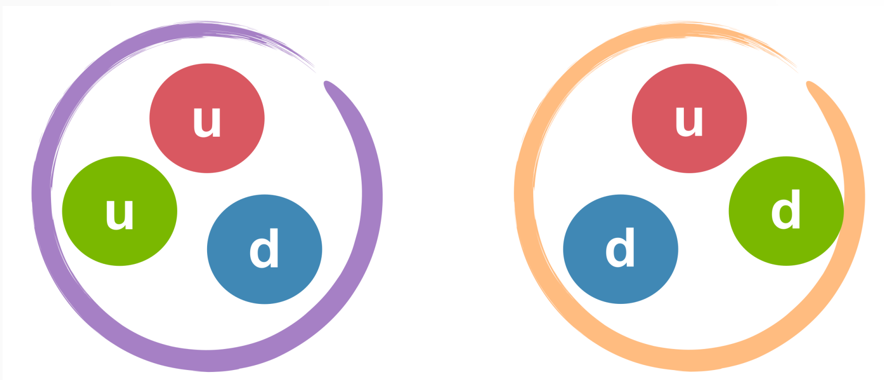
Workshop on Near-Threshold Production of Heavy Quarkonium
19-23 February 2024, Huizhou

The nucleon mass: Trace Anomaly



proton neutron

1. Building blocks of visible matter (99% of the mass)
2. Bound states of QCD
3. Three quark mass ~ 1% (higgs mechanism)

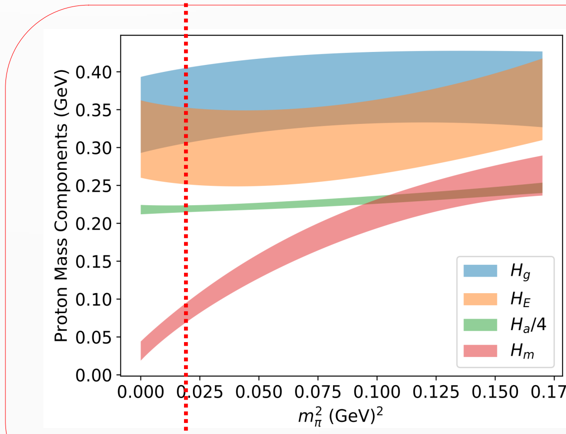
1. The nucleon mass is related to the trace of energy-momentum tensor (EMT)

$$\langle N | T^{\mu}_{\mu} | N \rangle = 2 P^{\mu} P_{\mu} = 2 M_N^2$$

2. At low energy, the heavy quarks decouple:

$$M_N = \langle \frac{\beta}{2g} F^2 + \sum_f \gamma_m m_f \overline{\psi}_f \psi_f \rangle_{\rm H} + \sum_f m_f \langle \overline{\psi}_f \psi_f \rangle_{\rm H}$$

3. For pions: trace anomaly vanish in the chiral limit.



Proton mass on Lattice

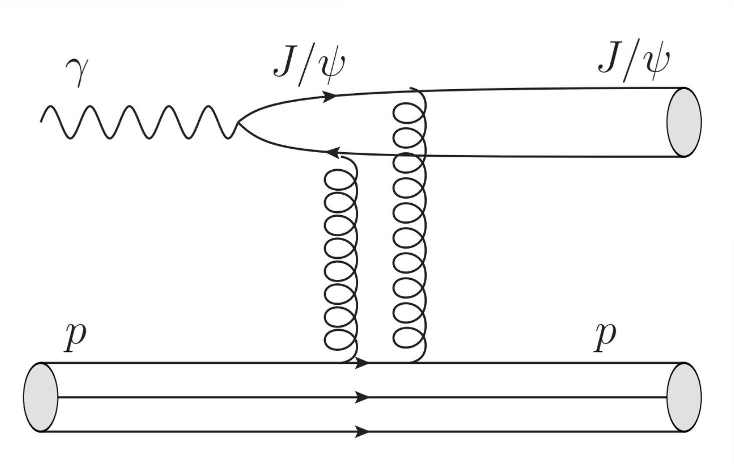
$$\begin{aligned} M_N &= H_m + H_a \\ &= H_m + H_E + H_g + H_a/4 \end{aligned}$$

Y.-B. Yang et al., (χQCD), PRL 121, 212001 (2018)

More recent progress by Y.-B. Yang's talk

Why J/ψ photoproduction ?

Vector-meson-dominance model (VMD)



1. Quarkonium only couples to gluons, not light quarks $J/\psi, \Upsilon(1S)$...
2. Nucleons interact with a heavy quarkonium through multiple-gluon exchange.
3. Sensitive to gluonic structure of the proton
4. Possible pentaquark states.

$$T_{\gamma p \to J/\psi p} = g_{\gamma\psi} T_{J/\psi p \to J/\psi p}$$

$g_{\gamma\psi}$ is determined by the $J/\psi \to e^+e^-$ width

$$g_{\gamma\psi}^2 = \frac{3\Gamma(J/\psi \to e^+e^-)}{\alpha m_{J/\psi}}.$$

$$\frac{d\sigma_{\gamma N \to \psi N}}{dt}(s, t=0) = \frac{3\Gamma(\psi \to e^+e^-)}{\alpha m_\psi} \left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2 \frac{d\sigma_{\psi N \to \psi N}}{dt}(s, t=0)$$

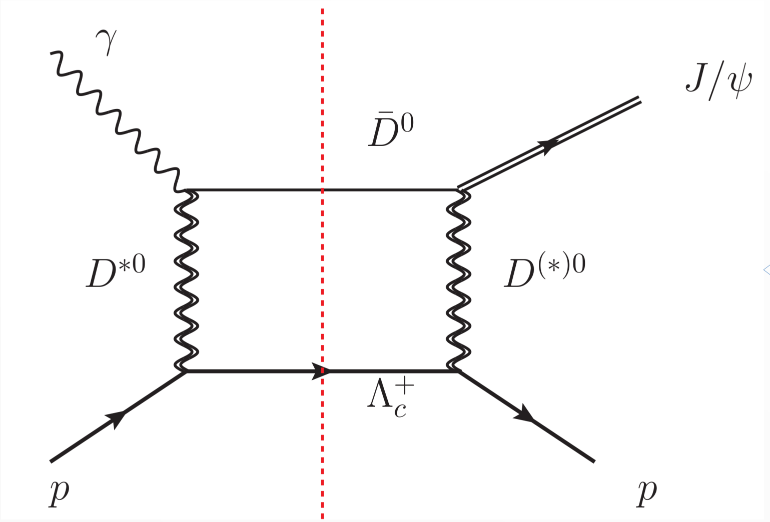
Kharzeev, Satz, *et. al.*, EPJC9(1999)459

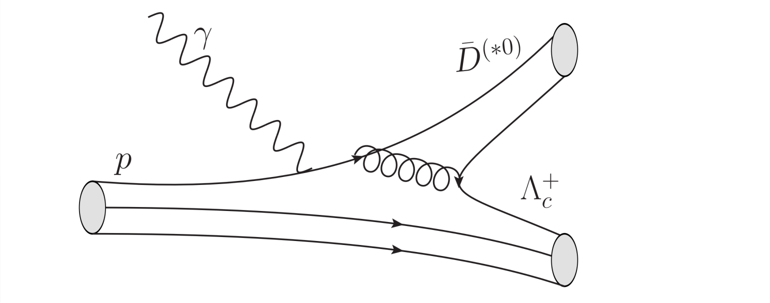
Here t never $= 0$!

The J/ψ attached to the photon is highly off-shell, while the J/ψ scattering length is defined for on-shell scattering.

Coupled-channel (CC) mechanism

The $\Lambda_c^+\bar{D}^0$ threshold is only 116 MeV above the $J/\psi p$ threshold, rendering the contribution from the $\Lambda_c\bar{D}$ channel potentiallly sizeable.





Mechanism for the near-threshold J/ψ photoproduction through $\Lambda_c\bar{D}^{(*)}$ which then rescatter into $J/\psi p$.

The relation to the trace anomaly lost.

$$\mathrm{Im}\mathcal{A}_{\gamma p\to J/\psi p} = \mathcal{A}_{\gamma p\to\Lambda_c^+\bar{D}^0}\,\rho\,\mathcal{A}_{\Lambda_c^+\bar{D}^0\to J/\psi p}$$

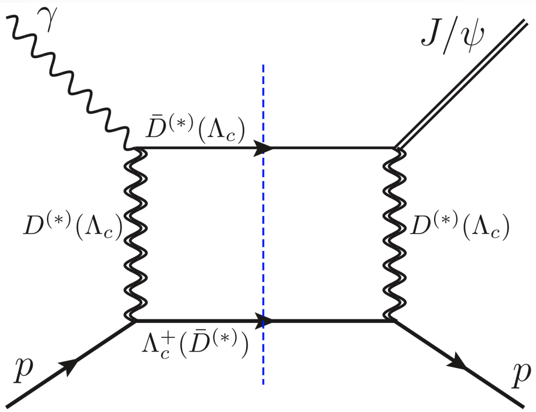
The two tree diagrams valuated by phomenological models

At the $\Lambda_c^+\bar{D}^0$ threshold,

choosing $\rho(s=(m_{J/\psi}+m_p)^2)$, and $\mathcal{A}_{\gamma p\to J/\psi p}\sim \mathrm{Im}\mathcal{A}_{\gamma p\to J/\psi p}$,

$\Rightarrow$ $\sigma \sim 1$ nb

Effective Lagrangian and couplings



Feynman diagram for the proposed CC mechanism

$$\begin{aligned}
\mathcal{L}_{\Lambda_c DN} &= -g_{D^*N\Lambda_c}\bar{\Lambda}_c\gamma_\mu N D^{*\mu} - i g_{DN\Lambda_c}\bar{\Lambda}_c\gamma_5 N D \\
&\quad -g_{D^*N\Lambda_c}\bar{N}\gamma_\mu\Lambda_c D^{*\mu\dagger} - i g_{DN\Lambda_c}\bar{N}\gamma_5\Lambda_c D^\dagger, \quad (1)\\
\mathcal{L}_\psi &= -g_{\psi DD^*}\psi_\mu\epsilon_{\mu\nu\alpha\beta}\left(\partial_\nu D^*_\alpha\partial_\beta D^\dagger - \partial_\nu D\partial_\beta D^{*\dagger}_\alpha\right),\\
&\quad + i g_{\psi D^*D^*}\psi^\mu\left(D^{*\nu}\partial_\nu D^{*\dagger}_\mu - \partial_\nu D^*_\mu D^{*\nu\dagger}\right.\\
&\quad \left. -D^{*\nu}\overleftrightarrow{\partial}_\mu D^{*\dagger}_\nu\right) - i g_{\psi DD} D^\dagger\overleftrightarrow{\partial}_\mu D\psi^\mu\\
&\quad + g_{\psi\Lambda_c\Lambda_c}\bar{\Lambda}_c\gamma_\mu\psi^\mu\Lambda_c, \quad (2)\\
\mathcal{L}_\gamma &= -g_{\gamma DD^*}F_{\mu\nu}\epsilon^{\mu\nu\alpha\beta}\left(D^*_\alpha\overleftrightarrow{\partial}_\beta D^\dagger - D\overleftrightarrow{\partial}_\beta D^{*\dagger}_\alpha\right)\\
&\quad - i g_{\gamma D^*D^*}F^{\mu\nu}D^{*\dagger}_\mu D^*_\nu - e\bar{\Lambda}_c\gamma_\mu A^\mu\Lambda, \quad (3)
\end{aligned}$$

TABLE I. Values of the couplings in the Lagrangians in Eqs. (1)-(3) used in the calculation.

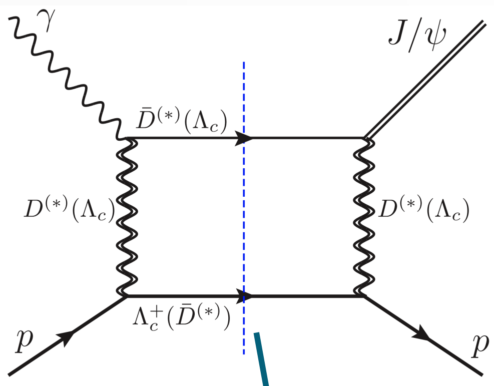
Coupling	$g_{\gamma DD^*}$	$g_{\gamma D^*D^*}$	$g_{DN\Lambda_c}$	$g_{D^*N\Lambda_c}$	$g_{\psi\Lambda_c\Lambda_c}$	$g_{\psi DD}$
Value	0.134 GeV^{-1}	0.641	-4.3	-13.2	-1.4	7.44
Source	Experimental data [44]		SU(4) [45, 46]			VMD [45, 46]

1. The magnetic coupling for $\gamma D^{(*)}D^*$ determined by the width of $D^{*0}\to D^0\gamma$.

2. HQSS: $g_{\psi DD} = g_2 m_D\sqrt{m_{J/\psi}}$,
$g_{\psi DD^*} = g_2\sqrt{m_{J/\psi}m_D/m_{D^*}}$,
$g_{\psi D^*D^*} = g_2 m_{D^*}\sqrt{m_{J/\psi}}$.

[44] P. A. Zyla *et al.* [Particle Data Group], PTEP **2020**, 083C01 (2020).
[45] W. Liu, C. M. Ko and Z. W. Lin, nucl-th/0107058.
[46] Y. Oh, W. Liu and C. M. Ko, Phys. Rev. C **75**, 064903 (2007) [nucl-th/0702077].

Estimate the box diagram



Feynman diagram for the proposed CC mechanism

S-wave

$$= \frac{1}{\pi}\int_{\rm th}^{s_{\rm cut}} \frac{\mathcal{A}_{\gamma p\to\Lambda_c^+\bar{D}^{(*)0}}(s')\rho(s')\mathcal{A}_{J/\psi p\to\Lambda_c^+\bar{D}^{(*)0}}(s')}{s'-s}ds'$$

$$\sqrt{s_{\rm cut}} = \sqrt{q_{\rm max}^2+m_{\Lambda_c}^2}+\sqrt{q_{\rm max}^2+m_D^2}$$

The exchanged particles (doubly-wavy) are off-shell with a potentially large virtuality:

$$F(t) = \frac{\Lambda^2-m_{\rm ex}^2}{\Lambda^2-t}$$

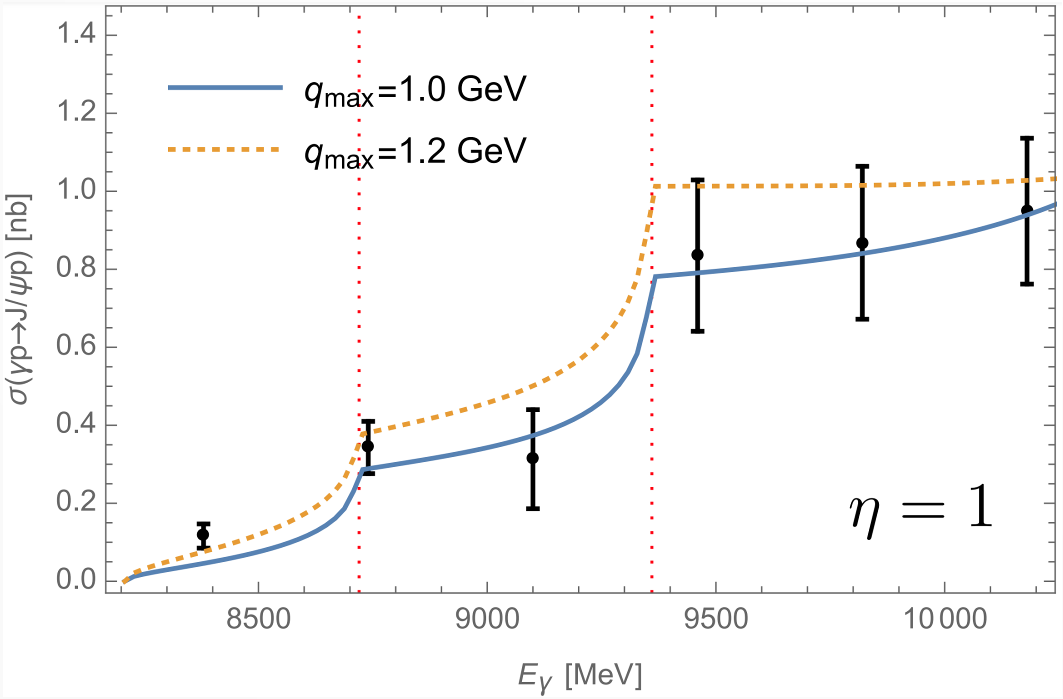
Λ:~ the mass of the lowest neglected exchange particles

$$\Lambda = m_{\rm ex}+\eta\Lambda_{\rm QCD}, \qquad \Lambda_{\rm QCD} = 250\ {\rm MeV}$$

$$\eta \sim 1$$

Comparison with data [GlueX (2019)]

MLD, Baru, *et. al.*, EPJC 80 (2020) 1053



No parameter is fitted or fine-tuned!

1. Right order of magnitude;

2. It demonstrate a shape compatible with the data;

3. It hints at the importance of the CC mechanism to the J/ψ photoproduction.

The approach suffers from several uncertianties:

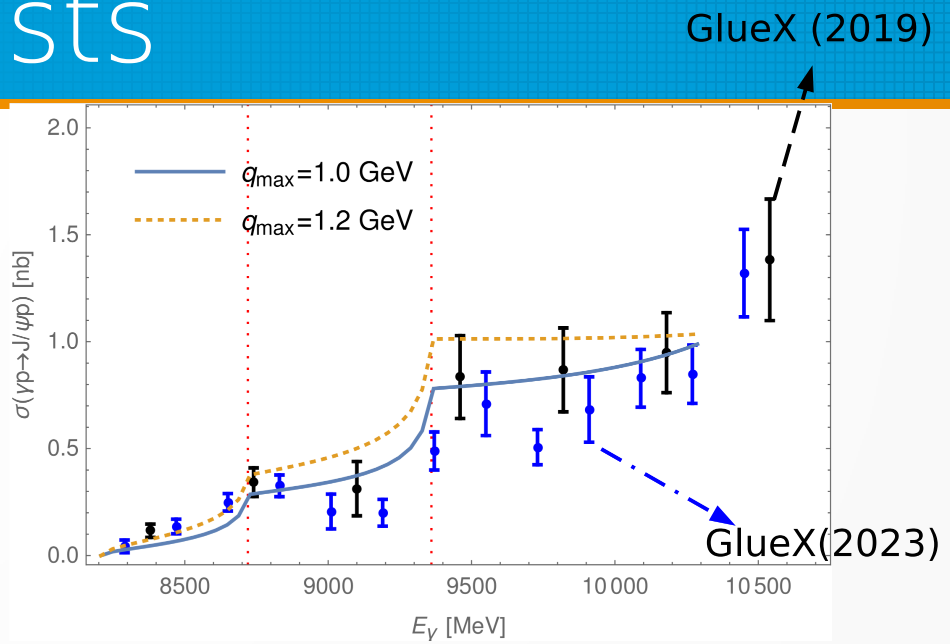
1. Badly determined couplings
2. Form factors
3. A limited set of diagrams

   ...

Predictions and possible tests

- Threshold cusps (unique signature of CC mechanism):

  sizeable cusps at the $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ thresholds.

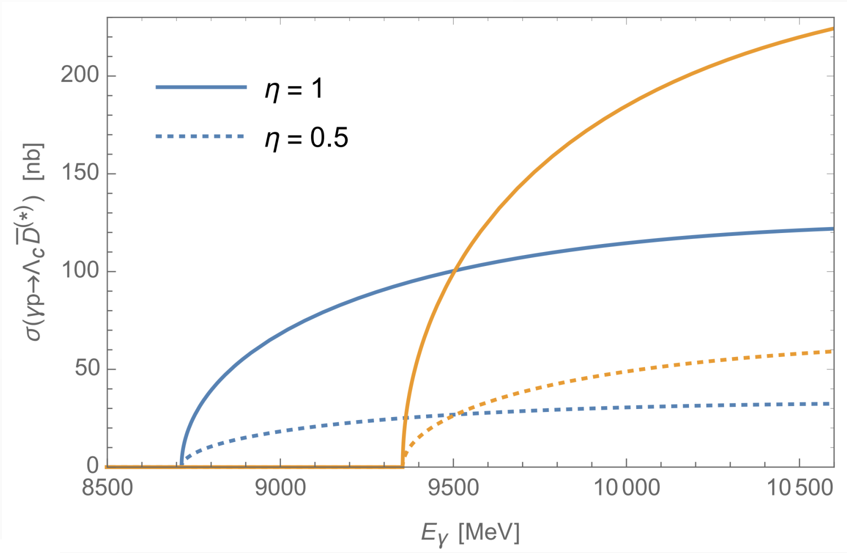


- Production of open-charm final states:

  an order-of-magnitude estimate

  larger than the estimate from s-channel P_c and t-channel D^* exchange using VMD.

  J.-J. Wu, T.-S.H. Lee, and B.-S. Zou, PRC100(2019)035026



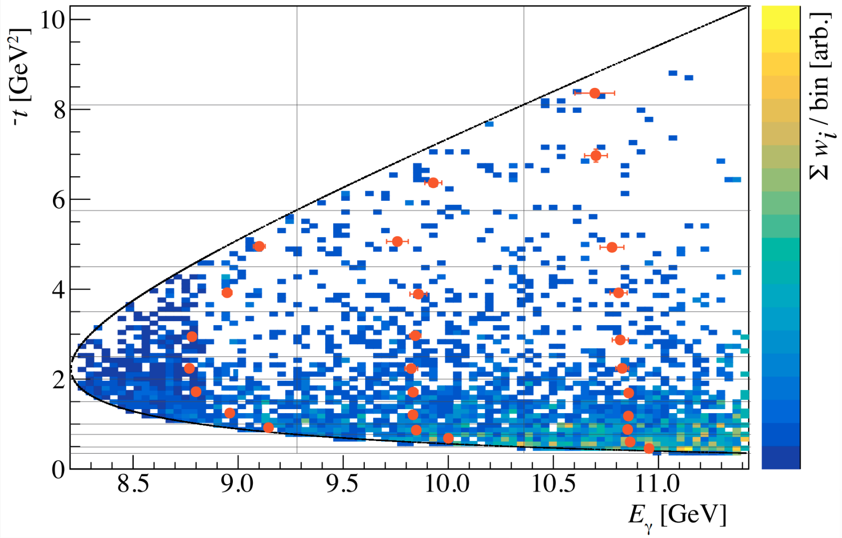
- J/ψ-proton scattering lengths (η =[0.5,2])

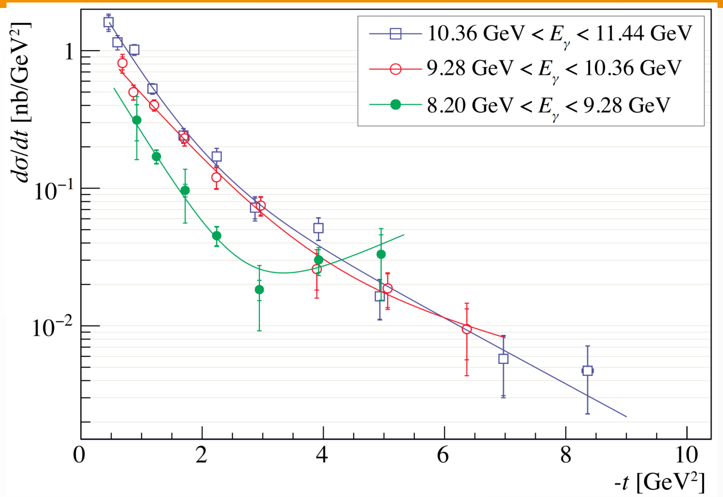
$$\left|a^{J=1/2}\right| = 0.2\ldots3.1 \text{ mfm}, \quad \left|a^{J=3/2}\right| = 0.2\ldots3.0 \text{ mfm},$$

comparable with that from the VMD model (with GlueX data)
much smaller than the 2-gluon exchange using the multipole expansion

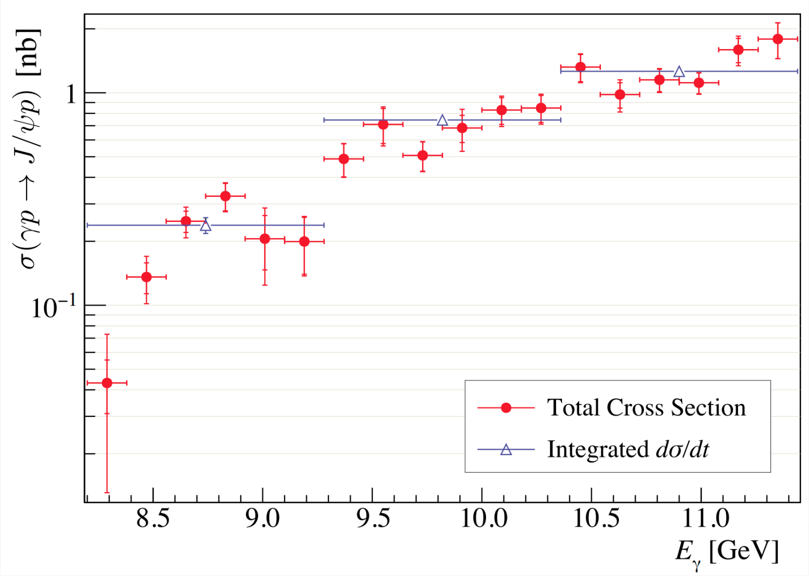
GlueX (2023) [GlueX, PRC 108(2023)025201]

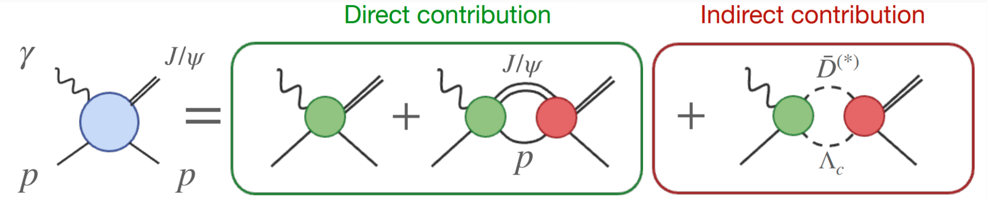
Talk by Z. Zhang





T-dependence implies important contributions from partial waves rather than S-wave.



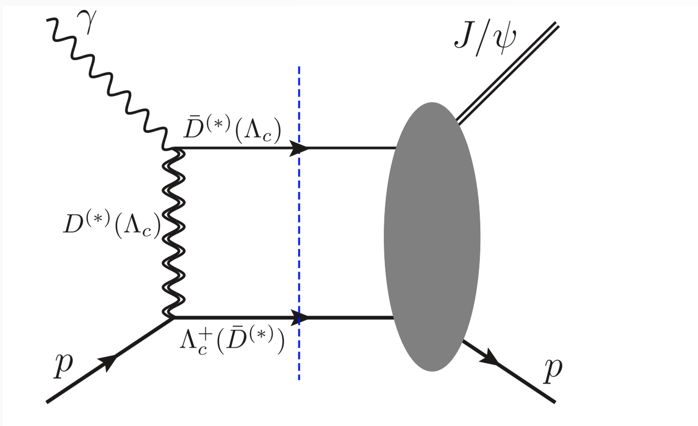


1. Described by a few partial waves enforcing low-energy unitarity
2. A nonnegligible contribution from $\Lambda_c \bar{D}^{(*)}$

JPAC, PRD108(2023)054018

See A. Pilloni's talk

Revisit the CC photoproduction mechanism



Feynman diagram for the proposed CC mechanism

In order to describe the t-dependence, we introduce P-wave and D-wave:

P-wave

$$g_P(\epsilon\cdot\epsilon^* p_\gamma\cdot p_\psi - \epsilon\cdot p_\psi \epsilon^*\cdot p_\gamma)\bar{u}u$$

D-wave

$$g_D\epsilon\cdot\epsilon^*((\mathbf{p}_\gamma\cdot\mathbf{p}_\psi)^2 - 3\mathbf{p}_\gamma^2\mathbf{p}_\psi^2)\bar{u}u$$

S-wave

1. The S-wave $\Lambda_c\bar{D}^{(*)}$ expressed in terms of $|s_Q\otimes j_\ell\rangle$,

$$|\Lambda_c\bar{D}\rangle_{J=1/2} = -\frac{1}{2}|0\otimes\frac{1}{2}\rangle + \frac{\sqrt{3}}{2}|1\otimes\frac{1}{2}\rangle,$$

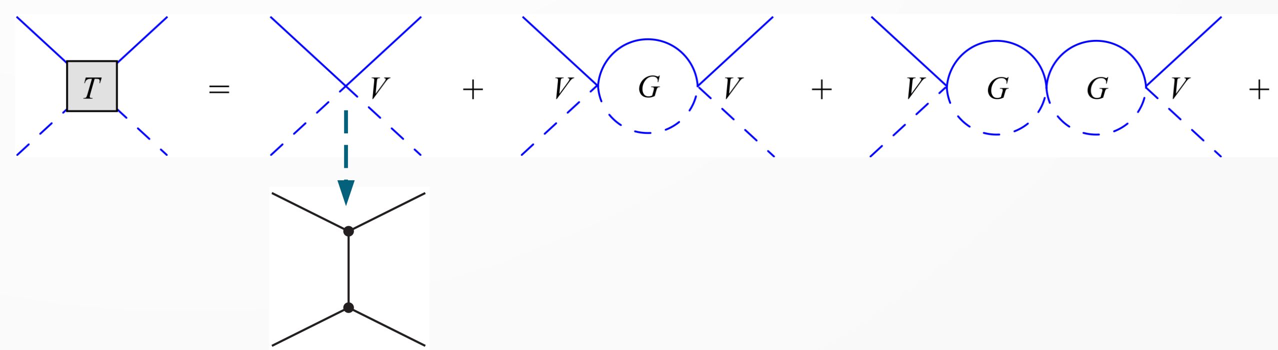
$$|\Lambda_c\bar{D}^*\rangle_{J=1/2} = \frac{\sqrt{3}}{2}|0\otimes\frac{1}{2}\rangle + \frac{1}{2}|1\otimes\frac{1}{2}\rangle,$$

$$|\Lambda_c\bar{D}^*\rangle_{J=3/2} = |1\otimes\frac{1}{2}\rangle.$$

$$|J/\psi p\rangle_S = |1\otimes\frac{1}{2}\rangle, \qquad |J/\psi p\rangle_D = |1\otimes\frac{3}{2}\rangle.$$

Only S-wave $J/\psi p$ survives in the HQ limit.

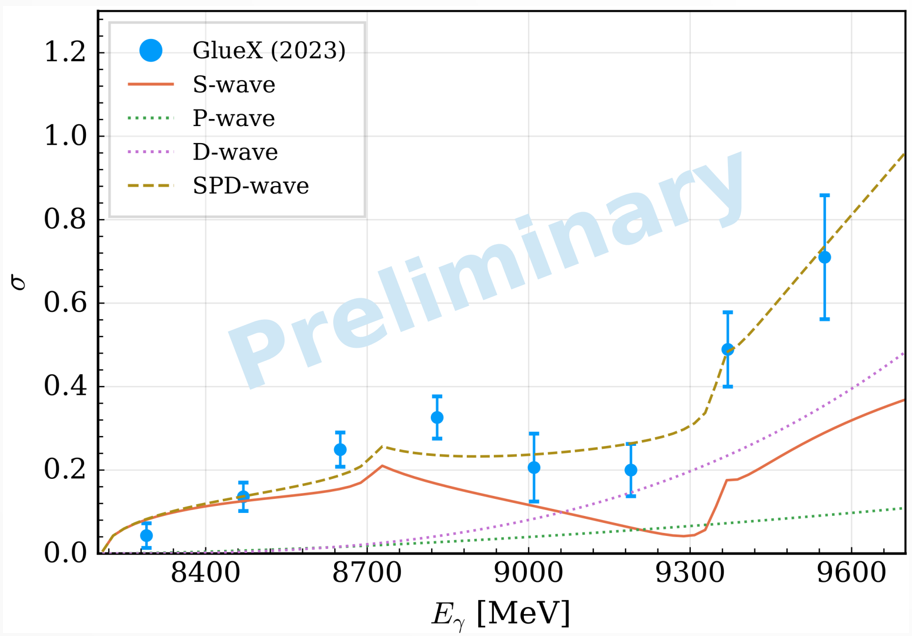
2. Low-energy unitarity:



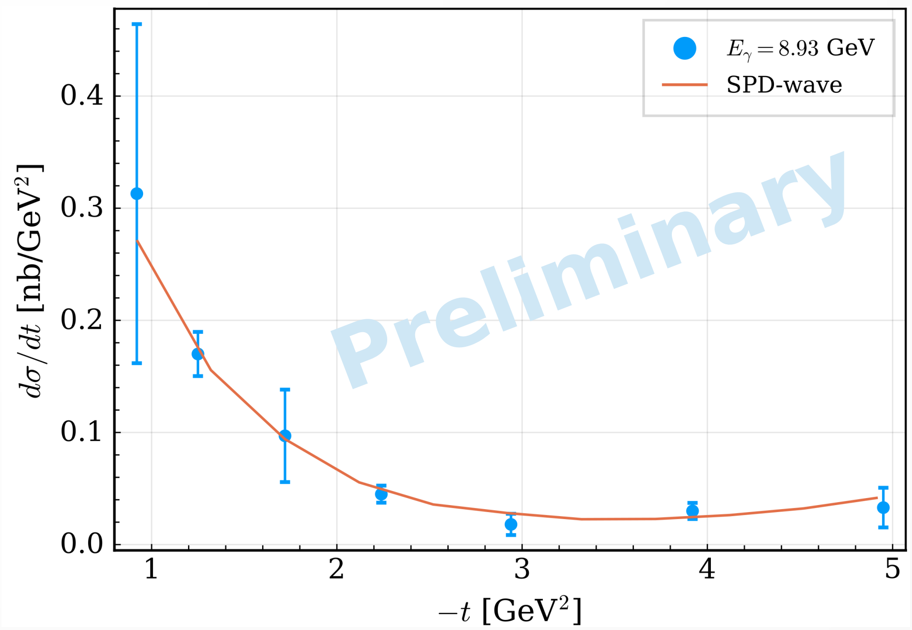
3. Parameterizing the transition: $V_{\Lambda_c\bar{D}^{(*)}\to\Lambda_c\bar{D}^{(*)}} = C$

The potentials for other channels are evaluated by t-channel $D^{(*)}$ and u-channel Λ_c exchange.

Comparison with data [GlueX 2023]



Preliminary Results

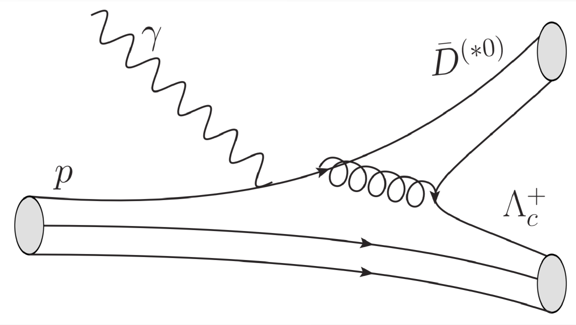


Coupling	$g_{\gamma DD^*}$	$g_{\gamma D^* D^*}$	$g_{DN\Lambda_c}$	$g_{D^* N\Lambda_c}$	$g_{\psi\Lambda_c\Lambda_c}$	$g_{\psi DD}$
Value	0.134 GeV^{-1}	0.641	Fit parameters $\sim O(1)$			
Source	Experimental data [44]					

1. No poles are found in near-threshold region.
2. $\left|a^{J=1/2}\right| \sim [0,1]$ mfm, $\left|a^{J=3/2}\right| \sim [0,8]$ mfm. ?

Summary and outlook

- We have briefly reviewed the VMD model which relates the trace anomaly to the quarkonium photoproduction.
- A novel CC production mechanism via $\Lambda_c \bar{D}^{(*)}$ intermediate states could be important for the J/ψ photoproduction.
  - If the CC mechanism indeed dominate the J/ψ -nucleon scattering, the connection between the trace anomaly and the J/ψ -nucleon scattering length is lost.



- With the natural values of couplings, the experimental data on the J/ψ photoproduction can be described.
- The unique feature of the mechanism: threshold cusps!
- More experimental data should either consolidate or falsify the picture.
- The mechanism also implies the J/ψ-nucleon scattering length of order 1 mfm.
- To extend to higher energies, $\Sigma_c^{(*)} \bar{D}^{(*)}$ needs to be included, the pentaquark involve.

Thank you very much for your attention!

第七届强子谱与强子结构研讨会

电子科技大学 @ 成都   2024.4.26-30

https://indico.itp.ac.cn/event/200/

Thank you very much for your attention!