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Production of Λ_c states and $(\bar{D}N)$ states at EicC and EIC

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Based on Kai-Sa Qiao, Bing-Song Zou, arXiv:2412.03216

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Content

- Background
    - Λ_c Photo- and Electro-production in experiment
    - Brief introduction of EicC and EIC
    - Spin-parity assignment of $\Lambda_c(2940)$
- The equivalent photon approximation
- Photoproduction —— $\Lambda_c, \Lambda_c(2595), \Lambda_c(2940), (\bar{D}N)$
    - Coupling constants
        - $^3P_0$ model
        - Hadronic molecule
- Results
    - Photoproduction
    - Electroproduction at EicC and EIC
- Summary

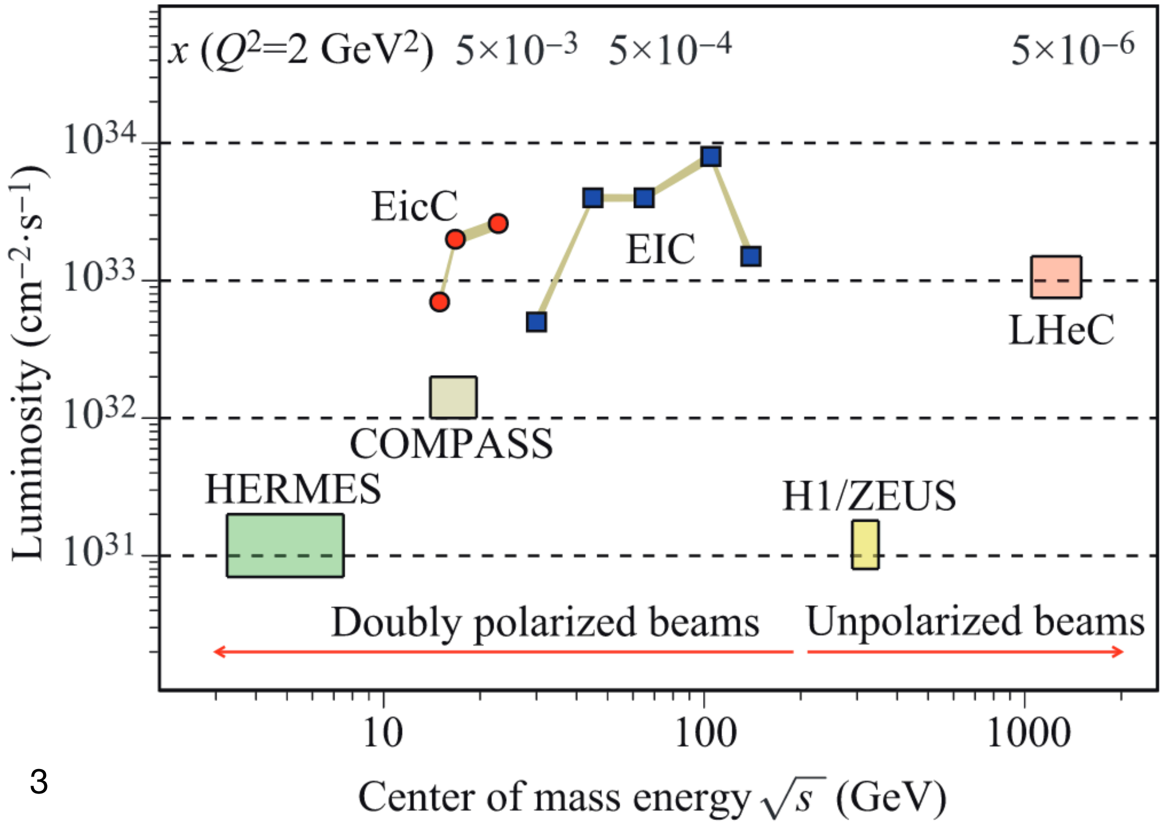
Background

Λ_c Photo- and Electro-production in experiment

Production	Time	Experiment	Particle
Photo-	1987	NA1 at CERN	9 Λ_c
	1990	NA14/2 at CERN	$29\pm8\ \Lambda_c(\bar{\Lambda}_c)$
	1993	E687 at Fermilab	1340 Λ_c
	1994	E687 at Fermilab	$39.7\pm8.7\ \Lambda_c(2625)$
Electro-	2005	ZEUS at HERA	$1440\pm220\ \Lambda_c$
	2013	ZEUS at HERA	$7682\pm964\ \Lambda_c$

EicC and EIC

- Estimate the yields of hadronic molecule candidates at EicC and EIC.
- Estimate the yields of candidates using both the **hadronic molecule** model and the **quark model** to determine whether it helps distinguish the particle **structures**.

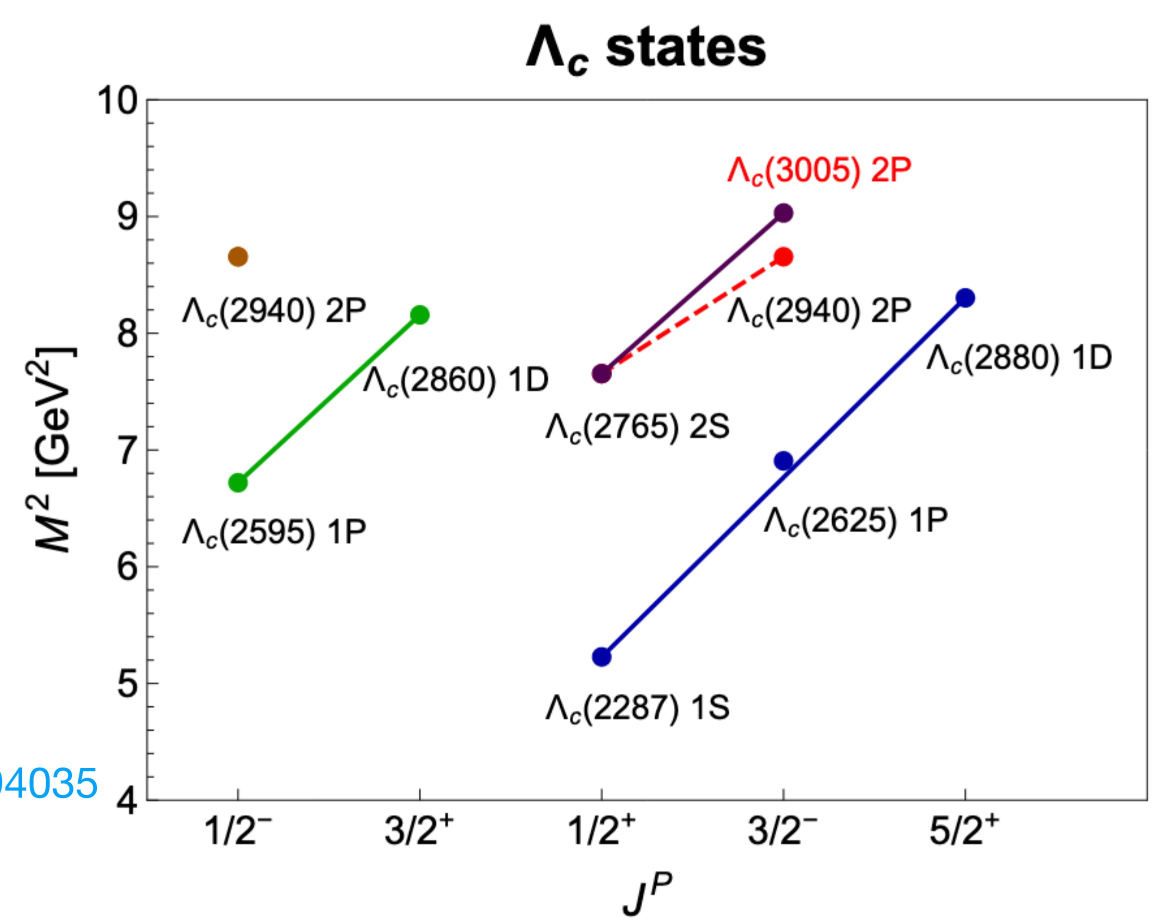


Background

spin-parity assignment of $\Lambda_c(2940)$

- Observed in the D^0p invariant mass distribution by the BaBar Collaboration(2007).
- spin-parity assignment is quite diverse
  - $\frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}, \frac{5}{2}^{\pm}, \frac{7}{2}^{+}$ Details see: H.-X. Chen *et al.*, Rep. Prog. Phys. **80**, 076201 (2017)
  - The closest states in quark model
    - $\Lambda_c(\frac{1}{2}^-, 2P)$, $\Lambda_c(\frac{3}{2}^-, 2P)$

      40 MeV and 60 MeV higher than $\Lambda_c(2940)$
  - Hadronic molecule
    - $1/2^-$
      X.-G. He *et al.*, Eur. Phys. J. C **51**, 883 (2007).
    - $1/2^+$
      Y. Dong *et al.*, Phys. Rev. D **81**, 014006 (2010).
    - $\Lambda_c(2910) : 1/2^-, \Lambda_c(2940) : 3/2^-$
      Z.-L. Yue, Q.-Y. Guo, and D.-Y. Chen, (2024).
    - $\Lambda_c(2940) : 1/2^-, 3/2^-$
      B. Wang, L. Meng, and S.-L. Zhu, Phys. Rev. D **101**, 094035 (2020).
  - Regge trajectories
    H.-Y. Cheng, (2022).



The equivalent photon approximation

Weizsäcker-Williams' method

- Ultra-relativistic electroproduction can be calculated using the Weizsäcker-Williams' method

  - $d\sigma_{ep} = \sigma_\gamma(\omega) dn(\omega, q^2)$

- The equivalent photon number or spectrum, dn, is defined by the $e \to e'\gamma^*$ vertex. In numerous cases that $\omega \gtrsim \Lambda_\gamma$:

$$dn(\omega, q^2) = \frac{\alpha}{\pi}\frac{d\omega}{\omega}\frac{d(-q^2)}{|q^2|}\ [1 - \frac{\omega}{E} + \frac{\omega^2}{2E^2} - (1 - \frac{\omega}{E})|\frac{q^2_{min}}{q^2}|]$$

- After integrate q^2: $q^2_{min} \leqslant -q^2 \leqslant q^2_{max}$:

$$d\sigma = \sigma_\gamma(\omega) dn(\omega)$$

$$dn(\omega) = \int_{q^2_{min}}^{q^2_{max}} dn(\omega, q^2) = N(\omega)\omega d\omega$$

$$N(\omega) = \frac{\alpha}{\pi}[(1 - \frac{\omega}{E} + \frac{\omega^2}{2E^2}) \ln \frac{\Lambda_\gamma^2 E(E-\omega)}{m_e^2 \omega^2} - (1 - \frac{\omega}{E})]$$

V. M. Budnev *et al.*, Physics Reports **15**, 181 (1975).

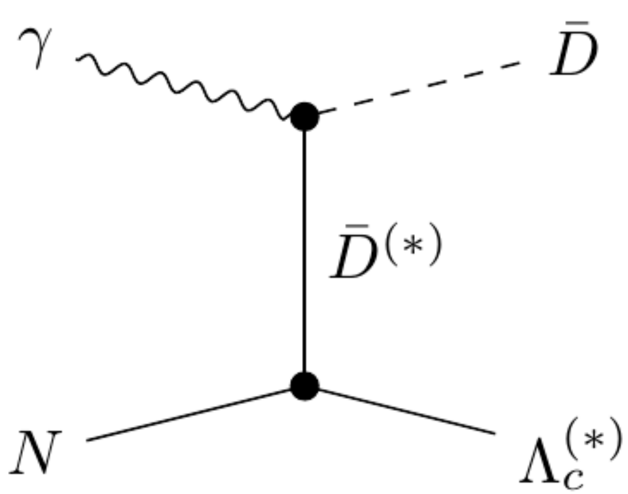
Y. Jia *et al.*, Phys. Rev. D **108**, 016015 (2023).

Λ_c states photoproduction

Λ_c, $\Lambda_c(2595)$, $\Lambda_c(2940)$

- Consider the dominant contribution channel: t-channel.

$$\gamma + p \to \bar{D}^0 + \Lambda_c^{(*)+}$$



Quantum number:

$\Lambda_c : 1/2^+$

$\Lambda_c(2595) : (\frac{1}{2}^-, 1P)$

$\Lambda_c(2940)$ molecule: $\frac{1}{2}^-$; quark model: $(\frac{1}{2}^-, 2P)$

Effective Lagrangians:

$$\mathcal{L}_{ND\Lambda_c(1/2^+)} = ig_{ND\Lambda_c}\bar{\Lambda}_c\gamma_5 ND + H.c.,$$

$$\mathcal{L}_{ND^*\Lambda_c(1/2^+)} = g_{ND^*\Lambda_c}\bar{\Lambda}_c\gamma_\mu ND^{*\mu} + H.c.,$$

$$\mathcal{L}_{ND\Lambda_c^*(1/2^-)} = g^{1/2^-}_{ND\Lambda_c^*} i\bar{\Lambda}_c^* ND + H.c.,$$

$$\mathcal{L}_{ND^*\Lambda_c^*(1/2^-)} = g^{1/2^-}_{ND^*\Lambda_c^*}\bar{\Lambda}_c^*\gamma_5\gamma_\mu ND^{*\mu} + H.c.,$$

$$\mathcal{L}_{\gamma NN} = -e\bar{N}(Q_N \not{A} + \frac{\kappa_N}{4m_N}\sigma^{\mu\nu}F_{\mu\nu})N,$$

$$\mathcal{L}_{\gamma DD} = ieA_\mu(D^+\partial^\mu D^- - \partial^\mu D^+ D^-),$$

$$\mathcal{L}_{\gamma DD^*} = g_{\gamma DD^*}\epsilon_{\mu\nu\alpha\beta}(\partial^\mu A^\nu)(\partial^\alpha D^{*\beta})D + H.c.,$$

Form factor

$$f_2(q^2) = (\frac{\Lambda_2^2 - m_{ex}^2}{\Lambda_2^2 - q^2})^2$$

Coupling constants

$^3P_0$ model

- Spatial wave function
  - Excitation mode:

$$p_\rho = \frac{1}{\sqrt{2}}(p_1 - p_2)$$

$$p_\lambda = \frac{1}{\sqrt{6}}(p_1 + p_2 - 2p_3)$$

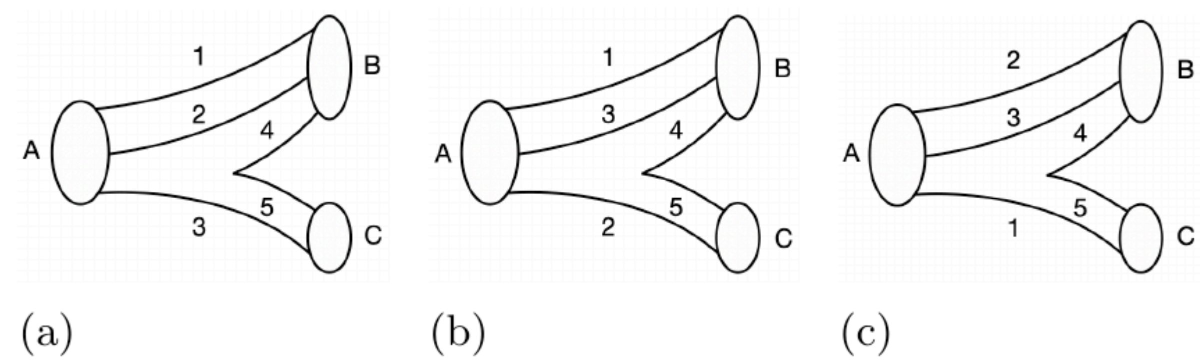
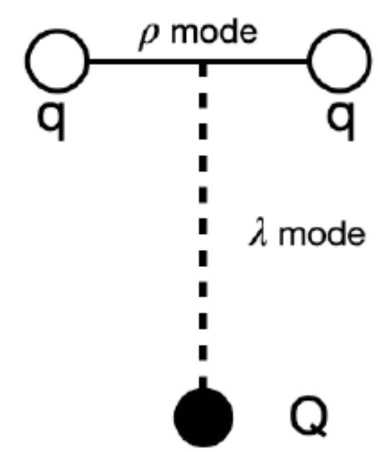


FIG. 3: The Vertex $A \to B + C$ in the $^3P_0$ model



- $\psi_A(\vec{p}) = N\psi_{n_\rho l_\rho m_{l\rho}}(\vec{p}_\rho)\psi_{n_\lambda l_\lambda m_{l\lambda}}(\vec{p}_\lambda)$
- Simple harmonic oscillator(SHO) wave function:
  - $\Psi_{nlm_l}(\boldsymbol{p}) = (-1)^n(-i)^l R^{l+\frac{3}{2}}\sqrt{\frac{2n!}{\Gamma(n+l+\frac{3}{2})}}\exp(-\frac{R^2\boldsymbol{p}^2}{2}) \times L_n^{l+1/2}(R^2\boldsymbol{p}^2)|\boldsymbol{p}|^l Y_{lm_l}(\Omega_p),$
  - $R = 2.5\,\mathrm{GeV}^{-1}$ for light mesons, $R = 1.67\,\mathrm{GeV}^{-1}$for D meson, $R = 1.94\,\mathrm{GeV}^{-1}$ for $D*$ meson
  - $\alpha_\rho = 0.4, \alpha_\lambda = (\frac{3m_Q}{2m_q + m_Q})^{1/4}\alpha_\rho$ for Baryon

Q.-F. Lü *et al.*, Eur. Phys. J. C **78**, 599 (2018).

Coupling constants

$^3P_0$ model

- Transition operator

$$T = -3\gamma \sum_m \langle 1\, m; 1\ -m|0\ 0\rangle \int \mathrm{d}^3\mathbf{k}_4\, \mathrm{d}^3\mathbf{k}_5 \delta^3(\mathbf{k}_4 + \mathbf{k}_5) \times \mathcal{Y}_1^m\left(\frac{\mathbf{k}_4 - \mathbf{k}_5}{2}\right) \chi^{45}_{1,-m}\, \varphi^{45}_0\ \ \omega^{45}_0\ b^\dagger_{4i}(\mathbf{k}_4)\ d^\dagger_{5j}(\mathbf{k}_5)\ (1)$$

- $\gamma = 9.83$ derived from fitting the $\Sigma_c(2520)^{++} \to \Lambda_c + \pi^+$process.

Q.-F. Lü and X.-H. Zhong, Phys. Rev. D **101**, 014017 (2020).

- Effective coupling constant

$$\Gamma = \pi^2 \frac{P}{M_A^2} \frac{\mathcal{S}}{(2J_A+1)} \sum_{M_{J_A}, M_{J_B}, M_{J_C}} |M^{M_{J_A} M_{J_B} M_{J_C}}|^2.$$

$$g_{ABC} = \sqrt{\frac{\sum_{spins} |\mathcal{M}_{^3P_0}(m_A^2, m_B^2, 0)|^2}{\sum_{spins} |\mathcal{M}'_{\mathcal{L}}(m_A^2, m_B^2, 0)|^2} (2\pi)^3}$$

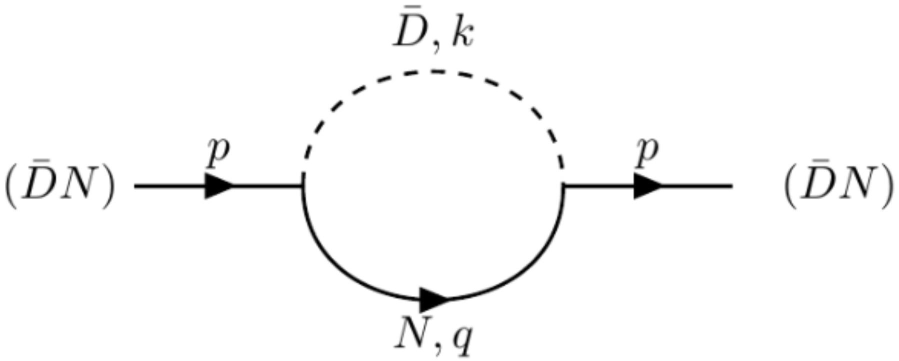
- Independent after summing over the spin index.
- $(2\pi)^3$ stems from the normalization difference.

- Results
- $g_{\Lambda_c^{(*)} D^* p}$:
  - $\Lambda_c(\frac{1}{2}^+, 1s)$, $2286.46:\quad 4.27$
  - $\Lambda_{c1}(\frac{1}{2}^-, 1p)$, $2592.25:\quad 1.21$
  - $\Lambda_{c1}(\frac{1}{2}^-, 2p)$, $2939.6:\quad 0.76$

Coupling constants

Hadronic molecule

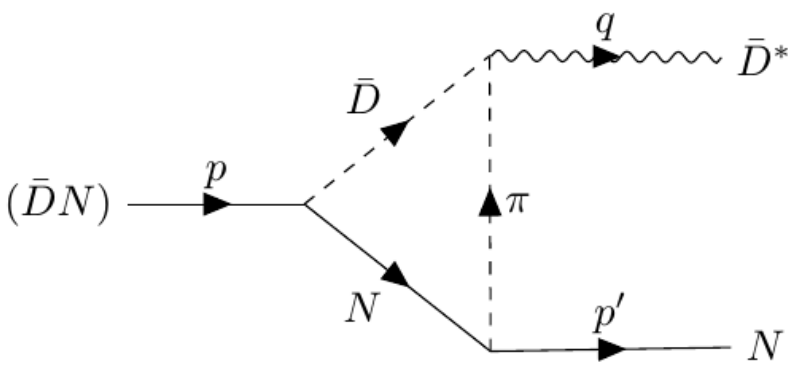
- Mass operators and vertex form factors
  - $Z = 1 - \Sigma'(m^2) = 0$
  - $\gamma_5 \Gamma^\mu(q^2) = \gamma_5[F_1(q^2)\gamma^\mu + F_2(q^2)p^\mu + F_3(q^2)p'^\mu]$



- Form factor in molecule vertex
  - $$\mathcal{L}_{\Lambda_c^*}(x) = g_{\Lambda_c^*} \bar{\Lambda}_c^*(x)\gamma_5\gamma_\mu \int d^4y \Phi(y^2) N(x + w_{D^*N}y) \times D^{*\mu}(x - w_{ND^*}y) + H.c.$$

$$\Phi(y^2) = \int \frac{d^4p}{(2\pi)^4} e^{-ipy} \widetilde{\Phi}(-p^2)$$

$$\tilde{\Phi}(p_E^2) \doteq \exp(-p_E^2/\Lambda^2)$$



Coupling constants

Hadronic molecule

- $\Lambda_c(2940), 1/2^-$

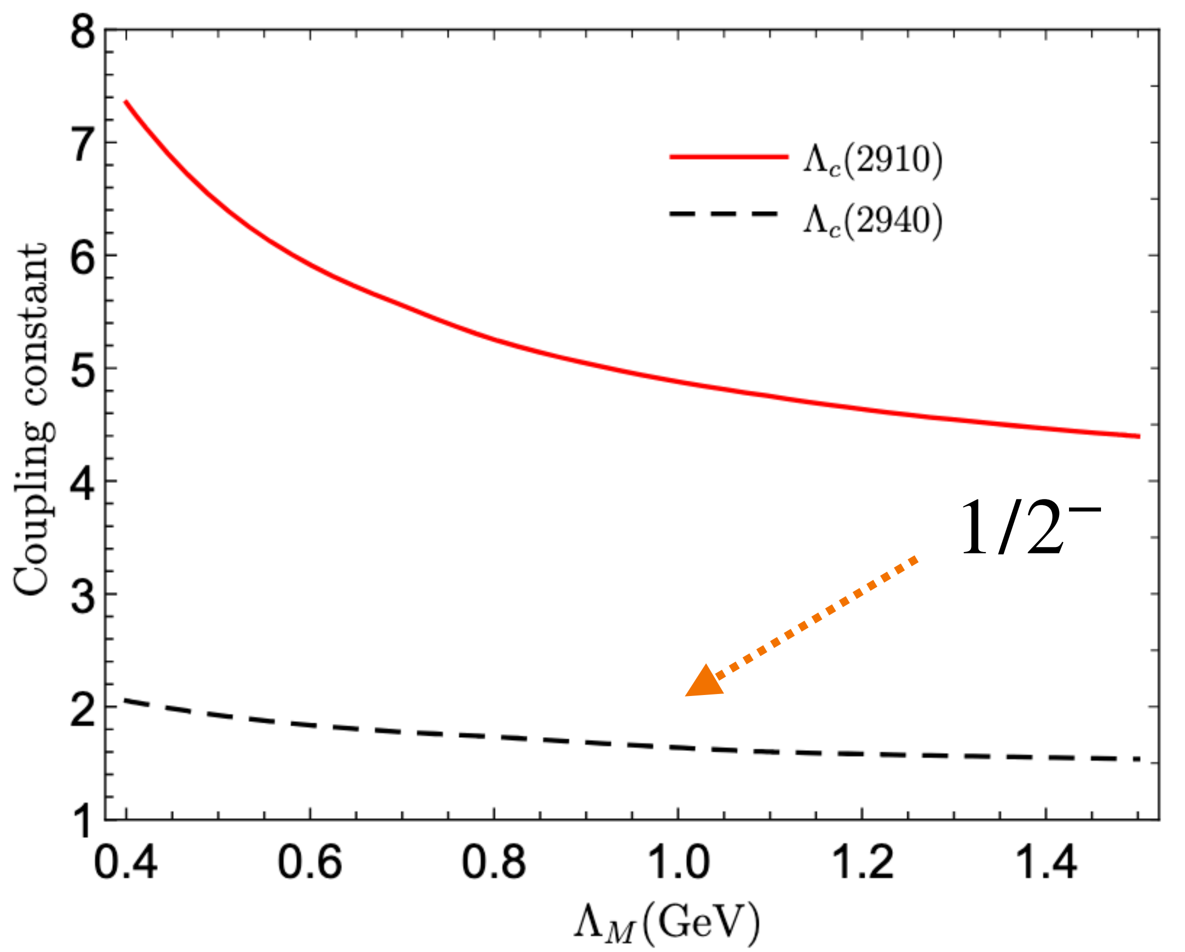
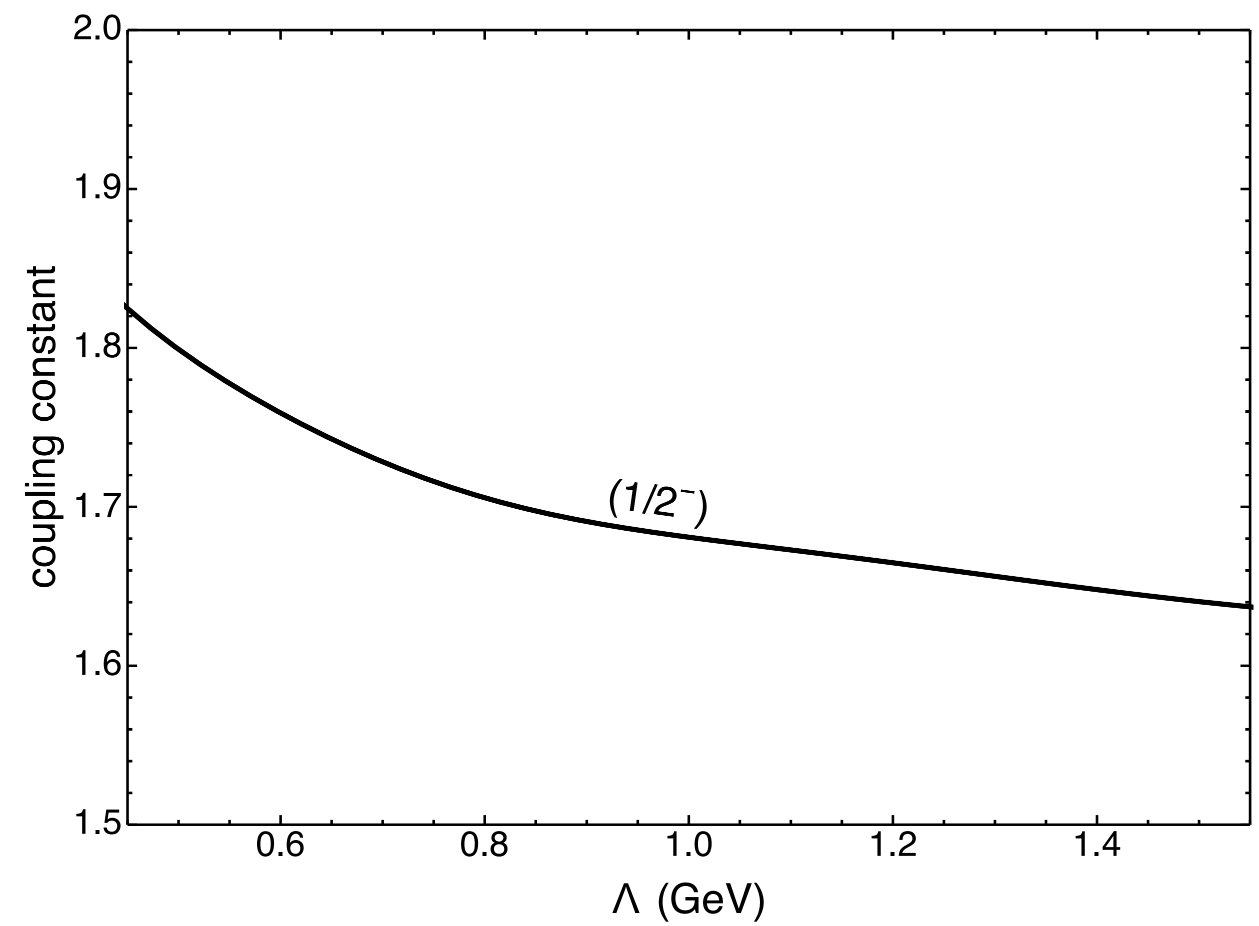


FIG. 7: The coupling constants $g^{1/2}_{\Lambda_c D^* N}$ and $g^{3/2}_{\Lambda_c D^* N}$ depending on the model parameter Λ_M in scenario B.

Z.-L. Yue, Q.-Y. Guo, and D.-Y. Chen, (2024).

- $(\bar{D}N), 1/2^-$



The cutoff is set to be $\Lambda = 1$ GeV.

$$g^{I=0}_{(\bar{D}N)} = 1.68$$

$$g^{I=1}_{(\bar{D}N)} = 2.62$$

Coupling constants

Hadronic molecule $(\bar{D}N) - \bar{D}^*N$ vertex

- Configuration

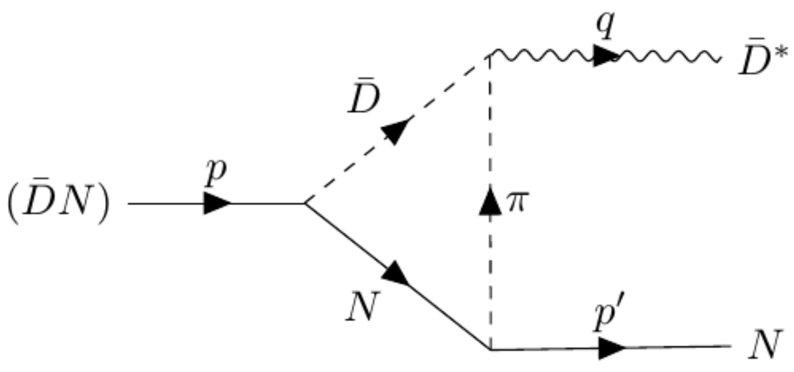
$$|(\bar{D}N), I=0\rangle = \frac{1}{\sqrt{2}}(|D^-p\rangle - |\bar{D}^0 n\rangle)$$

$$|(\bar{D}N), I=1, I_3=0\rangle = \frac{1}{\sqrt{2}}(|D^-p\rangle + |\bar{D}^0 n\rangle)$$

$$\mathcal{L}_{B'BV} = \bar{B'}_1 (g_{B'BV}\gamma_5\gamma_\mu + \frac{f_{B'BV}}{m_1 - m_2}\gamma_5\sigma^{\mu\nu}\partial_\nu) V_\mu B_2 + H.c.$$

$\bar{D}N$	B.E. (MeV)	Mixing ratio (%)	
$0(1/2^-)$	1.38	$\bar{D}N(^2S_{1/2})$	96.1
		$\bar{D}^*N(^2S_{1/2})$	1.94
		$\bar{D}^*N(^4D_{1/2})$	1.93
$1(1/2^-)$	5.99	$\bar{D}N(^2S_{1/2})$	88.9
		$\bar{D}^*N(^2S_{1/2})$	10.9
		$\bar{D}^*N(^4D_{1/2})$	0.11

Y. Yamaguchi, S. Yasui, and A. Hosaka, Phys. Rev. D **106**, 094001 (2022).



- Result

TABLE III: Coupling constants in $(\bar{D}N) - \bar{D}^*N$ vertex. The cutoff is set to $\Lambda = 1$ GeV and $\Lambda_1 = 1$ GeV.

States	I= 0	I= 1
$g_{(\bar{D}N)-\bar{D}^*N}$	0.40	-0.21
$f_{(\bar{D}N)-\bar{D}^*N}$	0.45	-0.24

- Form factor on exchanged particle

$$f_1(q^2) = \frac{\Lambda_1^4}{\Lambda_1^4 + (q^2 - m_{ex}^2)^2}$$

Results - photoproduction

Λ_c, $\Lambda_c(2595)$, $\Lambda_c(2940)$

- Empirically Λ_2 should be larger than m_{ex} by $0.4 \sim 1.0$ GeV
- The impact of the cutoff parameter
  - more than one order of magnitude from 2.4 GeV to 3.0 GeV
  - The ratio remains nearly unchanged in this range.

$$f_2(q^2) = (\frac{\Lambda_2^2 - m_{ex}^2}{\Lambda_2^2 - q^2})^2$$

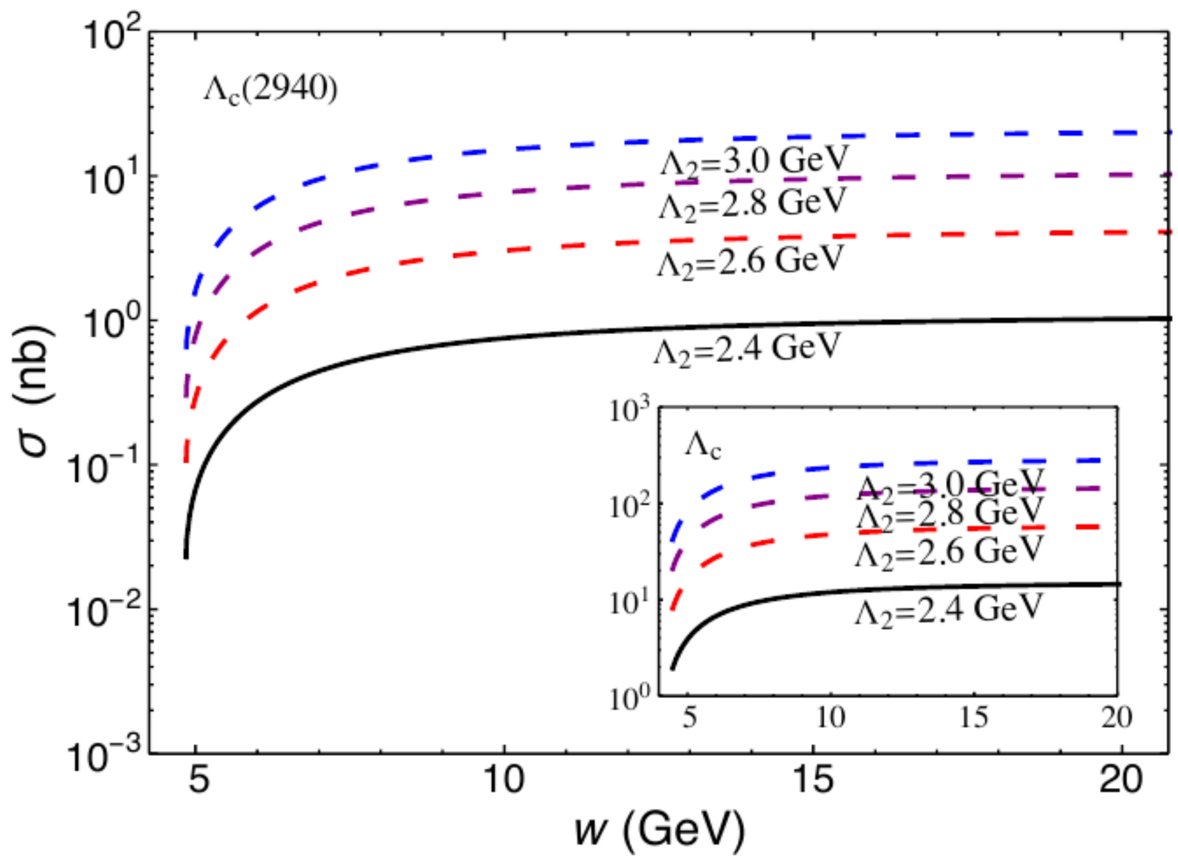


FIG. 5: Cross sections of Λ_c and $\Lambda_c(2940)$ for differen cutoff parameters Λ_2.

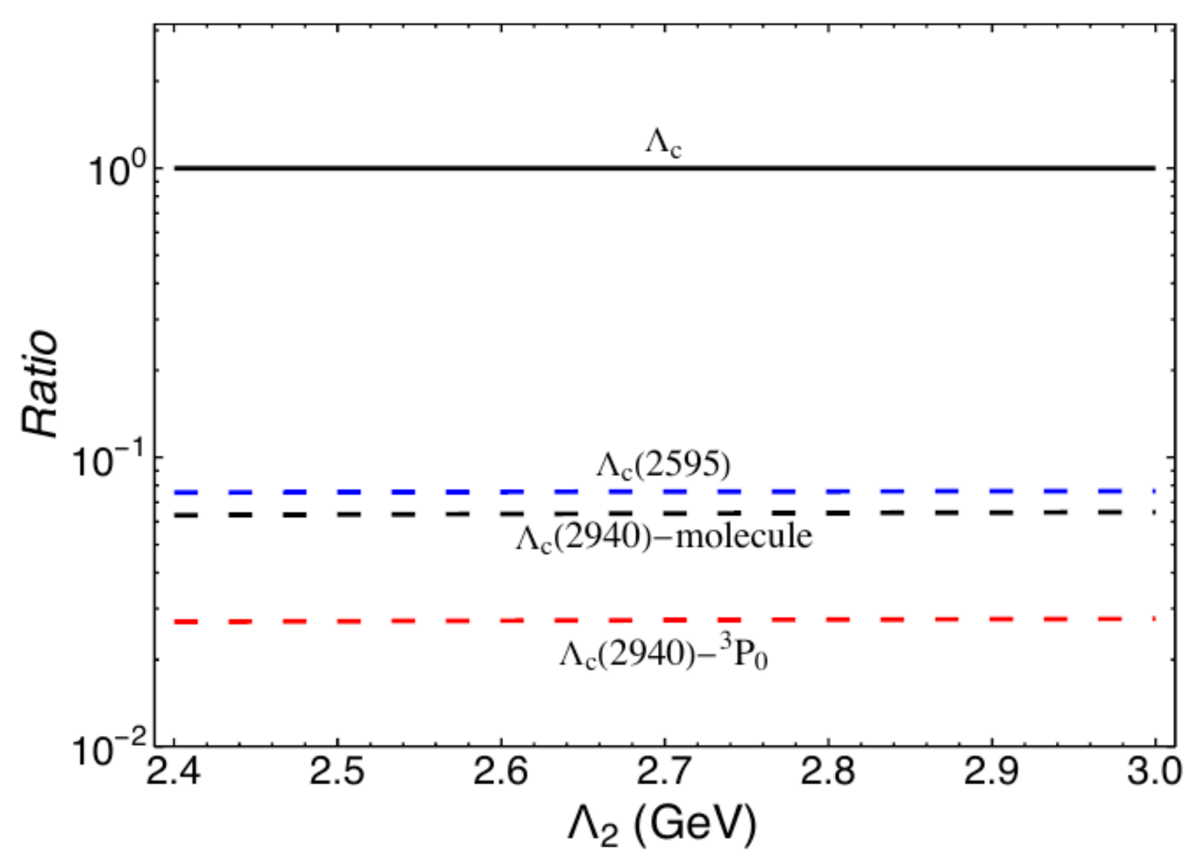


FIG. 6: Ratios of various channels to Λ_c for different cutoffs with $w = 10$ GeV.

Results - photoproduction

Λ_c, $\Lambda_c(2595)$, $\Lambda_c(2940)$ $\gamma + p \to \bar{D}^0 + \Lambda_c^{(*)+}$

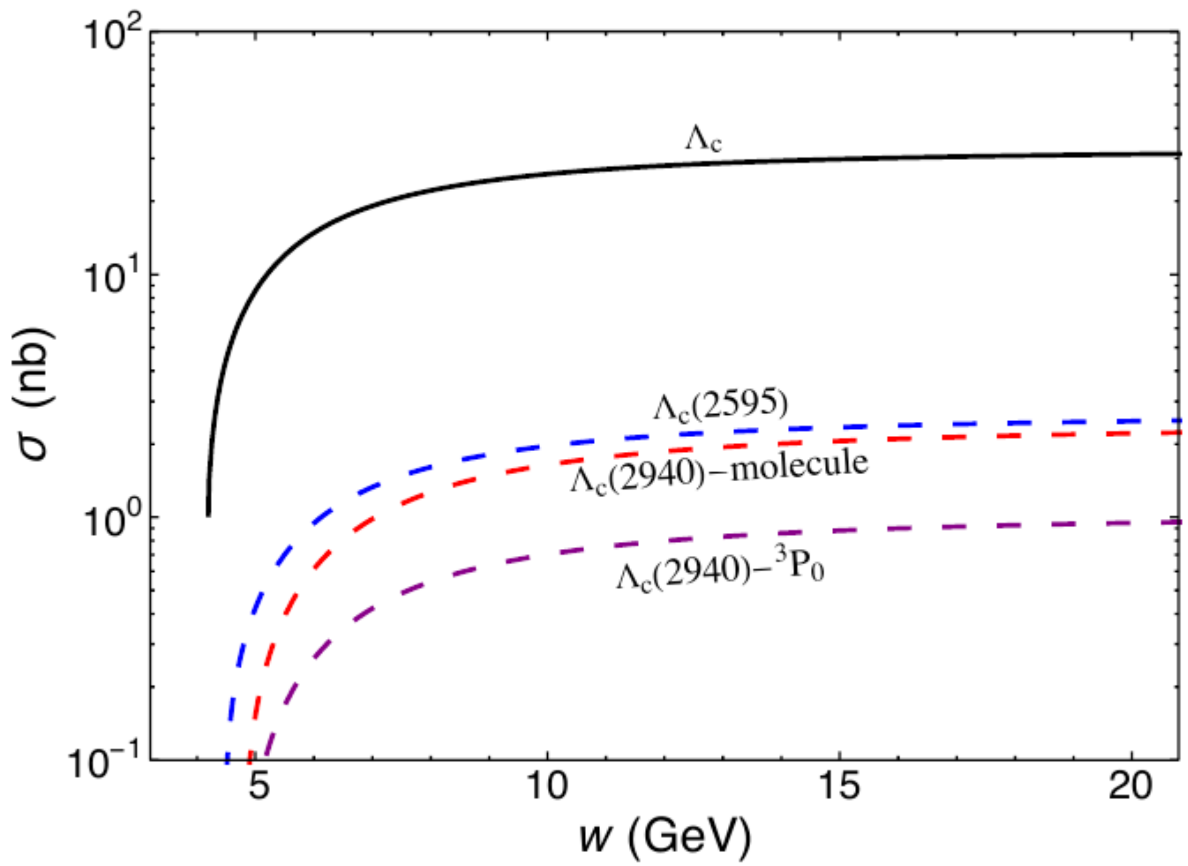


FIG. 7: Photoproduction cross sections of Λ_c, $\Lambda_c(2595)$, and $\Lambda_c(2940)$ in the $^3P_0$ model and the hadronic molecule model within the t-channel of the process $\gamma p \to \bar{D}^0 \Lambda_c^{(*)}$. The cutoff is set to $\Lambda_2 = 2.5$ GeV.

- t-channel D^* exchange of the process $\gamma p \to \bar{D}^0 \Lambda_c^{(*)}$
- $\Lambda_2 = 2.5$ GeV
- The hadronic molecule model shows an enhancing effect on $\Lambda_c(2940)$
  - Remain within the same magnitude range as the quark model predictions.
  - Judging the particle structure based on yields may not be feasible.

Results

$(\bar{D}N)$ states - photoproduction

- Mass

$\bar{D}N$	B.E. (MeV)	Mixing ratio (%)	
$0(1/2^-)$	1.38	$\bar{D}N(^2S_{1/2})$	96.1
		$\bar{D}^*N(^2S_{1/2})$	1.94
		$\bar{D}^*N(^4D_{1/2})$	1.93
$1(1/2^-)$	5.99	$\bar{D}N(^2S_{1/2})$	88.9
		$\bar{D}^*N(^2S_{1/2})$	10.9
		$\bar{D}^*N(^4D_{1/2})$	0.11

$m^{I=0}_{(\bar{D}N)} = 2804.8$ MeV

$m^{I=1}_{(\bar{D}N)} = 2800.2$MeV

Y. Yamaguchi, S. Yasui, and A. Hosaka, Phys. Rev. D **106**, 094001 (2022).

- nearly one order of magnitude lower than the yields of the $\Lambda_c(2940)$ states
  - the disparity between the coupling constants $g_{\gamma D^0 D^{*0}}$ and $g_{\gamma D^+ D^{*+}}$
  - the difference in the dominant contribution channels

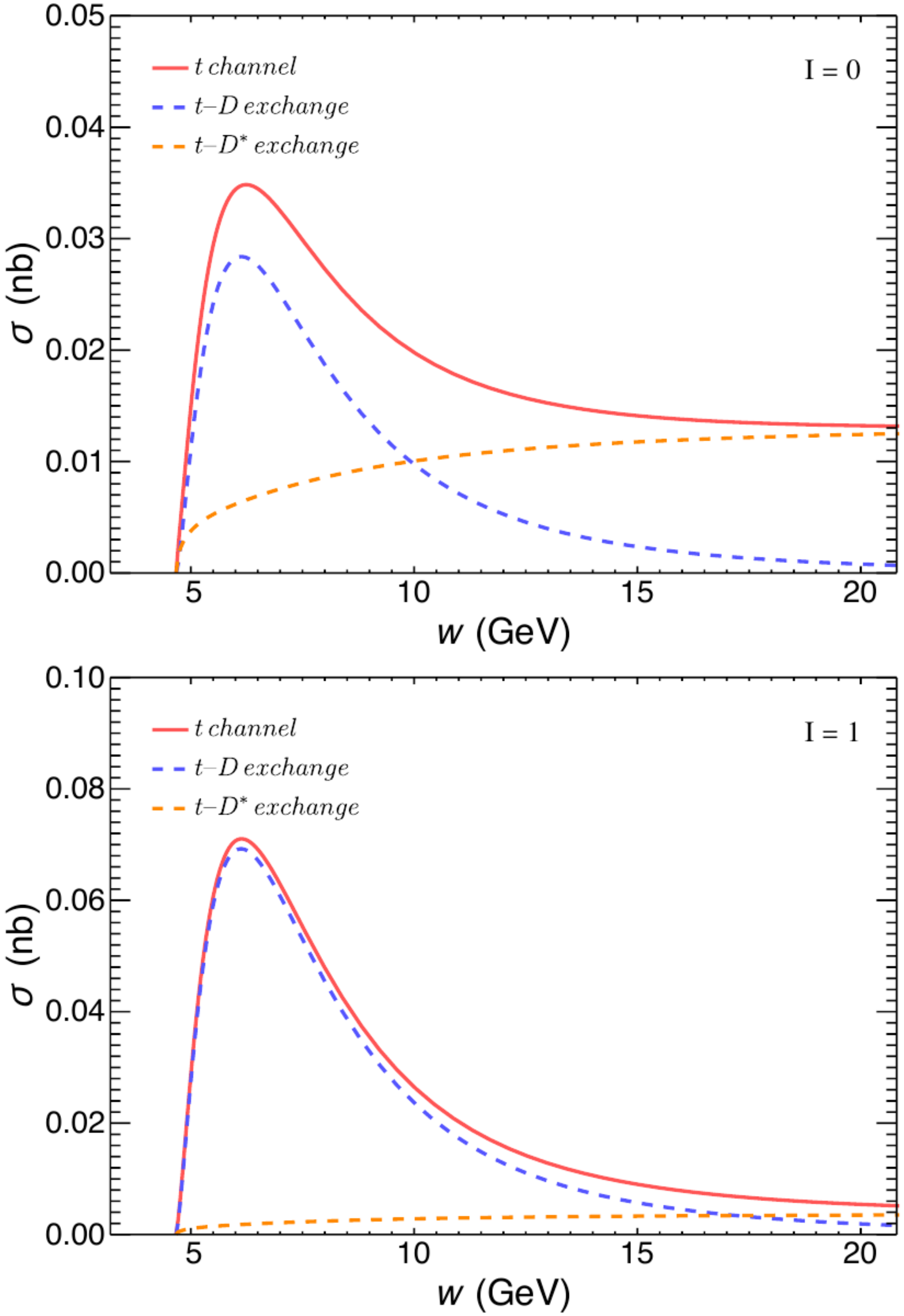


FIG. 8: Cross sections of $\gamma + p \to (\bar{D}N)_I + D^+$ for the $\bar{D}N$ molecules with isospin $I = 0$ and $I = 1$.

Results

Electroproduction at EicC and EIC

Facility	Center-of-Mass Energy(GeV)	Luminosity($cm^{-2} \cdot s^{-1}$)	Integrated Luminosity(fb^{-1})
EicC	15-20	2×10^{33}	50
EIC	20-140	10^{33-34}	10-100

TABLE I: Energy, luminosity, and integrated luminosity for EicC and EIC. Integrated luminosity for EicC corresponds to operating time accounting for 80% of the entire year. Integrated luminosity for EIC corresponds to 30 weeks of operations.

- Λ_c states

TABLE II: Estimated yields for the states Λ_c, $\Lambda_c(2595)$, and $\Lambda_c(2940)$ at EicC and EIC.

State	EicC	EIC
Λ_c	$(6.3 \sim 9.3) \times 10^7$	$(1.9 \sim 8.0) \times 10^8$
$\Lambda_c(2595)$	$(4.3 \sim 6.6) \times 10^6$	$(1.3 \sim 6.1) \times 10^7$
$\Lambda_c(2940)$-molecule	$(3.3 \sim 5.2) \times 10^6$	$(1.1 \sim 5.3) \times 10^7$
$\Lambda_c(2940)$-$^3P_0$	$(1.4 \sim 2.2) \times 10^6$	$(4.5 \sim 2.3) \times 10^7$

- $(\bar{D}N)$ states

TABLE IV: Estimated yields for the state $(\bar{D}N)$ in different isospin configurations at EicC and EIC.

State	Isospin	EicC	EIC
$(\bar{D}N)$	$I = 0$	$(7.5 \sim 9.8) \times 10^4$	$(2.0 \sim 5.3) \times 10^5$
	$I = 1, I_3 = 0$	$(1.3 \sim 1.6) \times 10^5$	$(3.2 \sim 6.0) \times 10^5$

- The yields difference for $(\bar{D}N)$ between EicC and EIC is not significant, while Λ_c states show a difference of an order of magnitude

Summary

- Investigate the Λ_c states, including Λ_c, $\Lambda_c(2595)$, $\Lambda_c(2940)$, and $(\bar{D}N)$ states, in both **photoproduction** and **electroproduction** processes
- The $\Lambda_c(2940)$ is studied in both the **hadronic molecule** model, assigned $J^P = \frac{1}{2}^-$, and the **quark model($^3P_0$)** as the $\Lambda_c(\frac{1}{2}^-, 2P)$state
    - The hadronic molecule model and the $^3P_0$ model predict production yields of the **same order of magnitude**.
        - Distinguishing the structure of $\Lambda_c(2940)$ based on yields may not be feasible.
    - The yields of Λ_c excited states are estimated to reach 10^6 **to** 10^7 at EicC and EIC.
- The yields of the $(\bar{D}N)$ molecules are approximately **one order of magnitude lower** than that of $\Lambda_c(2940)$
    - Yields reach 10^5 at EicC and EIC.

Thank you!