Inclusive productions of hidden/double-charm states at electron-proton facilities

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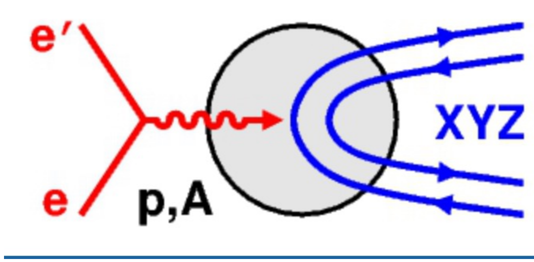
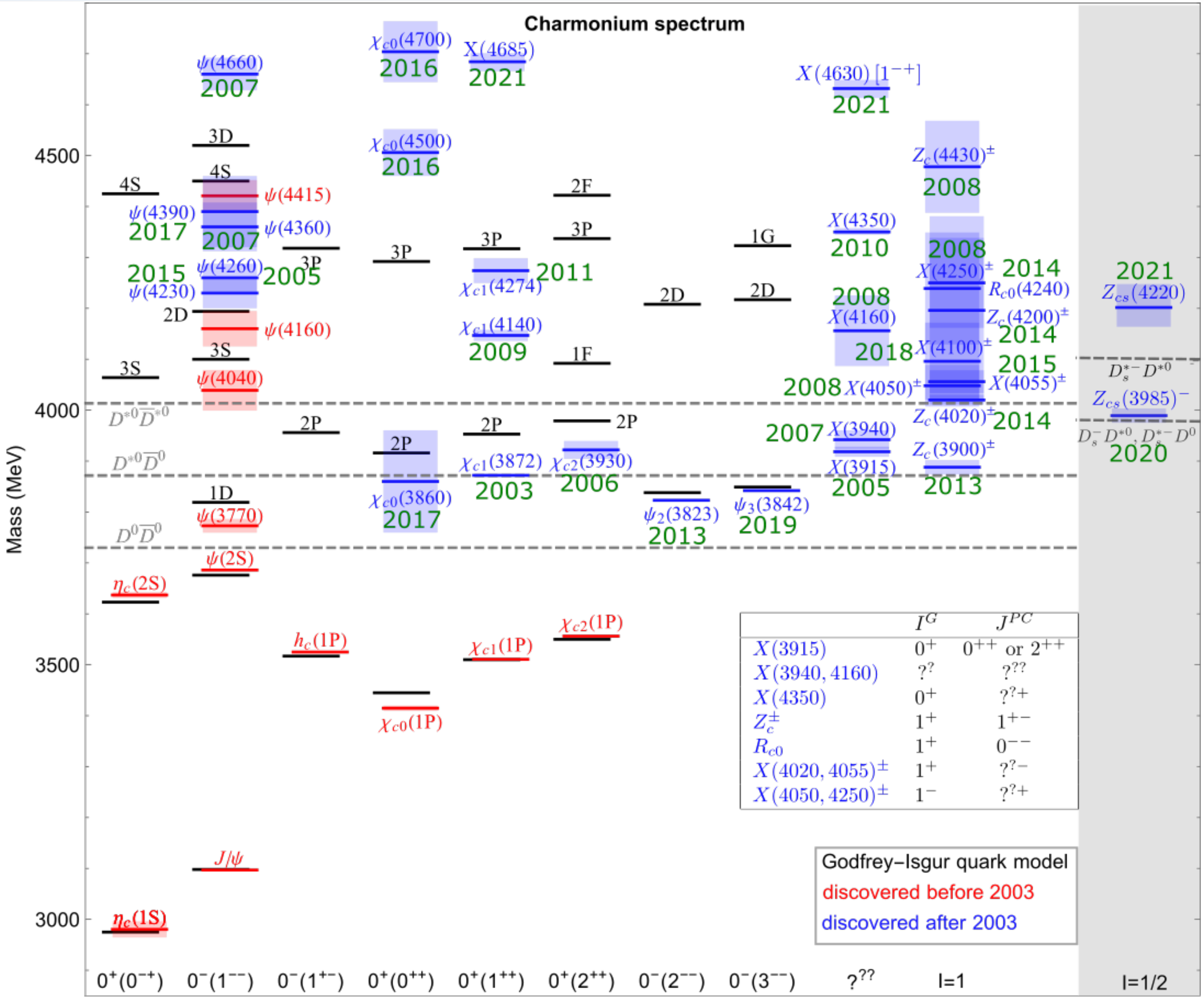


Exotic heavy meson spectroscopy and structure with EIC

15-19 August 2022

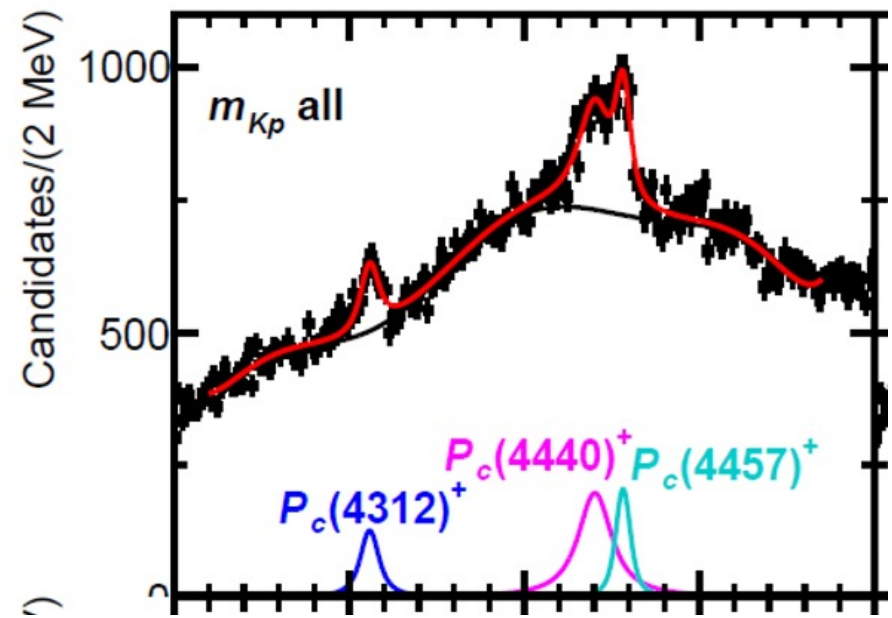
Based on
Z. Yang, FKG, Semi-inclusive lepto-production of hidden-charm exotic hadrons, arXiv:2107.12247;
P.-P. Shi, FKG, Z. Yang, Semi-inclusive electroproduction of hidden-charm and double-charm hadronic molecules, arXiv:2208.02639

Hidden-charm states



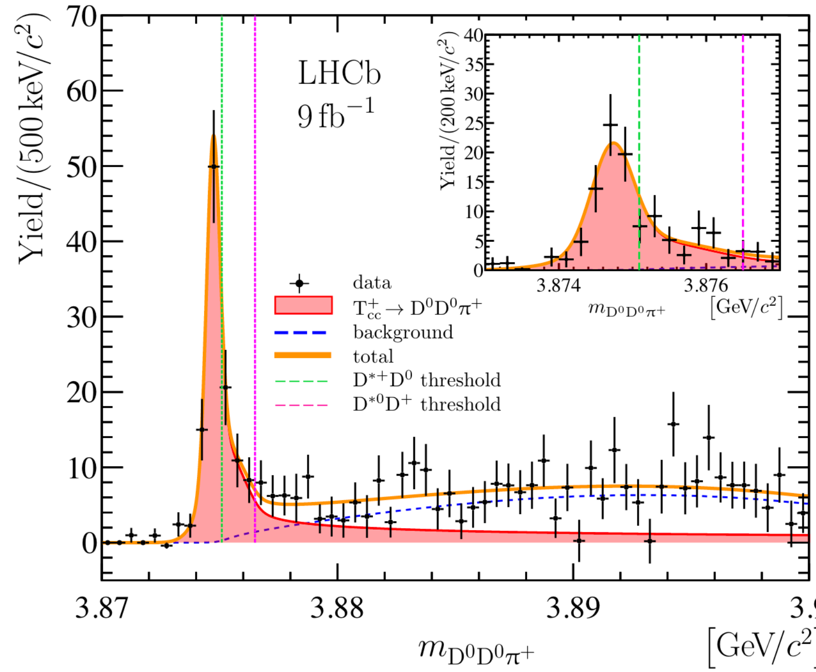
Hidden-charm and double-charm states

Hidden-charm P_c LHCb (2015, 2019)



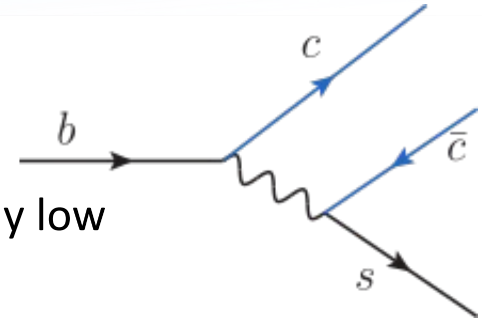
$$\Lambda_b^0 \to J/\psi\, p\, K^-$$

Double-charm T_{cc} LHCb (2021)

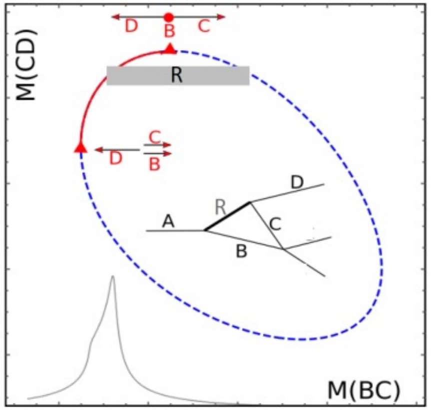


- Internal structure not understood
- Many structures are near threshold; candidates of hadronic molecules

Current experiments for the hidden-charm particles



- B-factories
  - From ISR processes
    - Cross sections and selection efficiency are relatively low
  - From B decays with $b \to s c\bar{c}$
    - Energy region limited: $< m_B - m_K \approx 4.8$ GeV
    - Final states with 3 or more hadrons: $B \to K\psi\phi, K\psi\omega, K\psi\pi\pi$, …
      Often difficult due to multi-hadron final states to get unambiguous properties of broad resonances

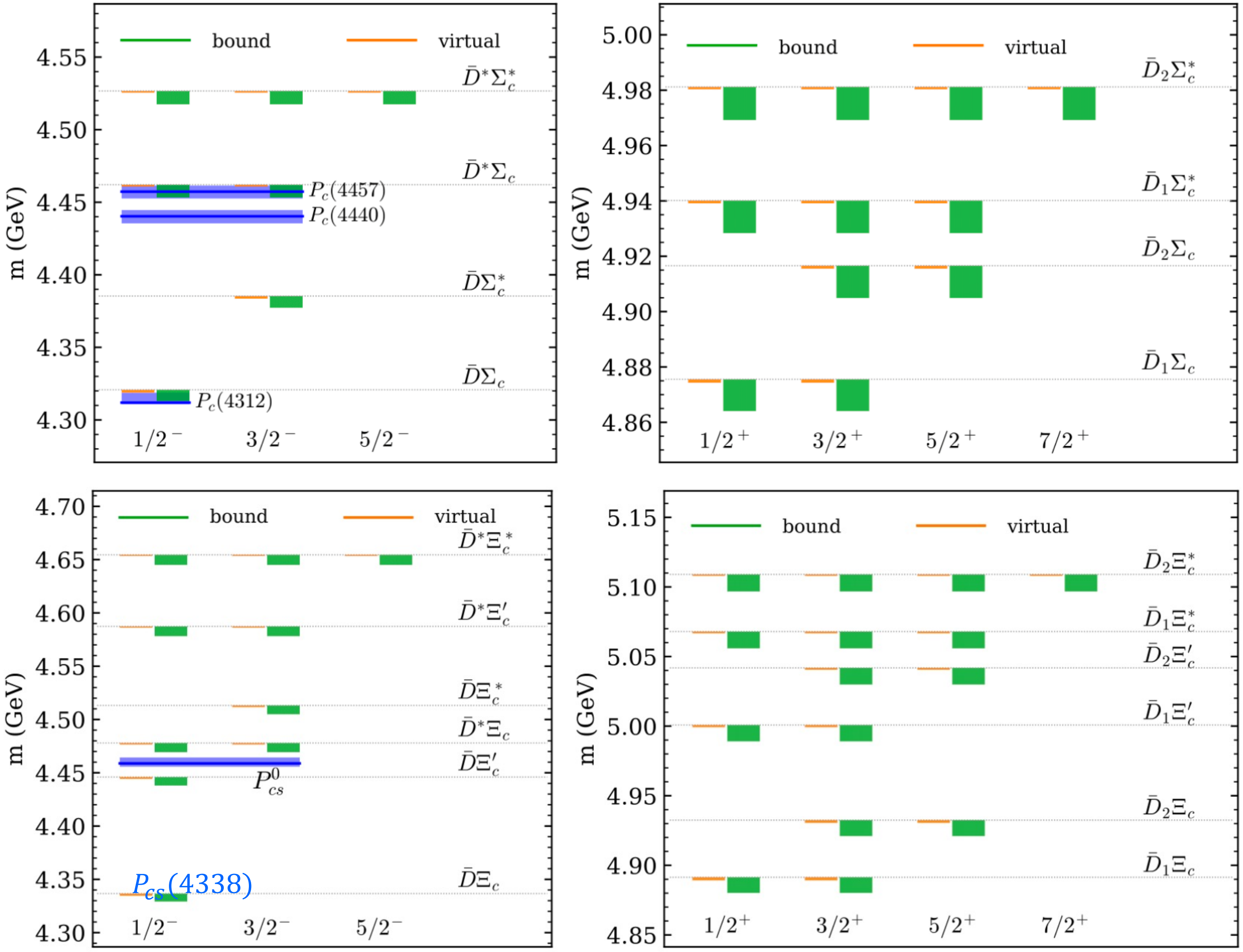


- Hadron colliders
  - From Λ_b decays with $b \to s c\bar{c}$
    - Energy region limited: $< m_{\Lambda_b} - m_{\Lambda} \approx 4.8$ GeV
    - Final states with 3 or more hadrons
  - Prompt productions: high background
- BESIII
  - Energy so far $\lesssim 4.96$ GeV, to be upgraded to 5.6 GeV
  - Low production rates (radiative transition) for $C = +$ states
  - Luminosity: less than $1{\times}10^{33}$ cm^{-2} s^{-1} above 4 GeV

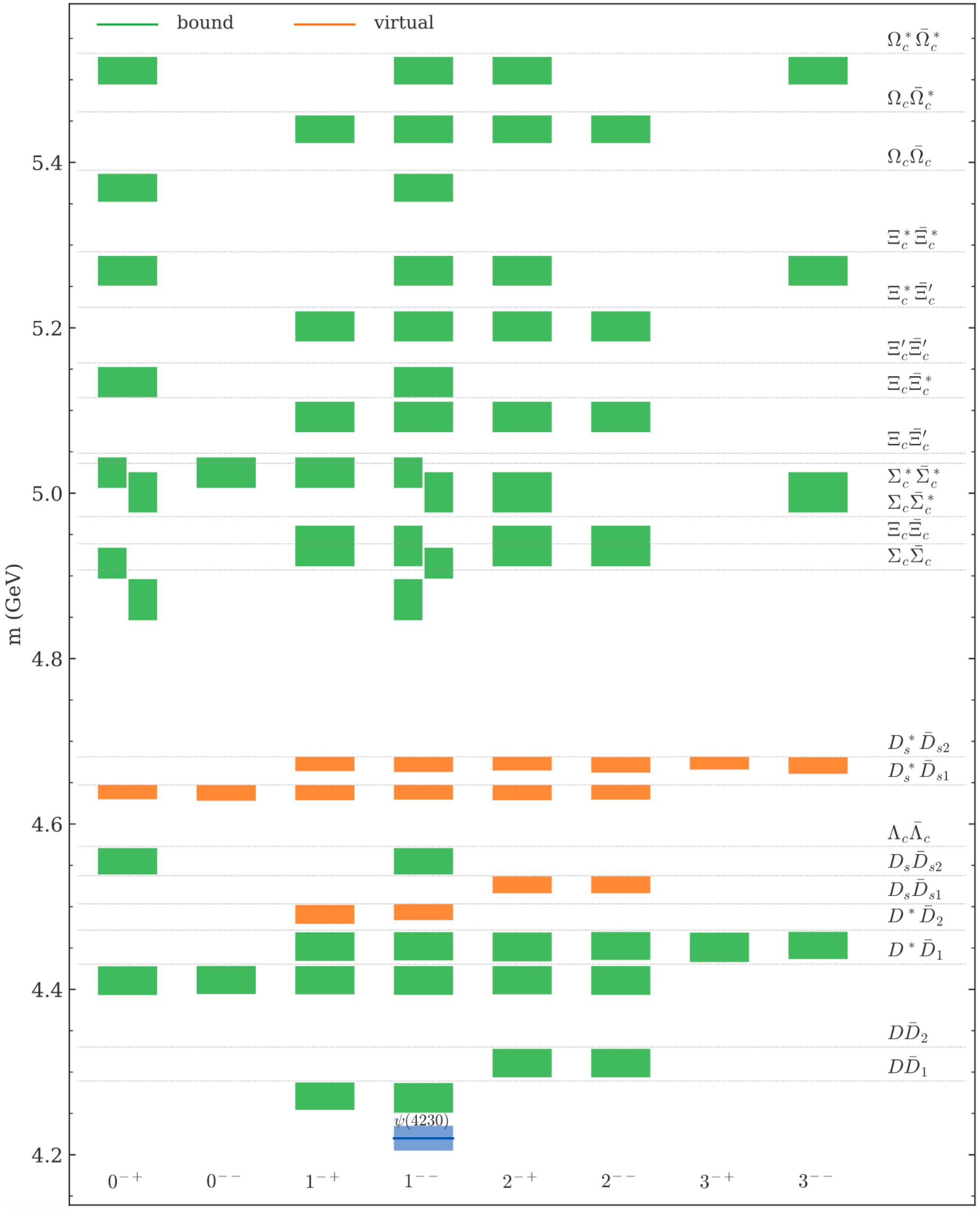
More hadronic molecules are expected

- Survey of hadronic molecular spectrum with a simple vector-exchange model
- Hidden-charm hadronic molecules

X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41 (2021) 65



More hadronic molecules are expected

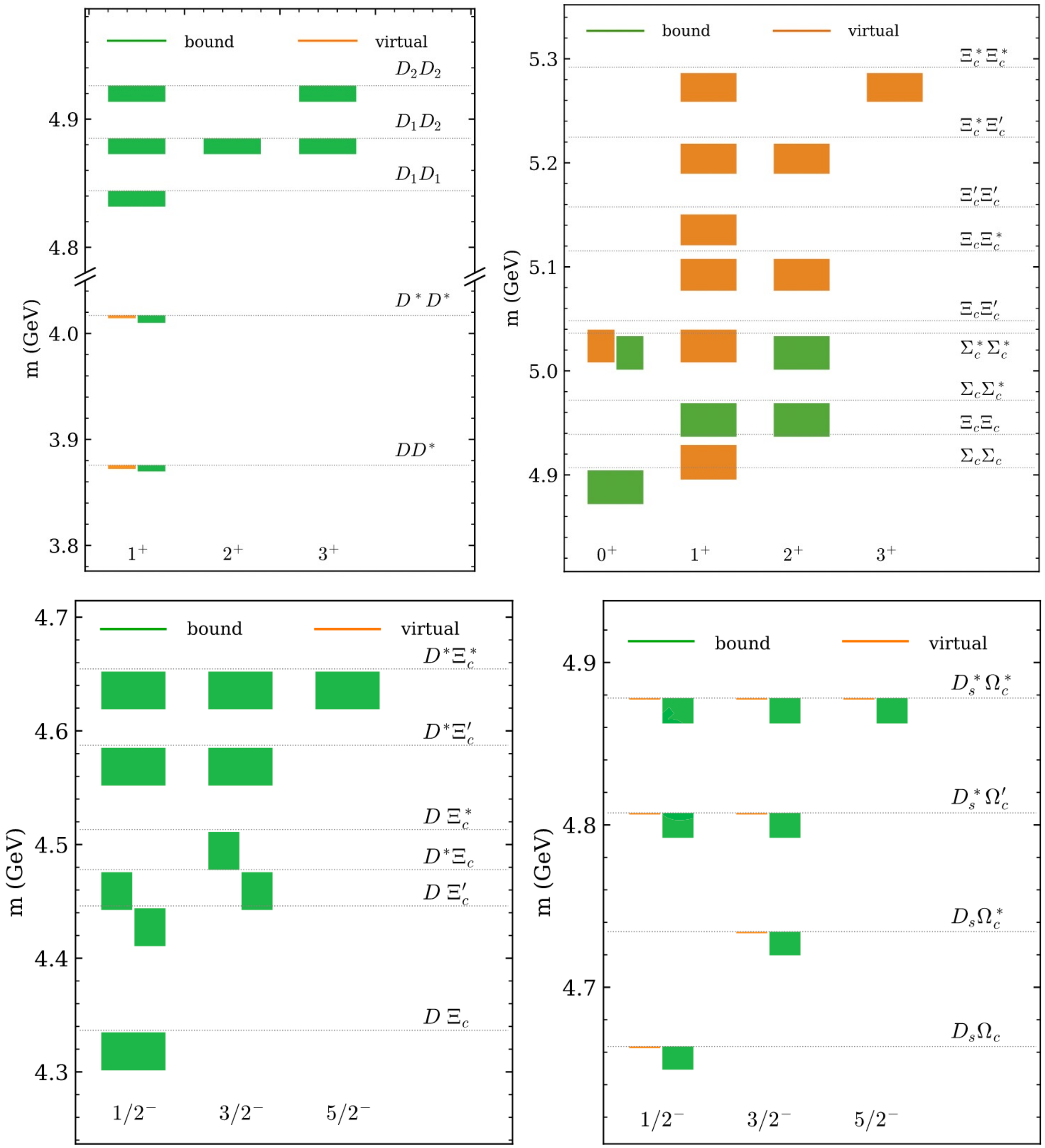


- Hidden-charm hadronic molecules

  X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41 (2021) 65

➢ High-luminosity experiments covering the energy range above 5 GeV are needed

More hadronic molecules are expected

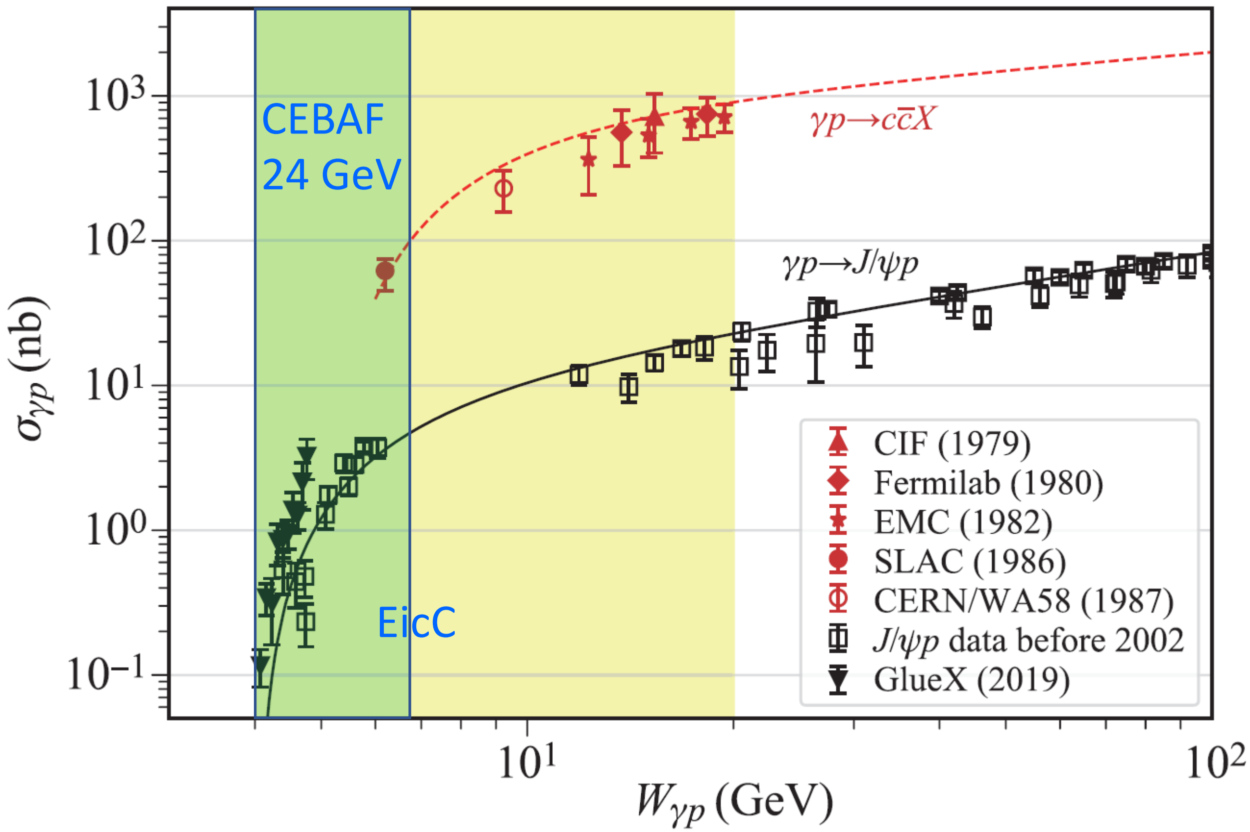


- Double-charm hadronic molecules

X.-K. Dong, FKG, B.-S. Zou, CTP73 (2021) 125201

Photoproduction: charm

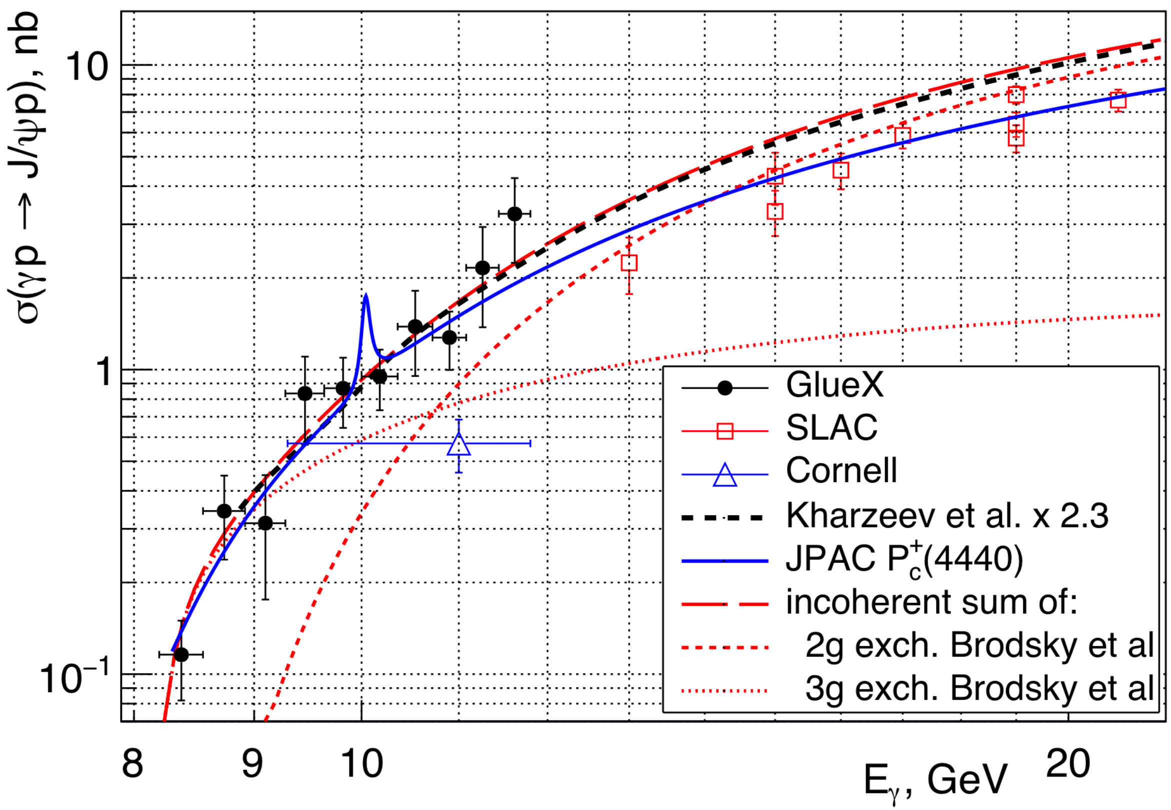
Figure from D. P. Anderle et al., Front.Phys. 16 (2021) 64701



- Leptoproduction: cross sections are roughly two orders of magnitude (α) smaller
- Many more open-charm hadrons D and Λ_c

Near-threshold J/ψ production at GlueX

No evidence of P_c in the J/ψ photoproduction at GlueX



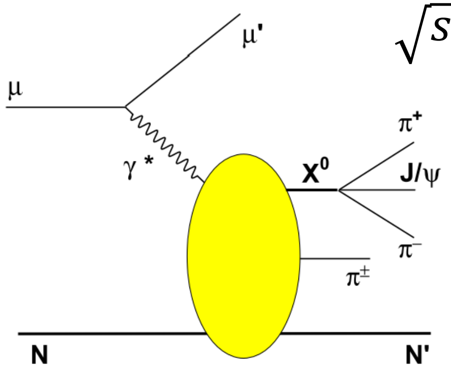
GlueX, PRL 122 (2019) 222001

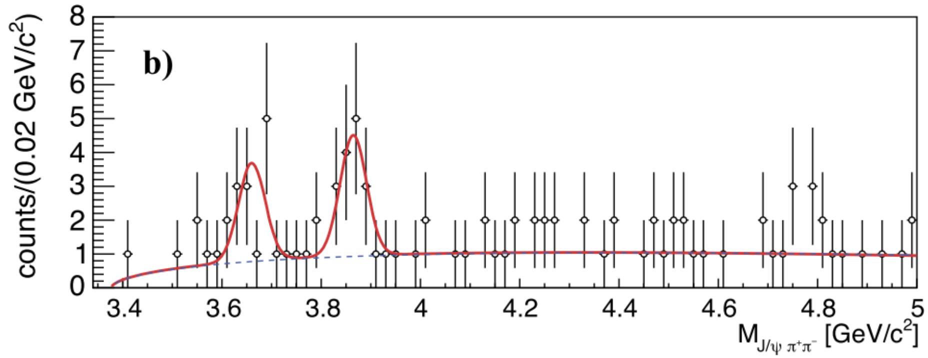
Hidden-charm exotics at COMPASS

- Observation of $\tilde{X}(3872)$ in $\gamma^* N \to X^0 \pi^\pm N'$ with 4.1σ COMPASS, PLB783(2018)334

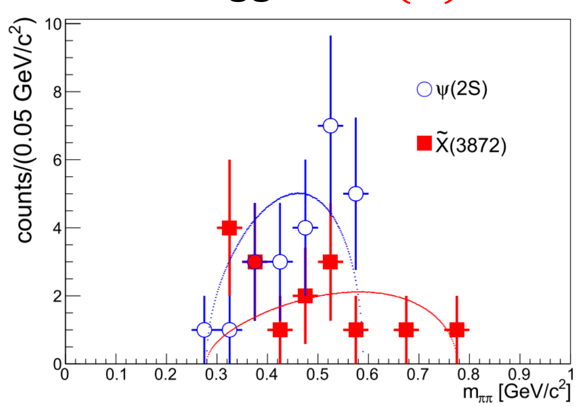
$\sqrt{s_{\gamma N}} \in [8, 18]$ GeV

$M_{\tilde{X}} = (3860.4 \pm 10.0)$ MeV

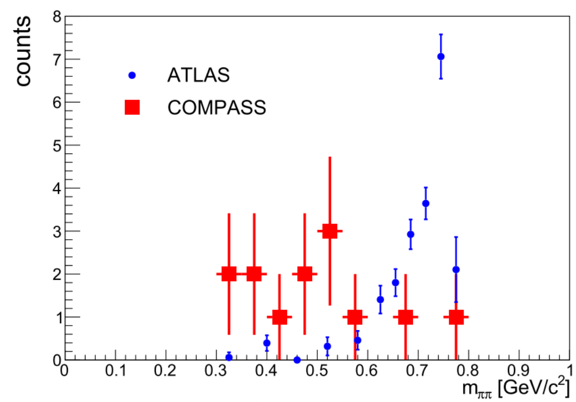




- The $\pi\pi$ invariant mass suggests $C(\tilde{X}) = -1$



(a)



(b)

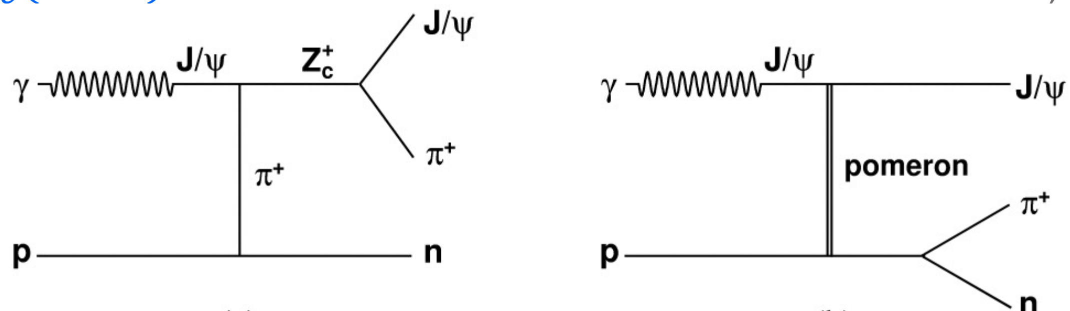
- Cross sections: $\sigma(\gamma N \to \tilde{X}\pi N') \times \mathcal{B}(\tilde{X} \to J/\psi \pi^+\pi^-) = (71 \pm 28 \pm 39)$ pb

$$\sigma(\gamma N \to X(3872) N') \times \mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-) < 2.9 \text{ pb (CL} = 90\%)$$

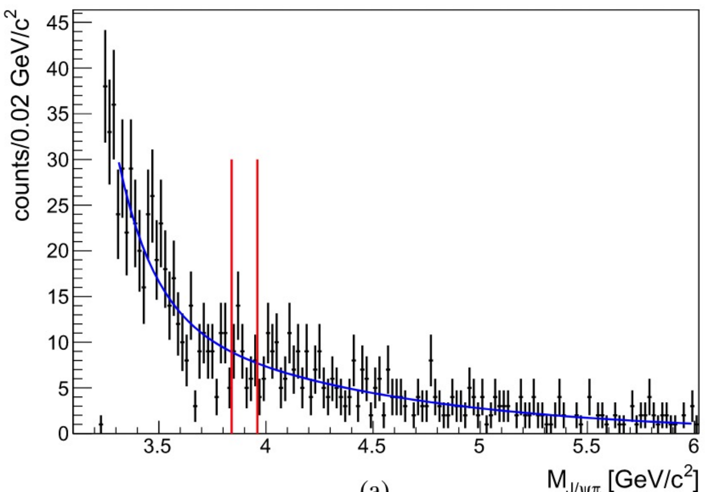
Hidden-charm exotics at COMPASS

- No evidence of $Z_c(3900)$ seen

COMPASS, PLB742(2015)330



$$\mu^+ N \to \mu^+ Z_c^\pm(3900) N \to \mu^+ J/\psi\, \pi^\pm N \to \mu^+\mu^+\mu^-\pi^\pm N \qquad \sqrt{s_{\gamma N}} \in [7, 19]\ \text{GeV}$$



(a)

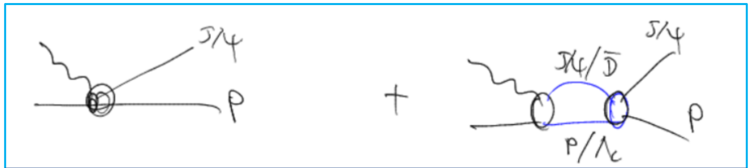
- Cross sections:

$$BR\left(Z_c^\pm(3900) \to J/\psi\pi^\pm\right) \times \sigma_{\gamma N \to Z_c^\pm(3900) N}\Big|_{\left\langle\sqrt{s_{\gamma N}}\right\rangle = 13.8\ \text{GeV}} < 52\ \text{pb}$$

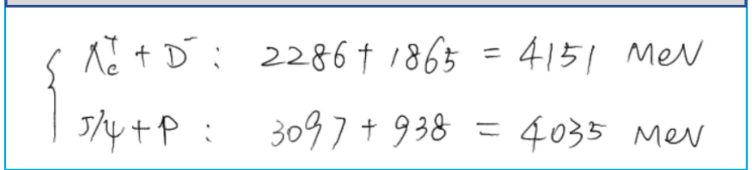
Coupled-channel effects

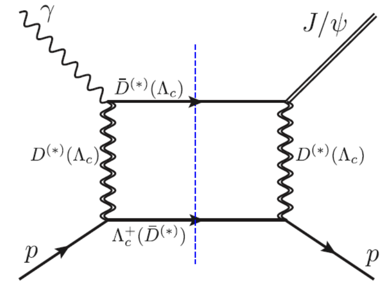
- Open-charm channels easier to be produced than $J/\psi p$; thresholds nearby

M.-L. Du, V. Baru, FKG, C. Hanhart, U.-G. Meißner, A. Nefediev, I. Strakovsky, EPJC80(2020)1053

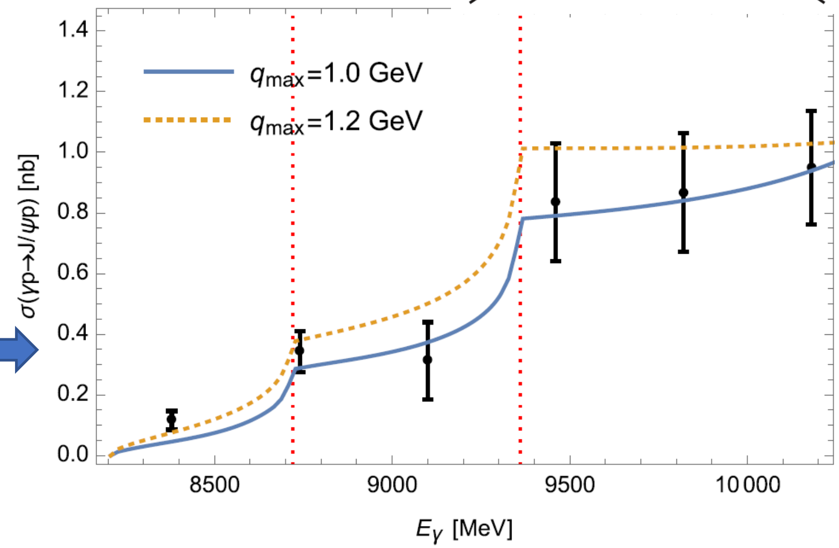


Unitarity: $J/\psi p \to J/\psi p$ enters w/o VMD, but cannot be singled out





- Estimated cross section w/ couplings taken from literature
- Unique prediction: cusps at $\Lambda_c \bar{D}^{(*)}$ thresholds



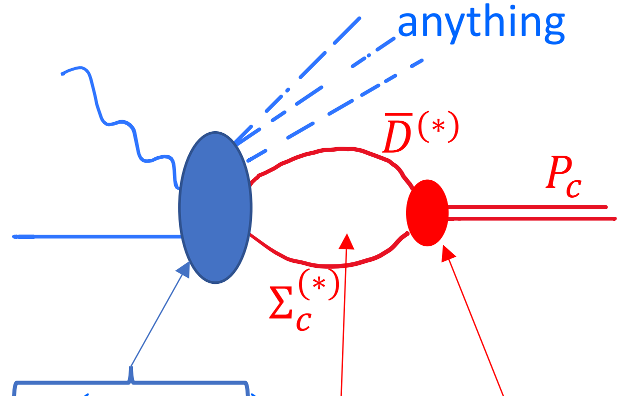
- The same mechanism for $J/\psi p \to J/\psi p$ leads to small scattering length; need to compare with the scattering length from gluon exchanges (ongoing):

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

Cross section estimates

- Order-of-magnitude estimates of inclusive lepto-production of near-threshold hadronic molecules
- The cross section can be estimated as

  e.g., for P_c states

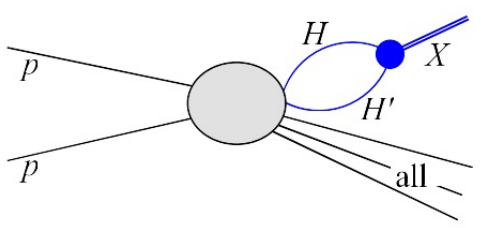


$$\propto \sigma\left(\Sigma_c^{(*)}\bar{D}^{(*)}\right) \times |G^\Lambda|^2 \times |g_{\rm eff}|^2$$

Event generators

- The method has been used to estimate the X(3872) production at hadron colliders; despite the debates regarding the X(3872) structure, correct order of magnitude was reproduced

Artoisenet, Braaten, PRD83(2011)014019; FKG, Meißner, W. Wang, Z. Yang, EPJC74(2014)3063



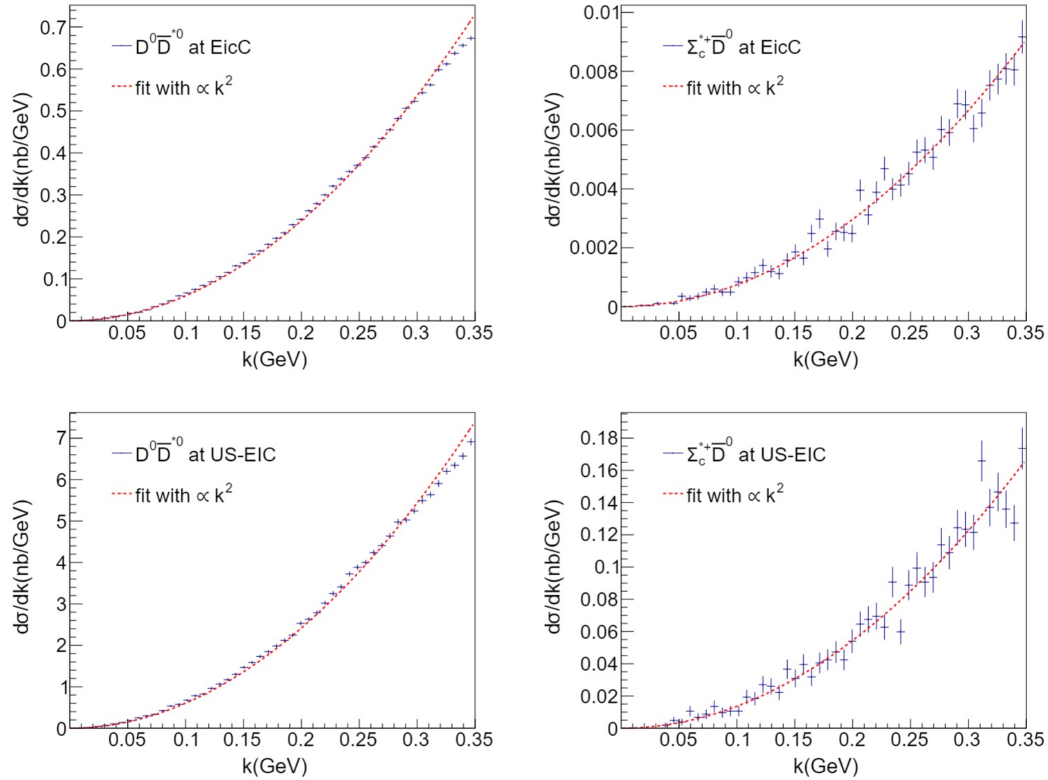
$\sigma(pp/\bar{p}\to X)$ [nb]	Exp.	Λ=0.5 GeV	Λ=1.0 GeV
Tevatron	37-115	7 (5)	29 (20)
LHC-7	13-39	13 (4)	55 (15)

Albaladejo, FKG, Hanhart et al., CPC41(2017)121001

Cross section estimates

Z. Yang, FKG, CPC 45 (2021) 123101

- Charm hadron pairs generated using Pythia6.4



- Considered machine configurations

	EicC	EIC	CEBAF (24 GeV)
e^- **energy** (GeV)	3.5	20	24
proton energy (GeV)	20	250	0
luminosity $\left(\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\right)$	2×10^{33}	10^{34}	10^{36}

Cross section estimates

Z. Yang, FKG, CPC 45 (2021) 123101; P.-P. Shi, FKG, Z. Yang, arXiv:2208.02639

- Order-of-magnitude estimates of the semi-inclusive electro-production of hidden/double-charm hadronic molecules (in units of pb)

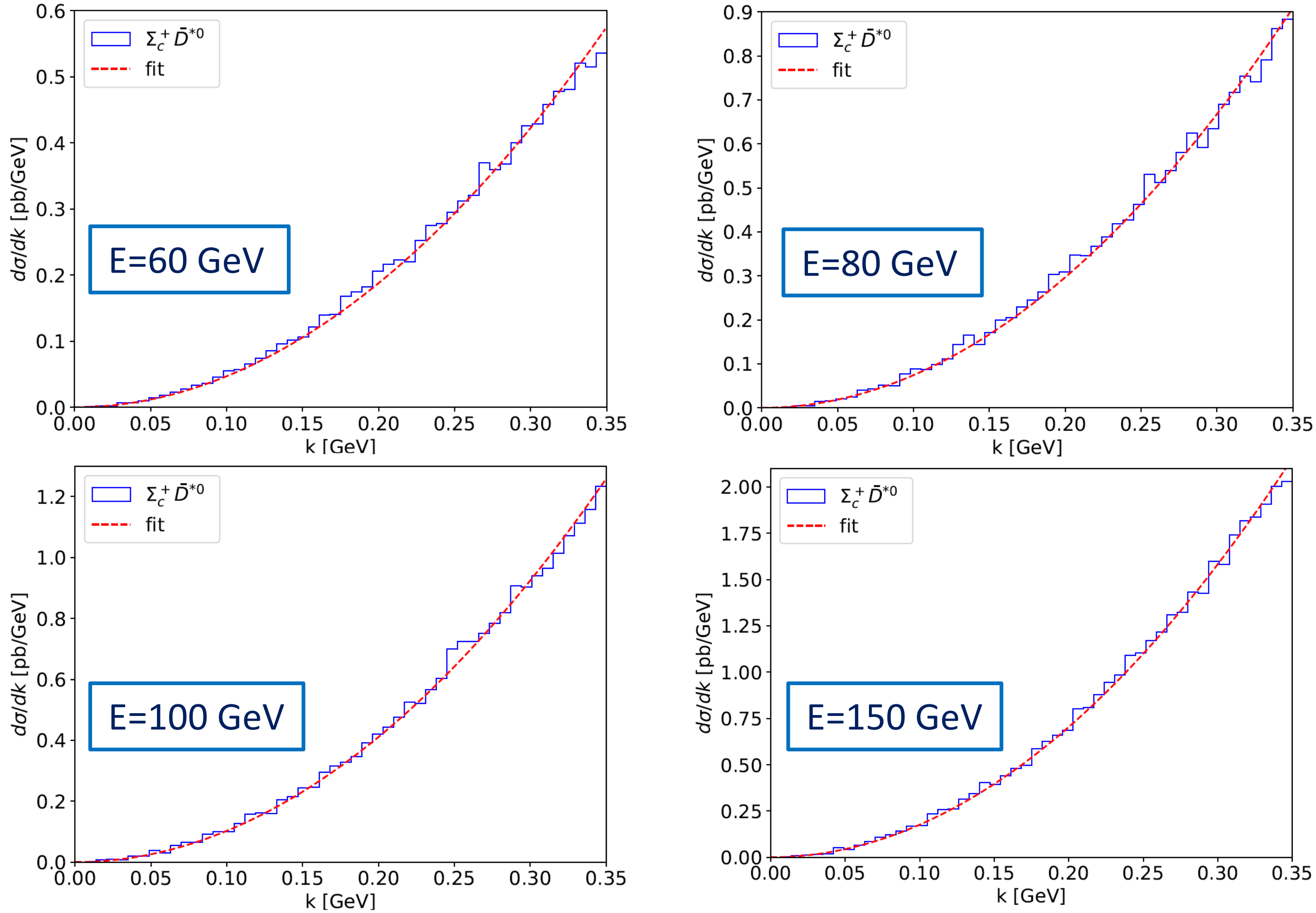
	Constituents	$I, J^{P(C)}$	EicC	EIC
$X(3872)$	$D\bar{D}^*$	$0, 1^{++}$	$21(89)$	$216(904)$
$Z_c(3900)^0$	$D\bar{D}^*$	$1, 1^{+-}$	$0.4\times10^3(1.3\times10^3)$	$3.8\times10^3(14\times10^3)$
Z_{cs}^-	$D^{*0}D_s^-$	$1/2, 1^+$	$19(69)$	$250(900)$
$P_c(4312)$	$\Sigma_c\bar{D}$	$1/2, 1/2^-$	$0.8(4.1)$	$15(73)$
$P_{cs}(4338)$	$\Xi_c\bar{D}$	$0, 1/2^-$	$0.1(1.6)$	$1.8\ (30)$
Predicted	$\Lambda_c\bar{\Lambda}_c$	$0, 0^{-+}$	$0.3\ (3.0)$	$10\ (110)$
Predicted	$\Lambda_c\bar{\Sigma}_c$	$1, 0^-$	$0.01\ (0.12)$	$0.5\ (5.5)$
T_{cc}^+	DD^*	$0, 1^+$	$0.3\times10^{-3}\ (1.2\times10^{-3})$	$0.1\ (0.5)$

Results for more systems can be found in the above refs.

Semi-inclusive production at CEBAF 24 GeV

P.-P. Shi, FKG, Z. Yang, arXiv:2208.02639

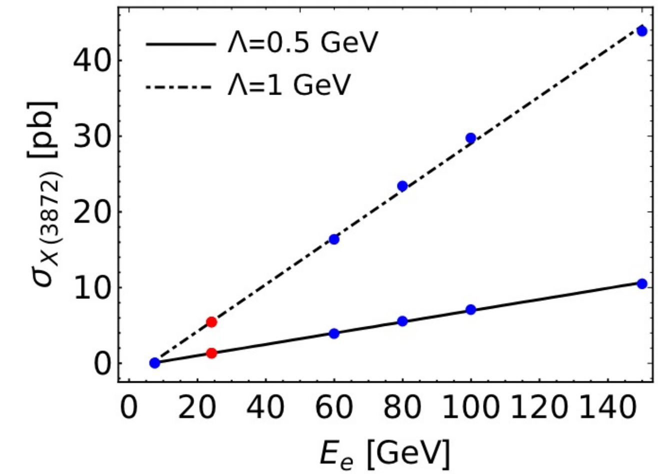
- For beam energy of 24 GeV, the *ep* c.m. energy: 6.77 GeV; too low for Pythia
- Choose a few higher energy points, and extrapolate the results done to 24 GeV
- Rough order-of-magnitude estimates

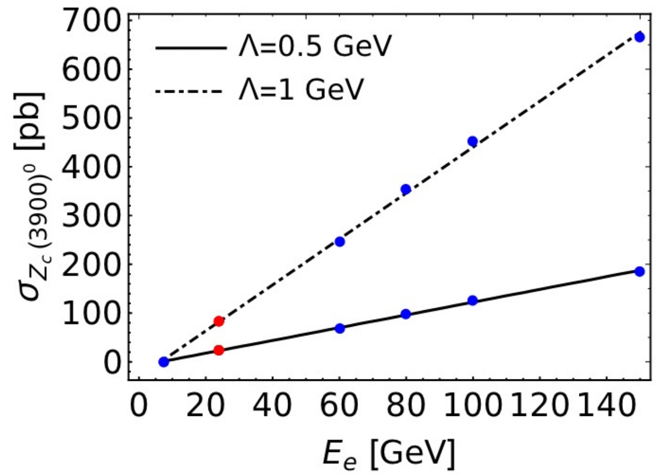


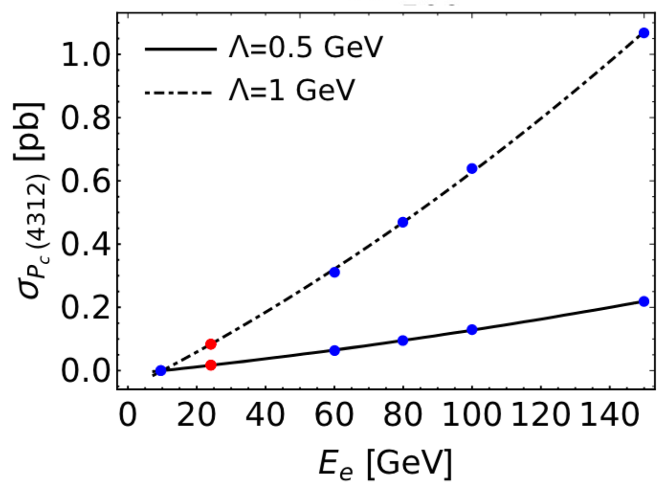
Semi-inclusive production at CEBAF 24 GeV

P.-P. Shi, FKG, Z. Yang, arXiv:2208.02639

- For beam energy of 24 GeV, the ep c.m. energy: 6.77 GeV; too low for Pythia
- Choose a few higher energy points, and extrapolate the results done to 24 GeV
- Rough order-of-magnitude estimates







Semi-inclusive production at CEBAF 24 GeV

P.-P. Shi, FKG, Z. Yang, arXiv:2208.02639

- Order-of-magnitude estimates of the electro-production cross sections with 24 GeV electron beam

	Constituents	$J^{P(C)}$	σ_X/pb
$X(3872)$	$D\bar{D}^*$	1^{++}	1.3 (5.5)
$Z_c(3900)^0$	$D\bar{D}^*$	1^{+-}	23 (82)
$P_c(4312)$	$\Sigma_c\bar{D}$	$1/2^-$	0.02 (0.08)
$P_{cs}(4459)$	$\Xi_c\bar{D}^*$	$3/2^-$	0.005 (0.03)

- Not surprising the GlueX observed no signal of P_c: $\sigma(\gamma p \to J/\psi p) = \mathcal{O}(1\ \mathrm{nb}) \gg 10^2 \times \sigma(e^- p \to P_c + \mathrm{anything})$, much higher statistics is needed
- With a luminosity of $10^{36}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, for an integrated luminosity of $10^7\ \mathrm{pb}^{-1}$, a large number of hidden-charm exotics can be produced

  even after having taken into account branching fractions, e.g., $\mathcal{B}(P_c \to J/\psi p) = \mathcal{O}(1\%)$, $\mathcal{B}(J/\psi \to \ell^+\ell^-) = 12\%$

Summary

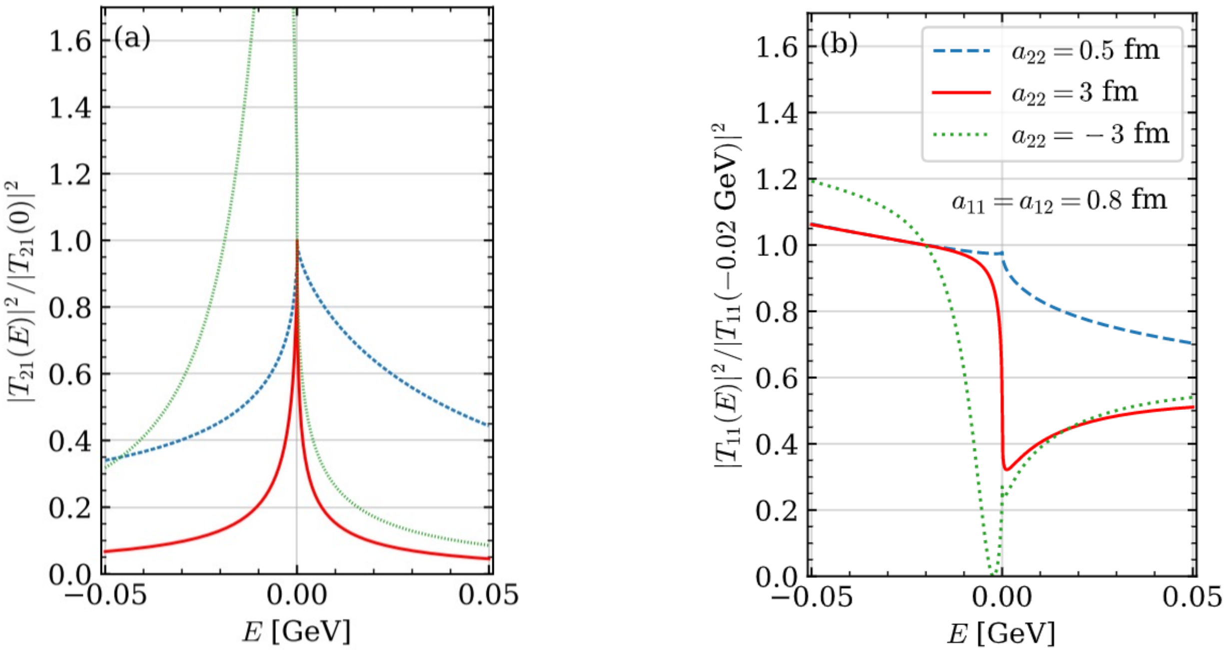
- Future electron-proton machines will be able to contribute a lot to hadron spectroscopy
- A large amount of hidden-charm exotic hadrons can be observed at CEBAF 24 GeV for a luminosity of $10^{36}\ \mathrm{cm^{-2}s^{-1}}$

Thank you for your attention!

Near-threshold structures

- Nontrivial near-threshold structure for S-wave short-range attraction

X.-K. Dong, FKG, B.-S. Zou, PRL126 (2021) 152001



- The same pole could lead to distinct line shapes in different reactions
- Hadronic molecules easily formed in the hidden/double-heavy-flavor region
- Other models also predict higher states

Interaction strengths from light-vector exchanges

X.-K. Dong, FKG, B.-S. Zou, CTP73 (2021) 125201

System	I	S	Thresholds [MeV]	Exchanged particles	F
$D^{(*)}\bar{D}^{(*)}/D^{(*)}D^{(*)}$	1	0/0	(3734, 3876, 4017)	ρ, ω	$-\frac{1}{2}, \frac{1}{2}/-\frac{1}{2}, -\frac{1}{2}$
	0				$\frac{3}{2}, \frac{1}{2}/\frac{3}{2}, -\frac{1}{2}$
$D_s^{(*)}\bar{D}^{(*)}/D_s^{(*)}D^{(*)}$	$\frac{1}{2}$	1/1	(3836, 3977, 3979, 4121)	K^*	$0/-1$
$D_s^{(*)}\bar{D}_s^{(*)}/D_s^{(*)}D_s^{(*)}$	0	0/2	(3937, 4081, 4224)	ϕ	$1/-1$
$\bar{D}^{(*)}\Lambda_c/D^{(*)}\Lambda_c$	$\frac{1}{2}$	0/0	(4154, 4295)	ω	$-1/1$
$\bar{D}_s^{(*)}\Lambda_c/D_s^{(*)}\Lambda_c$	0	$-1/1$	(4255, 4399)	–	0/0
$\bar{D}^{(*)}\Xi_c/D^{(*)}\Xi_c$	1	$-1/-1$	(4337, 4478)	ρ, ω	$-\frac{1}{2}, -\frac{1}{2}/-\frac{1}{2}, \frac{1}{2}$
	0				$\frac{3}{2}, -\frac{1}{2}/\frac{3}{2}, \frac{1}{2}$
$\bar{D}_s^{(*)}\Xi_c/D_s^{(*)}\Xi_c$	$\frac{1}{2}$	$-2/0$	(4438, 4582)	ϕ	$-1/1$
$\bar{D}^{(*)}\Sigma_c^{(*)}/D^{(*)}\Sigma_c^{(*)}$	$\frac{3}{2}$	0/0	(4321, 4385, 4462, 4527)	ρ, ω	$-1, -1/-1, 1$
	$\frac{1}{2}$				$2, -1/2, 1$
$\bar{D}_s^{(*)}\Sigma_c^{(*)}/D_s^{(*)}\Sigma_c^{(*)}$	1	$-1/1$	(4422, 4486, 4566, 4630)	–	0/0
$\bar{D}^{(*)}\Xi_c^{\prime(*)}/D^{(*)}\Xi_c^{\prime(*)}$	1	$-1/-1$	(4446, 4513, 4587, 4655)	ρ, ω	$-\frac{1}{2}, -\frac{1}{2}/-\frac{1}{2}, \frac{1}{2}$
	0				$\frac{3}{2}, -\frac{1}{2}/\frac{3}{2}, \frac{1}{2}$
$\bar{D}_s^{(*)}\Xi_c^{\prime(*)}/D_s^{(*)}\Xi_c^{\prime(*)}$	$\frac{1}{2}$	$-2/0$	(4547, 4614, 4691, 4758)	ϕ	$-1/1$
$\bar{D}^{(*)}\Omega_c^{(*)}/D^{(*)}\Omega_c^{(*)}$	$\frac{1}{2}$	$-2/0$	(4562, 4633, 4704, 4774)	–	0/0
$\bar{D}_s^{(*)}\Omega_c^{(*)}/D_s^{(*)}\Omega_c^{(*)}$	0	$-3/-1$	(4664, 4734, 4807, 4878)	ϕ	$-2/2$
$\Lambda_c\bar{\Lambda}_c/\Lambda_c\Lambda_c$	0	0/0	(4573)	ω	$2/-2$
$\Lambda_c\bar{\Xi}_c/\Lambda_c\Xi_c$	$\frac{1}{2}$	$1/-1$	(4756)	ω/K^*	$1, 0/-1, -1$
$\Xi_c\bar{\Xi}_c/\Xi_c\Xi_c$	1	$0/-2$	(4939)	ρ, ω, ϕ	$-\frac{1}{2}, \frac{1}{2}, 1/-\frac{1}{2}, -\frac{1}{2}, -1$
	0				$\frac{3}{2}, \frac{1}{2}, 1/\frac{3}{2}, -\frac{1}{2}, -1$
$\Lambda_c\bar{\Sigma}_c^{(*)}/\Lambda_c\Sigma_c^{(*)}$	1	0/0	(4740, 4805)	ω/K^*	$1, 0/-1, -1$

Interaction strengths from light-vector exchanges

X.-K. Dong, FKG, B.-S. Zou, CTP73 (2021) 125201

System	I	S	Thresholds [MeV]	Exchanged particles	F
$\Lambda_c\bar{\Xi}_c^{\prime(*)}/\Lambda_c\Xi_c^{\prime(*)}$	$\frac{1}{2}$	$1/-1$	(4865, 4932)	ω	$1/-1$
$\Lambda_c\bar{\Omega}_c^{(*)}/\Lambda_c\Omega_c^{(*)}$	0	$2/-2$	(4982, 5052)	–	$0/0$
$\Sigma_c^{(*)}\bar{\Xi}_c/\Sigma_c^{(*)}\Xi_c$	$\frac{3}{2}$	$1/-1$	(4923, 4988)	$\rho,\ \omega,\ K^*$	$-1,\ 1,\ 0/-1,\ -1,\ -2$
	$\frac{1}{2}$				$2,\ 1,\ 0/2,\ -1,\ -2$
$\Xi_c\bar{\Xi}_c^{\prime(*)}/\Xi_c\Xi_c^{\prime(*)}$	1	$0/-2$	(5048, 5115)	$\rho,\ \omega,\ \phi$	$-\frac{1}{2},\ \frac{1}{2},\ 1/-\frac{1}{2},\ -\frac{1}{2},\ -1$
	0				$\frac{3}{2},\ \frac{1}{2},\ 1/\frac{3}{2},\ -\frac{1}{2},\ -1$
$\Xi_c\bar{\Omega}_c^{(*)}/\Xi_c\Omega_c^{(*)}$	$\frac{1}{2}$	$1/-3$	(5165, 5235)	$\phi,\ K^*$	$2,\ 0/-2,\ -2$
$\Sigma_c^{(*)}\bar{\Sigma}_c^{(*)}/\Sigma_c^{(*)}\Sigma_c^{(*)}$	2	$0/0$	(4907, 4972, 5036)	$\rho,\ \omega$	$-2,\ 2/-2,\ -2$
	1				$2,\ 2/2,\ -2$
	0				$4,\ 2/4,\ -2$
$\Sigma_c^{(*)}\bar{\Xi}_c^{\prime(*)}/\Sigma_c^{(*)}\Xi_c^{\prime(*)}$	$\frac{3}{2}$	$1/-1$	(5032, 5097, 5100, 5164)	$\rho,\ \omega,\ K^*$	$-1,\ 1,\ 0/-1,\ -1-2$
	$\frac{1}{2}$				$2,\ 1,\ 0/2,\ -1,\ -2$
$\Sigma_c^{(*)}\bar{\Omega}_c^{(*)}/\Sigma_c^{(*)}\Omega_c^{(*)}$	0	$2/-2$	(5149, 5213, 5219, 5284)	–	$0/0$
$\Xi_c^{\prime(*)}\bar{\Xi}_c^{\prime(*)}/\Xi_c^{\prime(*)}\Xi_c^{\prime(*)}$	1	$0/-2$	(5158, 5225, 5292)	$\rho,\ \omega,\ \phi$	$-\frac{1}{2},\ \frac{1}{2},\ 1/-\frac{1}{2},\ -\frac{1}{2},\ -1$
	0				$\frac{3}{2},\ \frac{1}{2},\ 1/\frac{3}{2},\ -\frac{1}{2},\ -1$
$\Xi_c^{\prime(*)}\bar{\Omega}_c^{(*)}/\Xi_c^{\prime(*)}\Omega_c^{(*)}$	$\frac{1}{2}$	$1/-3$	(5272, 5341, 5345, 5412)	$\phi,\ K^*$	$2,\ 0/-2,\ -2$
$\Omega_c^{(*)}\bar{\Omega}_c^{(*)}/\Omega_c^{(*)}\Omega_c^{(*)}$	0	$0/-4$	(5390, 5461, 5532)	ϕ	$4/-4$