Production of $XYZP$ states at lepton-proton facilities

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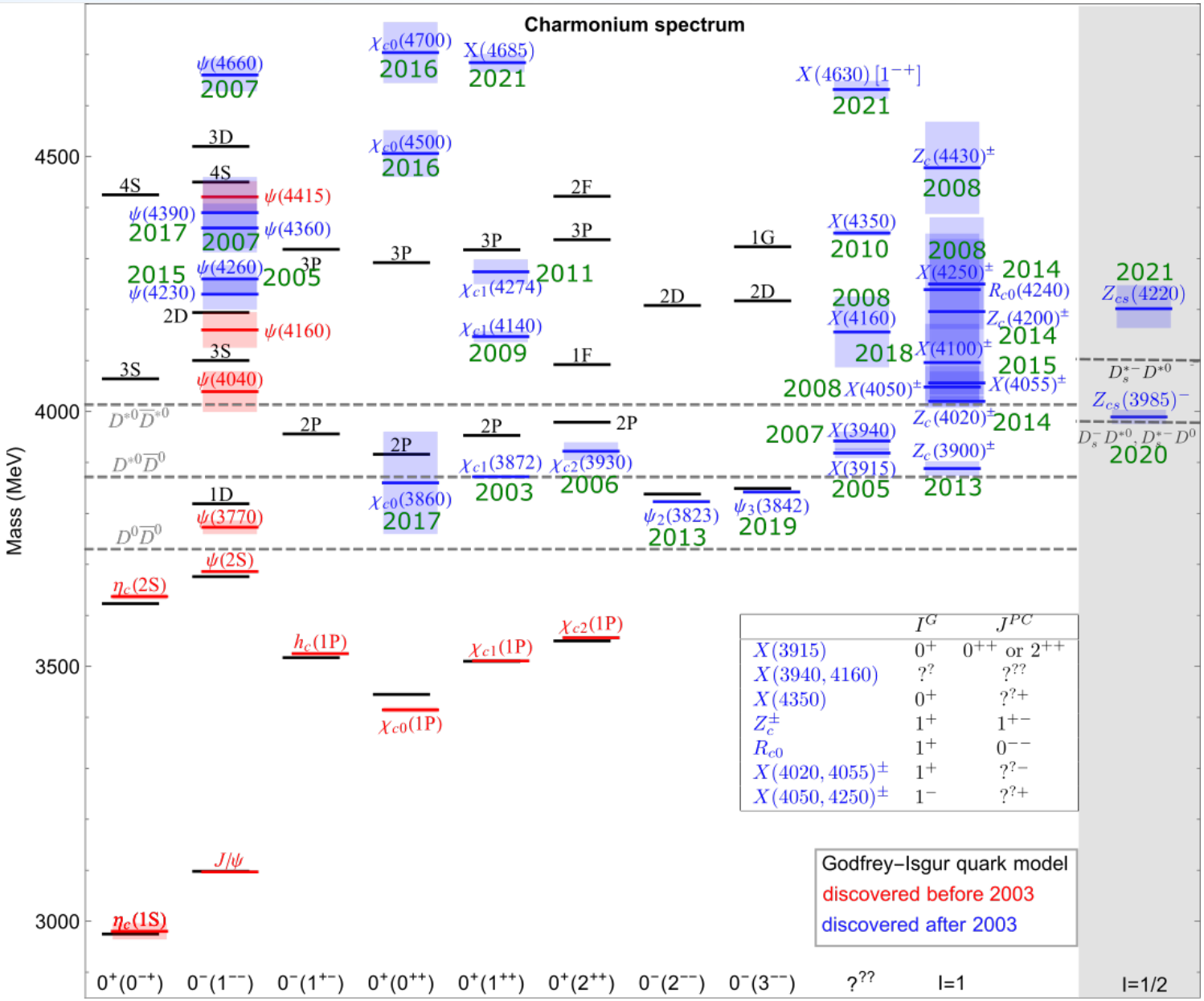
Hadron Spectroscopy with a CEBAF Energy Upgrade

16-17 June 2022
Hybrid

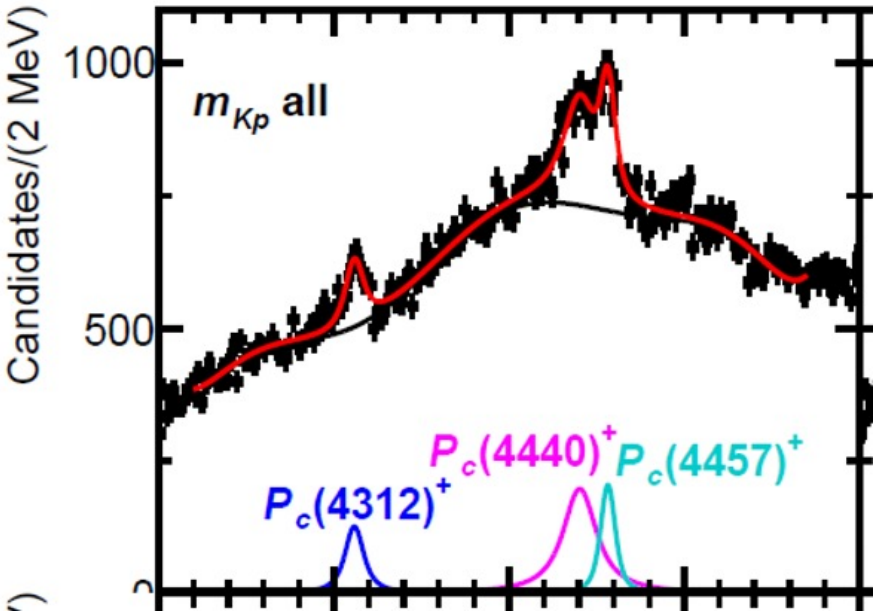
- Introduction
- Photoproduction of hidden-charm hadrons
- Estimates of cross sections for CEBAF 24 GeV

Hidden-charm states



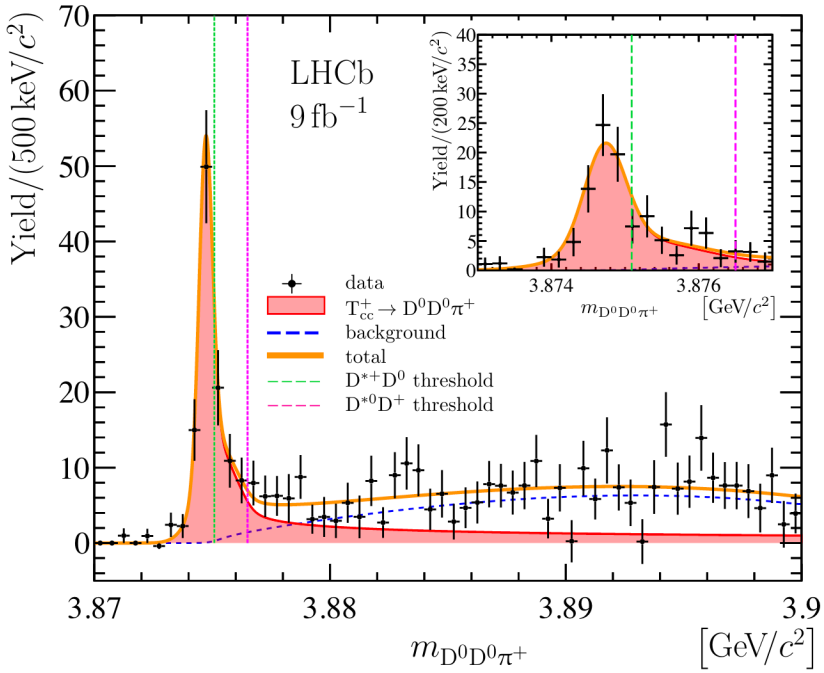
Hidden-charm and double-charm states

Hidden-charm P_c LHCb (2015, 2019)



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

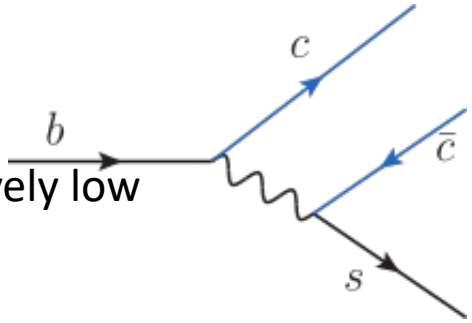
Double-charm T_{cc} LHCb (2021)



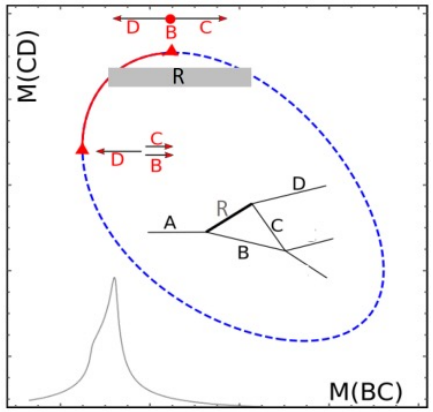
- Pattern of the $XYZPT$ states not understood
- Hints to confinement mechanism?

Current experiments for the hidden-charm particles

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



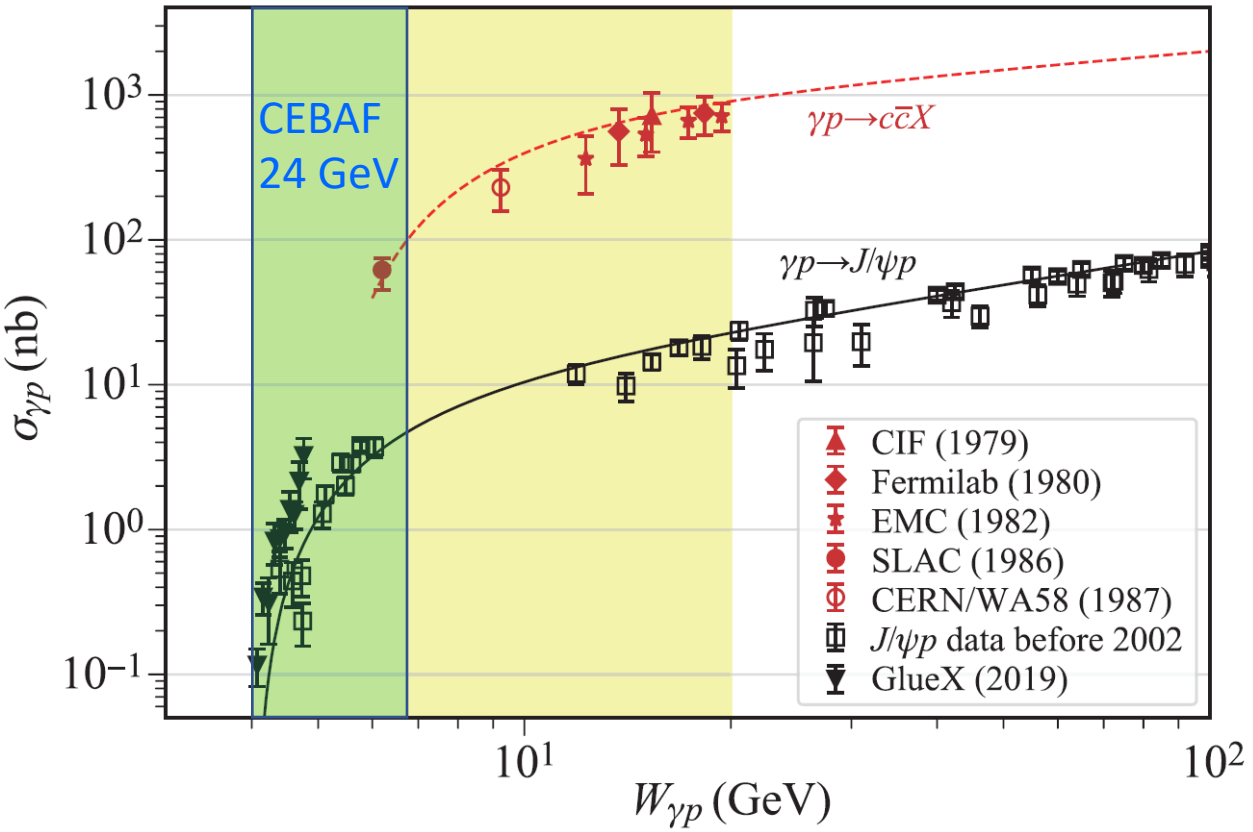
- Hadron colliders
  - From Λ_b decays with $b \to sc\bar{c}$
    - Energy region limited: $< m_{\Lambda_b} - m_{\Lambda} \approx 4.8$ GeV
    - Final states with 3 or more hadrons
  - Prompt productions: high background



- BESIII
  - Energy so far $\lesssim 4.9$ GeV, to be upgraded to 5.6 GeV
  - Low production rates (radiative transition) for $C = +$ states
  - Luminosity: less than 1×10^{33} cm^{-2} s^{-1} above 4 GeV

Photoproduction: charm

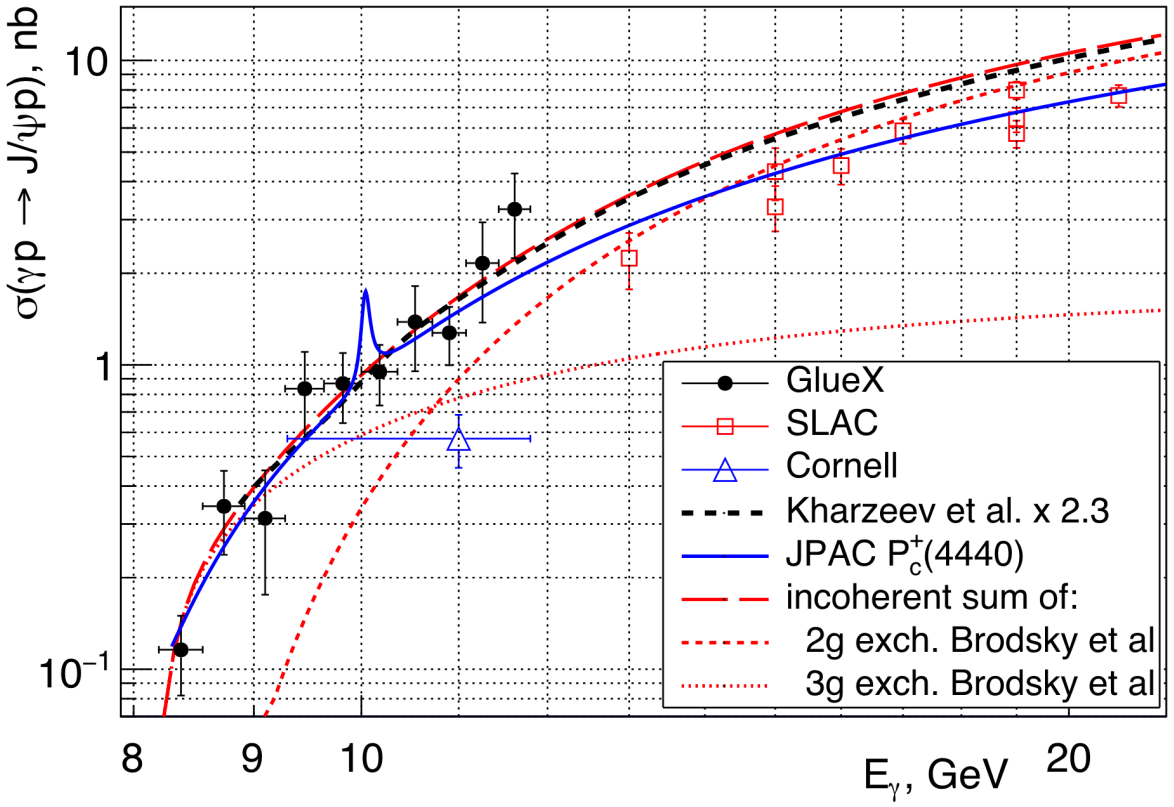
Figure from D. P. Anderle et al., Front.Phys. 16 (2021) 64701



- Photoproduction: $\sigma(\gamma p \to J/\psi p) \sim O(1\ \text{nb})$, (no resonant enhancement considered)
- 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

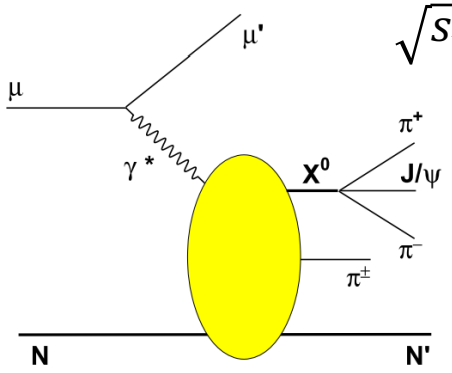


GlueX, PRL 122 (2019) 222001

Hidden-charm exotics at COMPASS

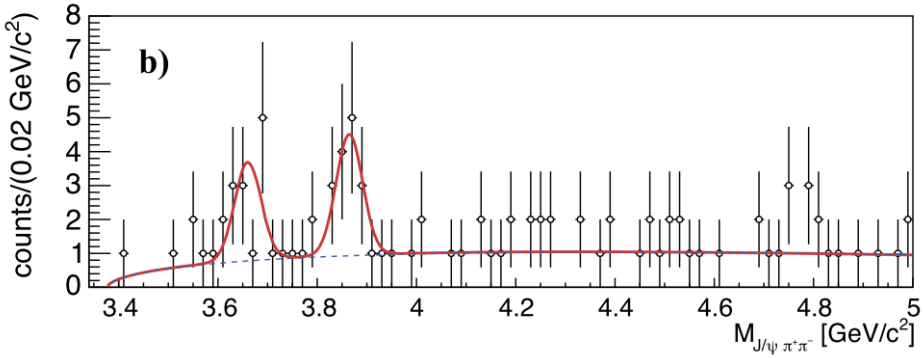
- Observation of $\tilde{X}(3872)$ in $\gamma^* N \to X^0 \pi^\pm N'$ with 4.1σ

COMPASS, PLB783(2018)334

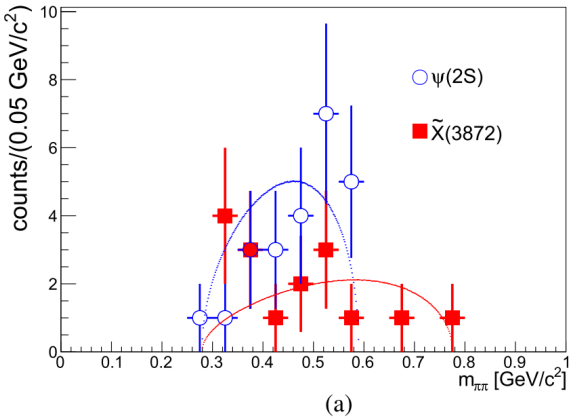


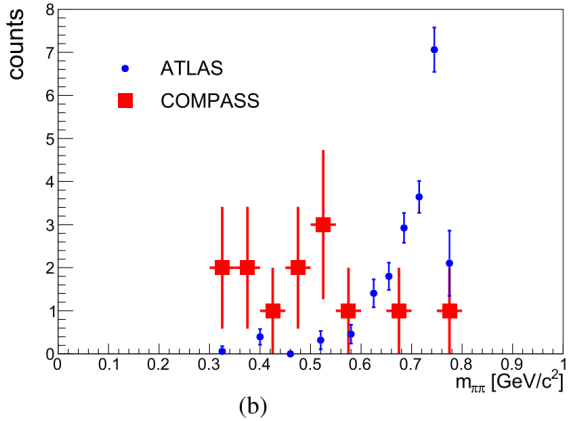
$\sqrt{s_{\gamma N}} \in [8, 18]$ GeV

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



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





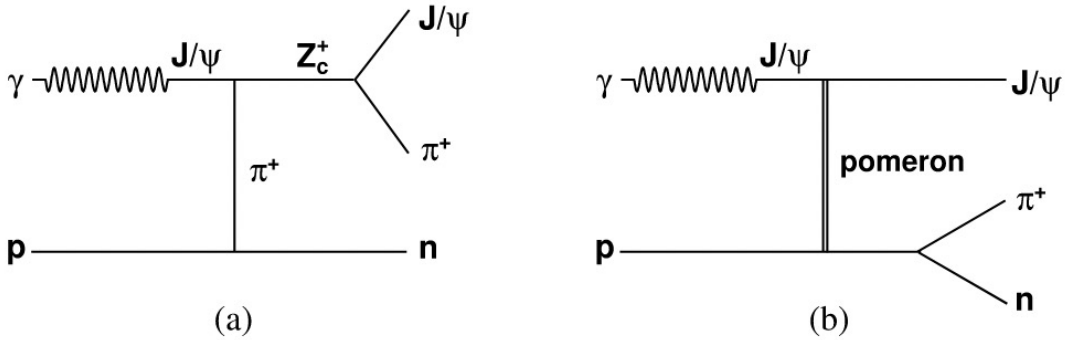
- Cross sections: $\sigma(\gamma N \to \tilde{X}\pi N') \times \mathcal{B}(\tilde{X} \to J/\psi\pi^+\pi^-) = (71 \pm 28 \pm 39)$ pb

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

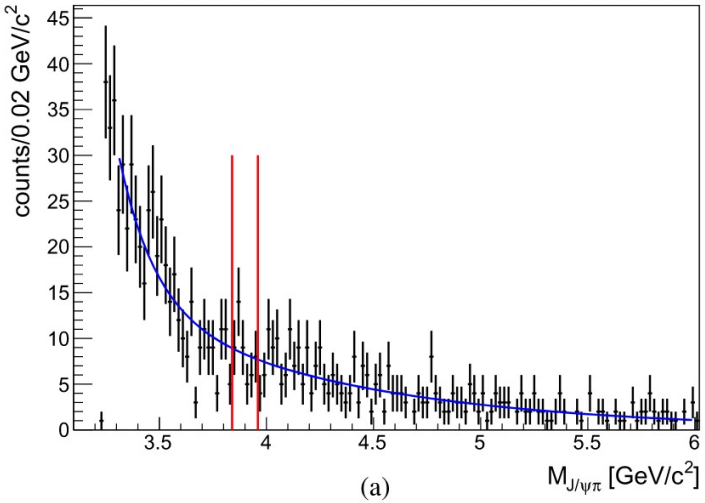
Hidden-charm exotics at COMPASS

- No evidence of $Z_c(3900)$ seen

COMPASS, PLB742(2015)330



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



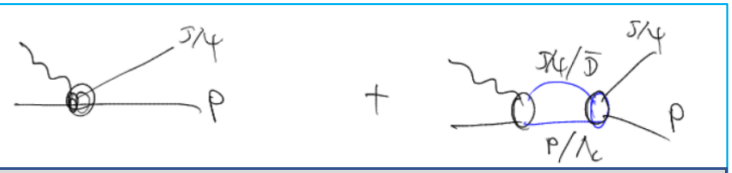
- Cross sections:

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

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

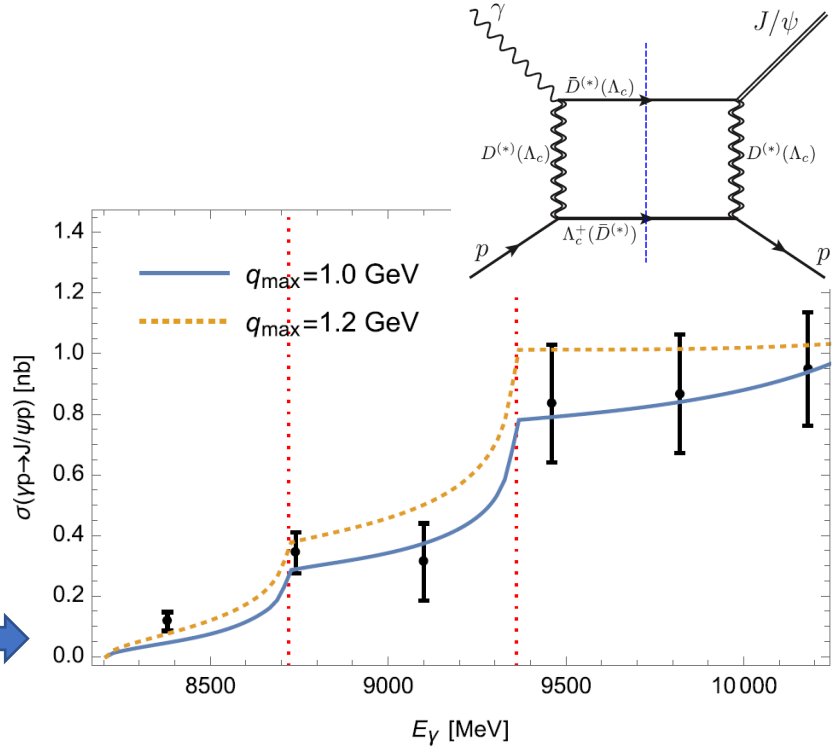


Unitarity: $J/\psi p \to J/\psi p$ enters w/o VMD, but cannot be singled out

$\Lambda_c^+ + \bar{D}^-$: 2286 + 1865 = 4151 MeV

$J/\psi + p$: 3097 + 938 = 4035 MeV

Estimated cross section w/ all couplings taken from literature



- 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):

$$\left|a^{J=1/2}\right| = 0.2 \ldots 3.1 \text{ mfm}, \quad \left|a^{J=3/2}\right| = 0.2 \ldots 3.0 \text{ mfm},$$

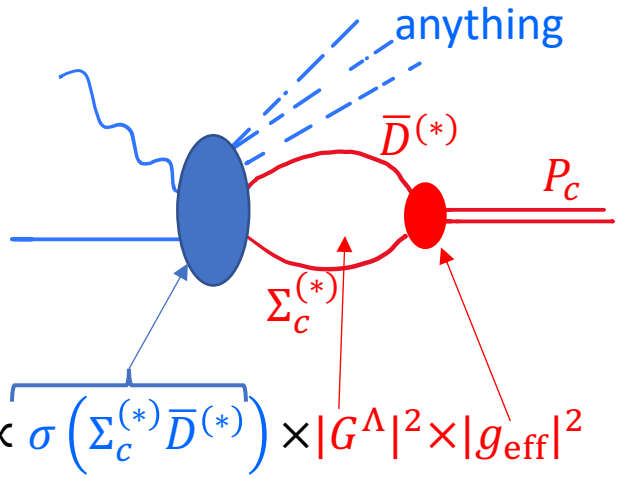
- See also a recent critical analysis of the VMD model using DSE,

Y.-Z. Yu, S.-Y. Chen, Z.-Q. Yao, D. Binosi, Z.-F. Cui, C. D. Roberts, EPJC81(2021)895

Cross section estimates

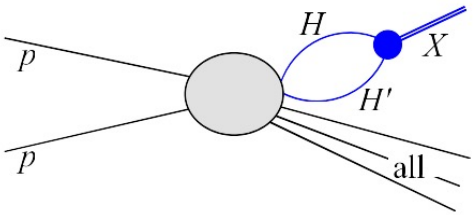
- Order-of-magnitude estimates of inclusive lepto-production of near-threshold hadronic molecules
- The cross section can be estimated as

  e.g., for P_c states



- 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



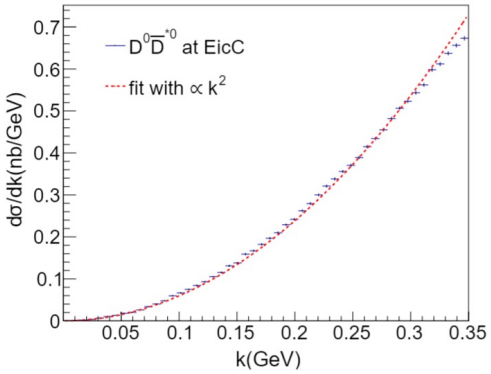
$\sigma(pp/\bar{p}\to X)$ [nb] Exp.		Λ=0.5 GeV	Λ=1.0 GeV
Tevatron	37-115	7 (5)	29 (20)
LHC-7	13-39	13 (4)	55 (15)

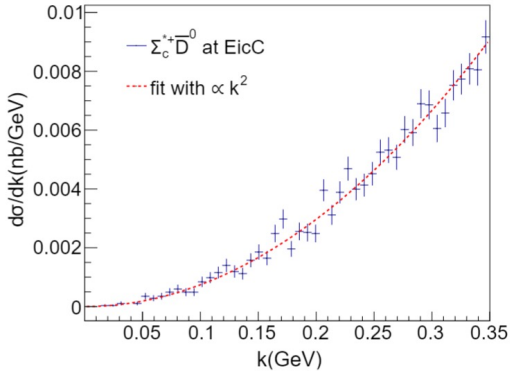
Albaladejo, FKG, Hanhart et al., CPC41(2017)121001

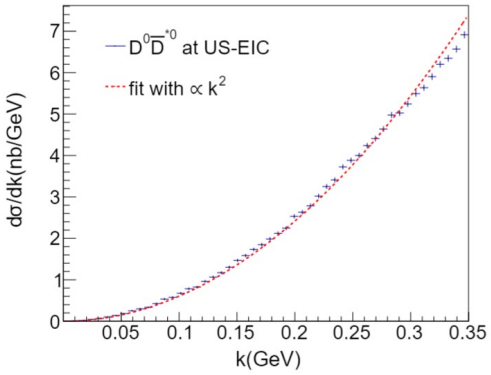
Cross section estimates

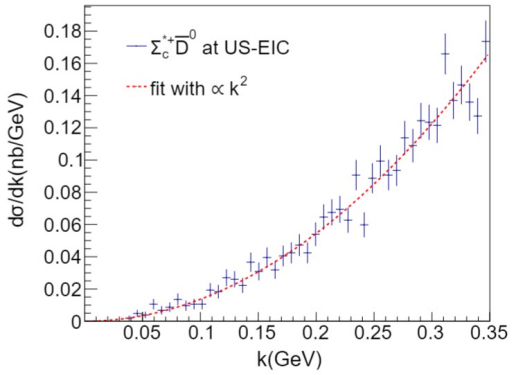
Z. Yang, FKG, CPC 45 (2021) 123101

- Charm hadron pairs generated using Pythia6.4









- Considered machine configurations

	COMPASS	EicC	US-EIC
lepton energy (GeV)	μ^-: 200	e^-: 3.5	e^-: 20
proton energy (GeV)	0	20	250
luminosity ($\mathrm{cm^{-2}s^{-1}}$)	2×10^{32}	2×10^{33}	10^{34}

Cross section estimates

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

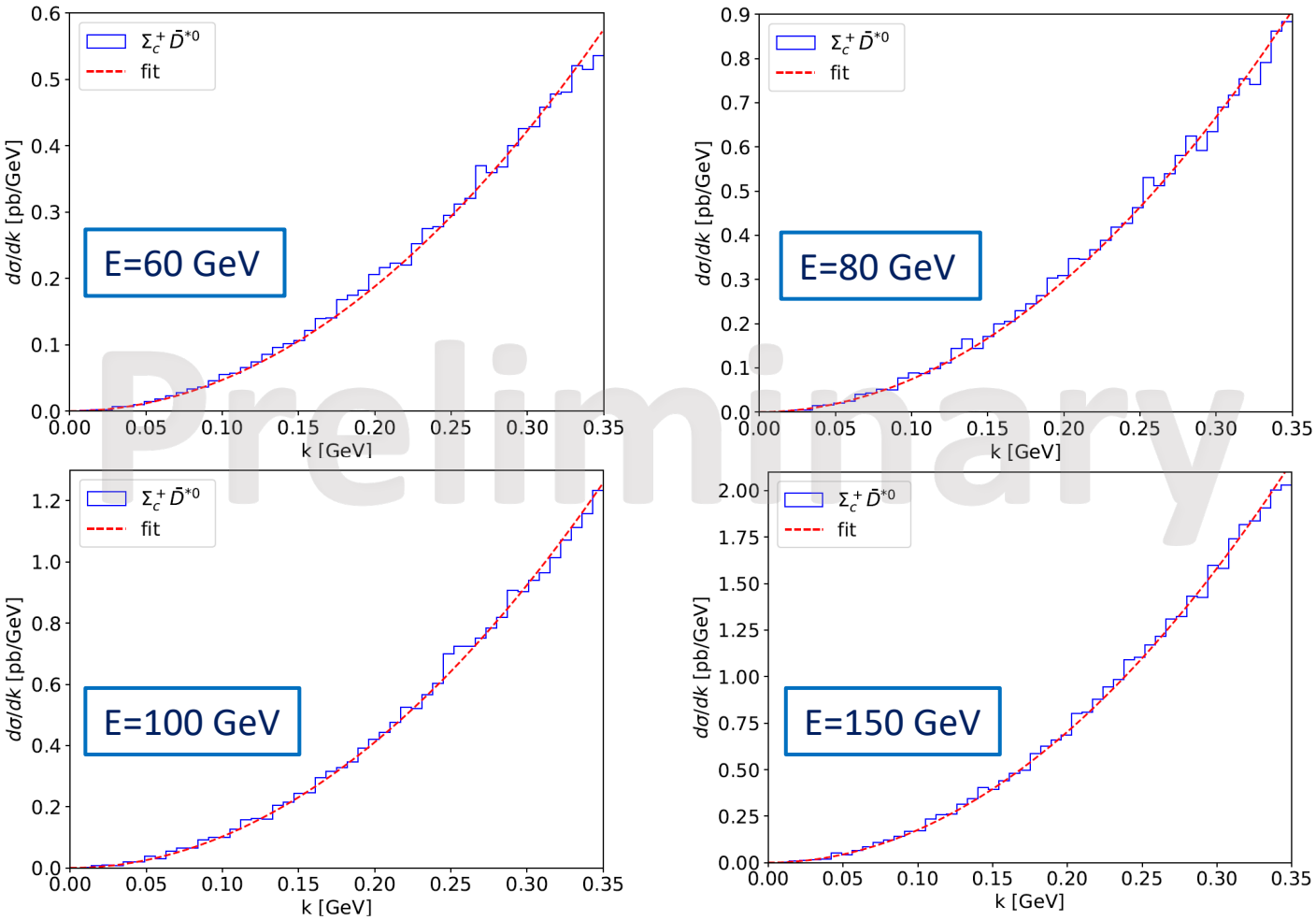
- Order-of-magnitude estimates of the semi-inclusive lepto-production of hidden-charm hadronic molecules (in units of pb)

	Constituents	$J^{P(C)}$	COMPASS	EicC	US-EIC
$X(3872)$	$D\bar{D}^*$	1^{++}	19(78)	21(89)	216(904)
$Z_c(3900)^0$	$D\bar{D}^*$	1^{+-}	$0.3\times10^3(1.2\times10^3)$	$0.4\times10^3(1.3\times10^3)$	$3.8\times10^3(14\times10^3)$
$Z_c(3900)^+$	$D^{*+}\bar{D}^0$	1^+	$0.2\times10^3(0.9\times10^3)$	$0.3\times10^3(1.0\times10^3)$	$2.7\times10^3(9.9\times10^3)$
$Z_c(4020)^0$	$D^*\bar{D}^*$	1^{+-}	$0.1\times10^3(0.5\times10^3)$	$0.2\times10^3(0.6\times10^3)$	$1.7\times10^3(6.3\times10^3)$
Z_{cs}^-	$D^{*0}D_s^-$	1^+	8.3(29)	19(69)	253(901)
Z_{cs}^{*-}	$D^{*0}D_s^{*-}$	1^+	6.2(22)	14(51)	192(679)
$P_c(4312)$	$\Sigma_c\bar{D}$	$1/2^-$	0.8(4.1)	0.8(4.1)	15(73)
$P_c(4440)$	$\Sigma_c\bar{D}^*$	$3/2^-$	0.6(4.3)	0.7(4.7)	11(79)
$P_c(4457)$	$\Sigma_c\bar{D}^*$	$1/2^-$	0.5(2.0)	0.6(2.2)	9.9(36)
$P_c(4380)$	$\Sigma_c^*\bar{D}$	$3/2^-$	1.6(8.0)	1.6(8.4)	30(155)
$P_c(4524)$	$\Sigma_c^*\bar{D}^*$	$1/2^-$	0.8(3.6)	0.8(3.9)	14(67)
$P_c(4518)$	$\Sigma_c^*\bar{D}^*$	$3/2^-$	1.2(6.6)	1.2(6.9)	22(123)
$P_c(4498)$	$\Sigma_c^*\bar{D}^*$	$5/2^-$	1.1(9.3)	1.2(9.8)	21(173)

Semi-inclusive production at CEBAF 24 GeV

P.-P. Shi, FKG, Z. Yang, in preparation

- 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



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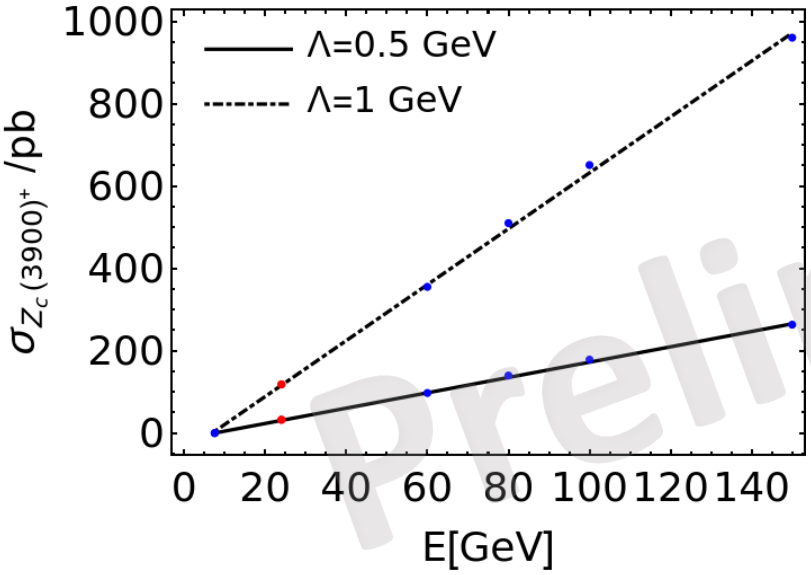
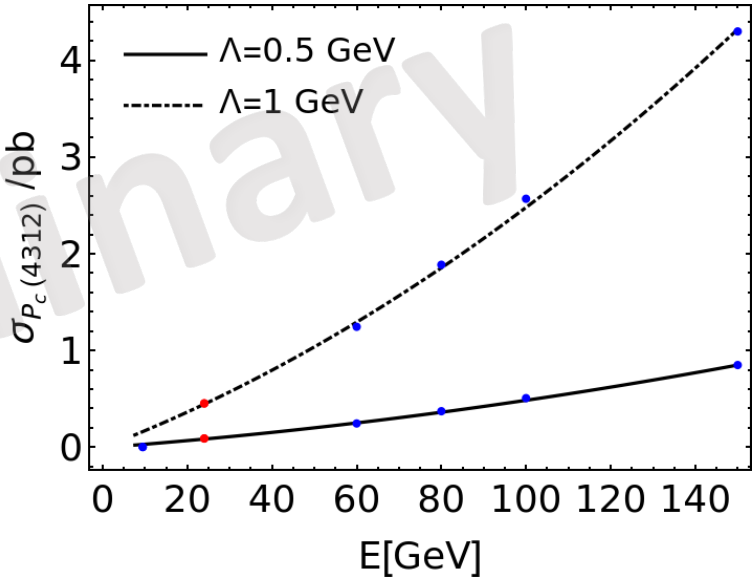




Semi-inclusive production at CEBAF 24 GeV

P.-P. Shi, FKG, Z. Yang, in preparation

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

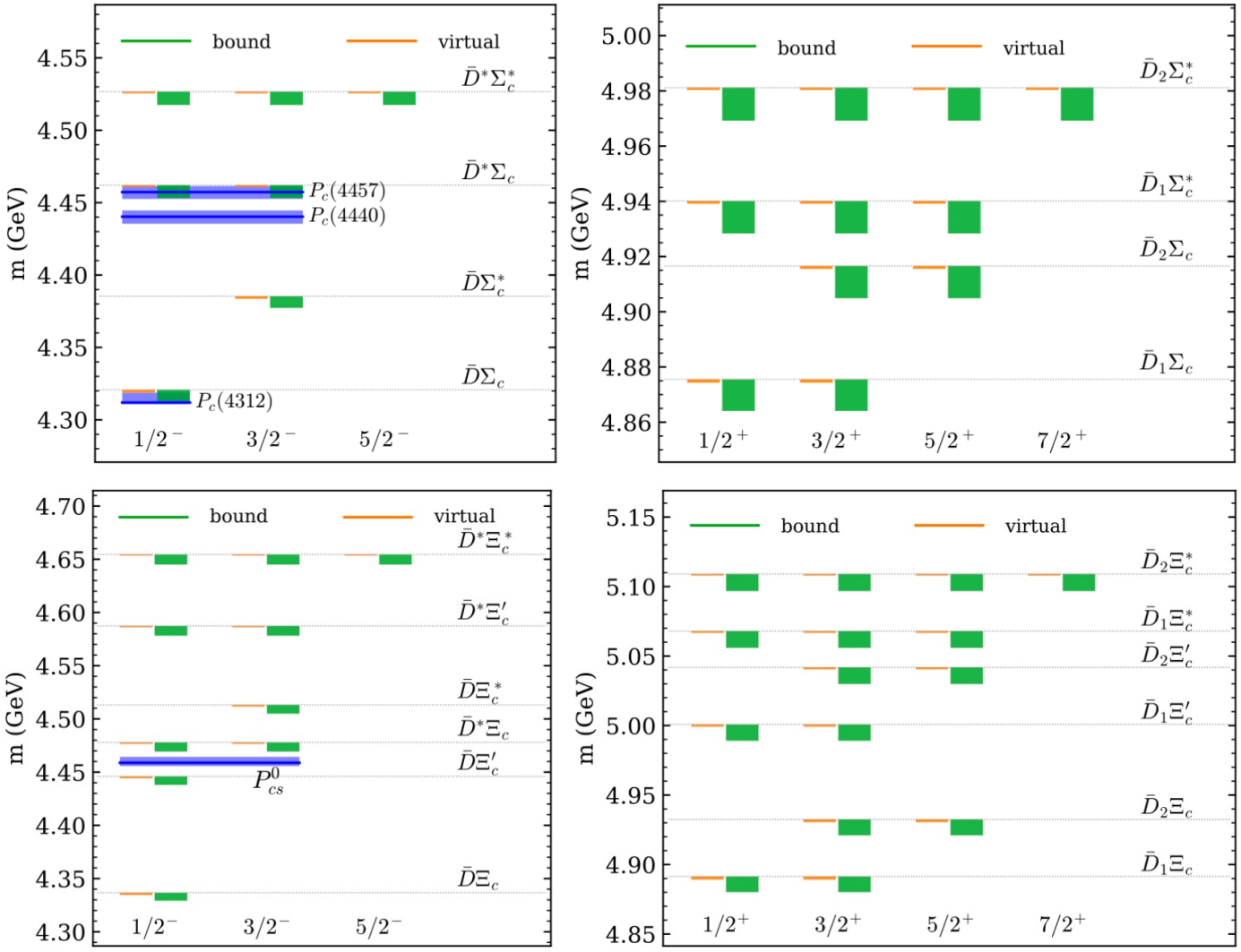
	Constituents	$J^{P(C)}$	σ_X/pb
$X(3872)$	$D\bar{D}^*$	1^{++}	3 (11)
$Z_c(3900)^0$	$D\bar{D}^*$	1^{+-}	46 (165)
$Z_c(3900)^+$	$D^*\bar{D}$	1^+	32 (118)
$P_c(4312)$	$\Sigma_c\bar{D}$	$1/2^-$	0.09 (0.45)
$P_c(4440)^+$	$\Sigma_c\bar{D}^*$	$3/2^-$	0.09 (0.53)
$P_c(4457)^+$	$\Sigma_c\bar{D}^*$	$1/2^-$	0.04 (0.26)
$P_c(4380)^+$	$\Sigma_c^*\bar{D}$	$3/2^-$	0.20 (0.84)
$P_{cs}(4459)$	$\Xi_c\bar{D}^*$	$3/2^-$	0.05 (0.31)

- Not surprising the GlueX observed no signal of P_c: $\sigma(\gamma p \to J/\psi p) = \mathcal{O}(1\ \text{nb}) \gg 10^2 \times \sigma(e^- p \to P_c + \text{anything})$, much higher statistics is needed
- With a luminosity of $10^{36}\ \text{cm}^{-2}\text{s}^{-1}$, for an integrated luminosity of $10^7\ \text{pb}^{-1}$ (?), a large amount of hidden-charm exotics can be produced
  even after having taken into account branching fractions, e.g., $\mathcal{B}(P_c \to J/\psi p) = \mathcal{O}(1\%)$, $\mathcal{B}(J/\psi \to \ell^+\ell^-) = 12\%$

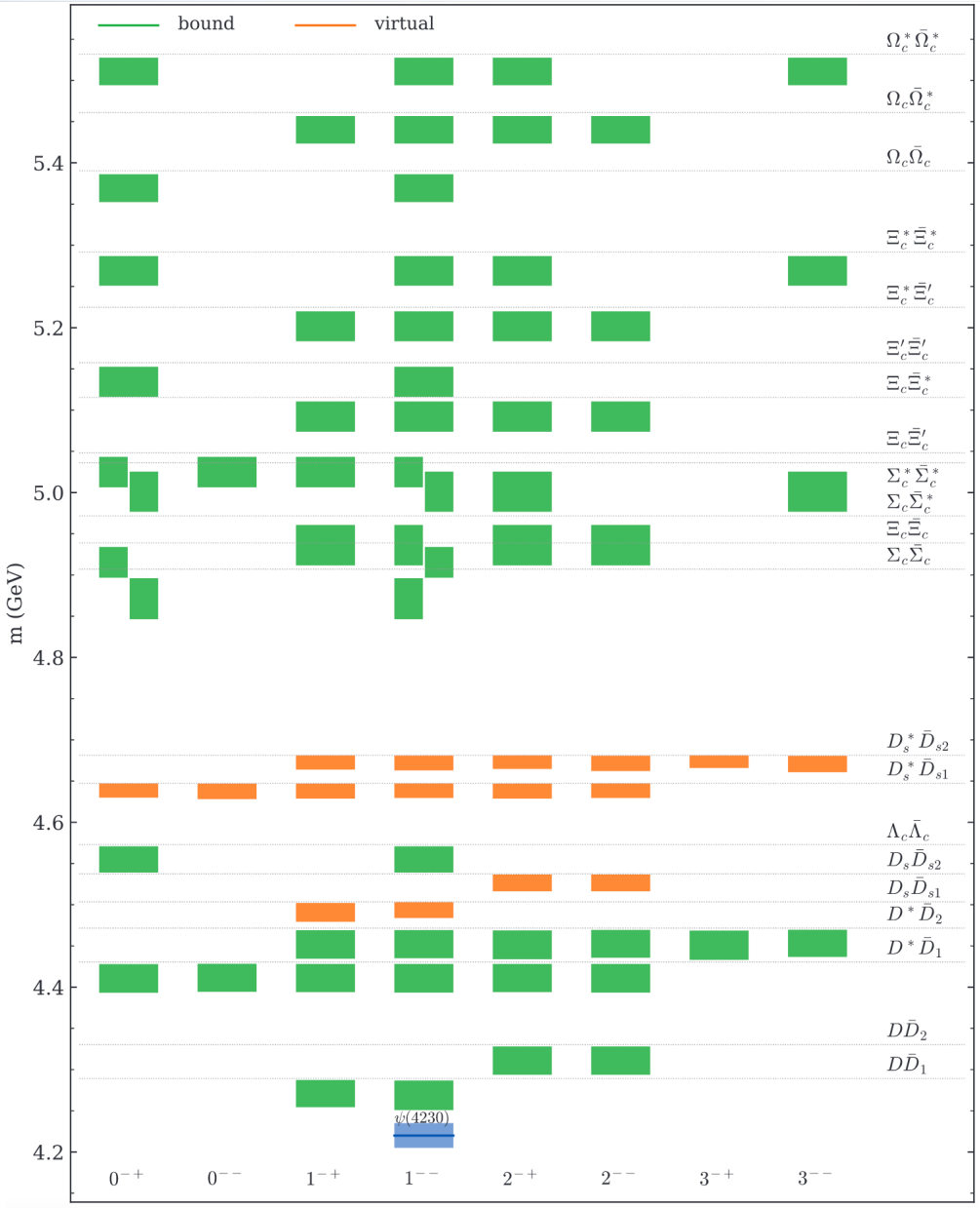
More hadronic molecules are expected

- Many more hidden-charm pentaquarks as hadronic molecules

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



More hadronic molecules are expected



- Hadronic molecules easily formed in the hidden-heavy-flavor region
- Nontrivial near-threshold structure for S-wave attraction

  X.-K. Dong, FKG, B.-S. Zou, PRL126 (2021) 152001; Progr.Phys.41 (2021) 65; CTP73 (2021) 125201

- Other models also predict higher states

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

Summary

- Future lepton-proton machines will also contribute a lot to hadron spectroscopy
- Huge amounts of hidden-charm exotic hadrons will be observed at CEBAF 24 GeV for a luminosity of $10^{36}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Thank you for your attention!