Exotic hadron spectroscopy and heavy flavors at EIC

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2nd PSQ@EIC Meeting: Precision Studies on QCD at EIC

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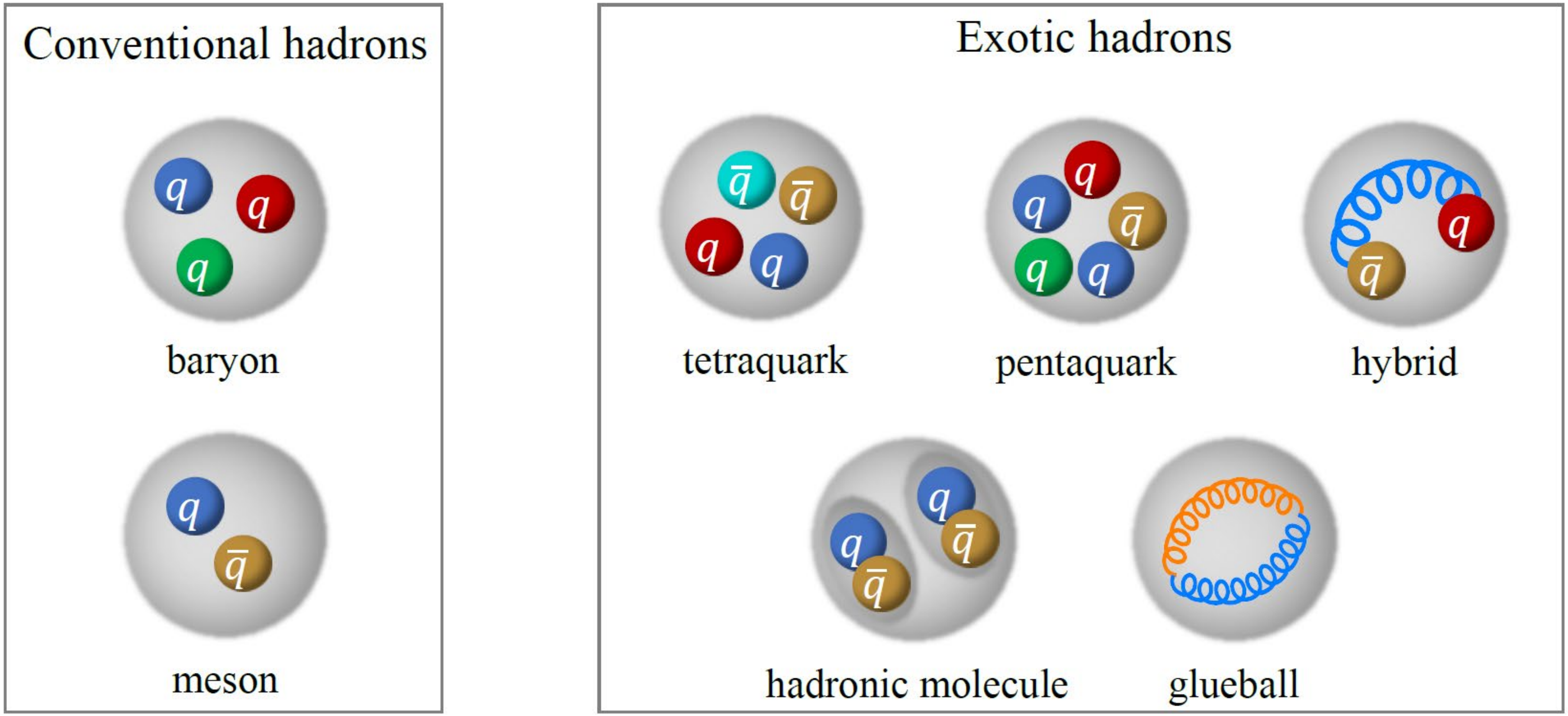
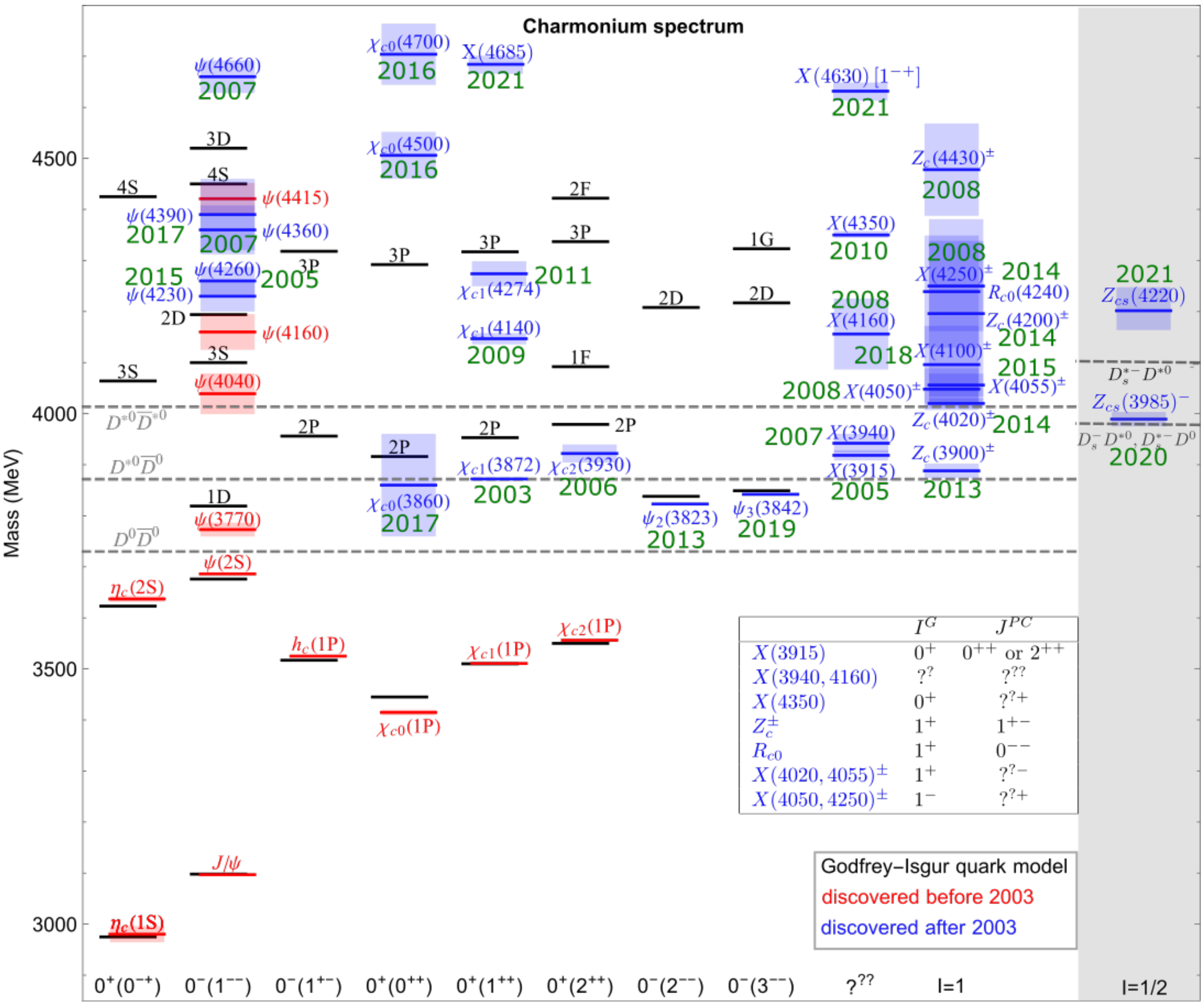
Conventional and exotic hadrons

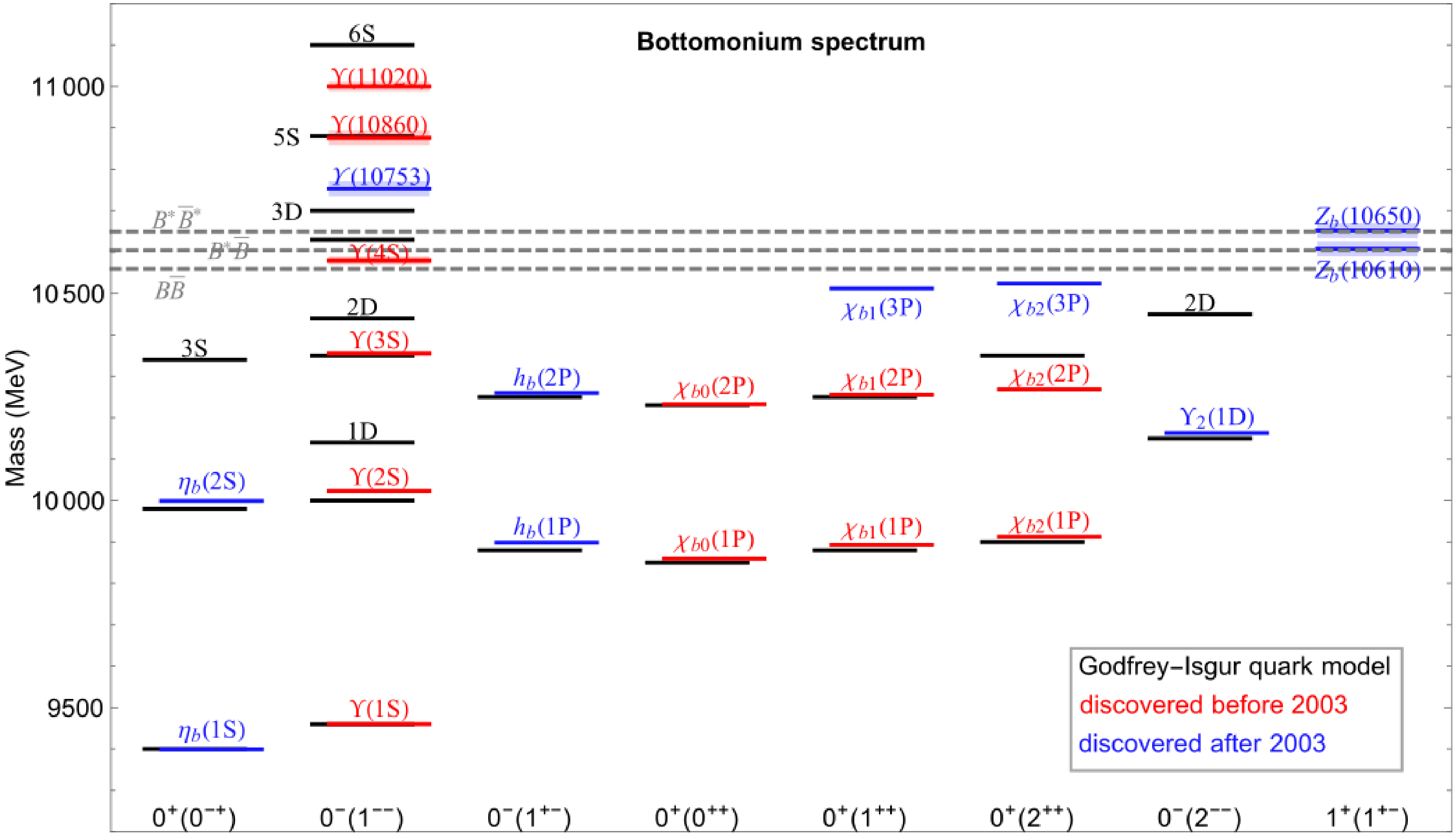


- Most hadrons observed prior to 2003 can be well described in terms of conventional hadrons
- Exotic hadrons are expected; focus of intensive search since long
- Novel experiments (B factories) brought surprises

Hidden-charm XYZ states

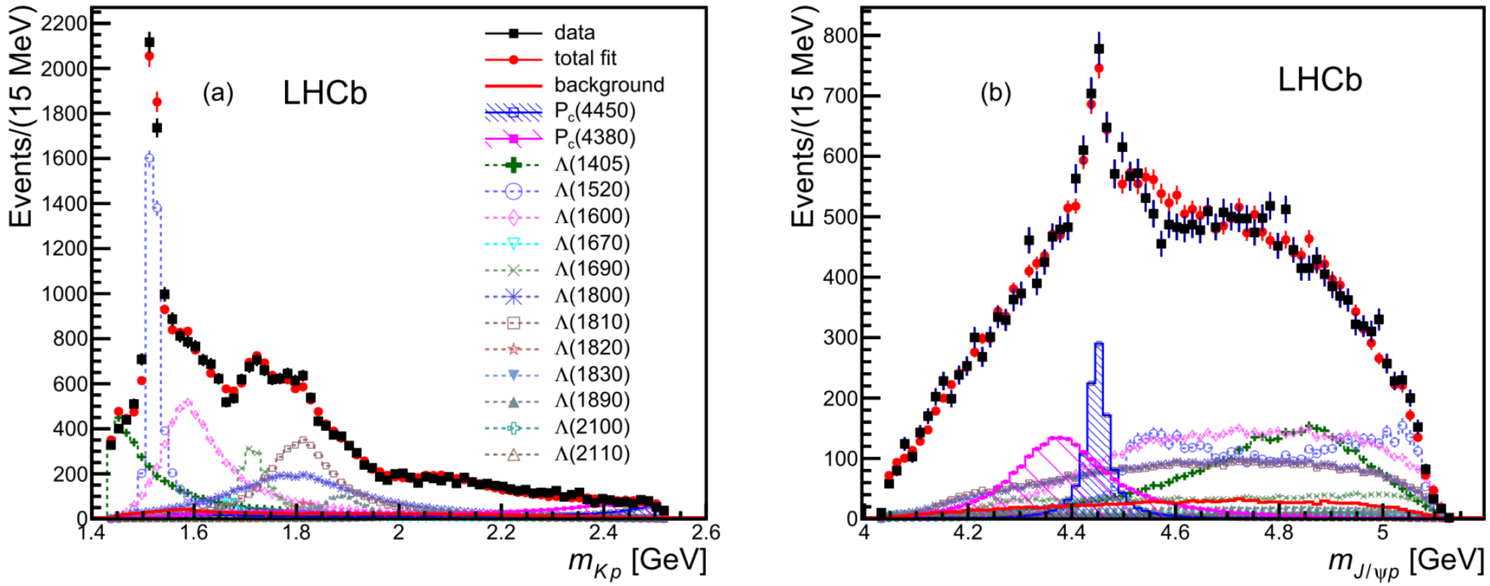


Bottomonium spectrum: much less states observed



Pentaquark candidates: P_c

PRL115(2015)072001 [arXiv:1507.03414]



$$M_1 = (4380 \pm 8 \pm 29)\ \text{MeV}, \qquad \Gamma_1 = (205 \pm 18 \pm 86)\ \text{MeV},$$

$$M_2 = (4449.8 \pm 1.7 \pm 2.5)\ \text{MeV}, \qquad \Gamma_2 = (39 \pm 5 \pm 19)\ \text{MeV}.$$

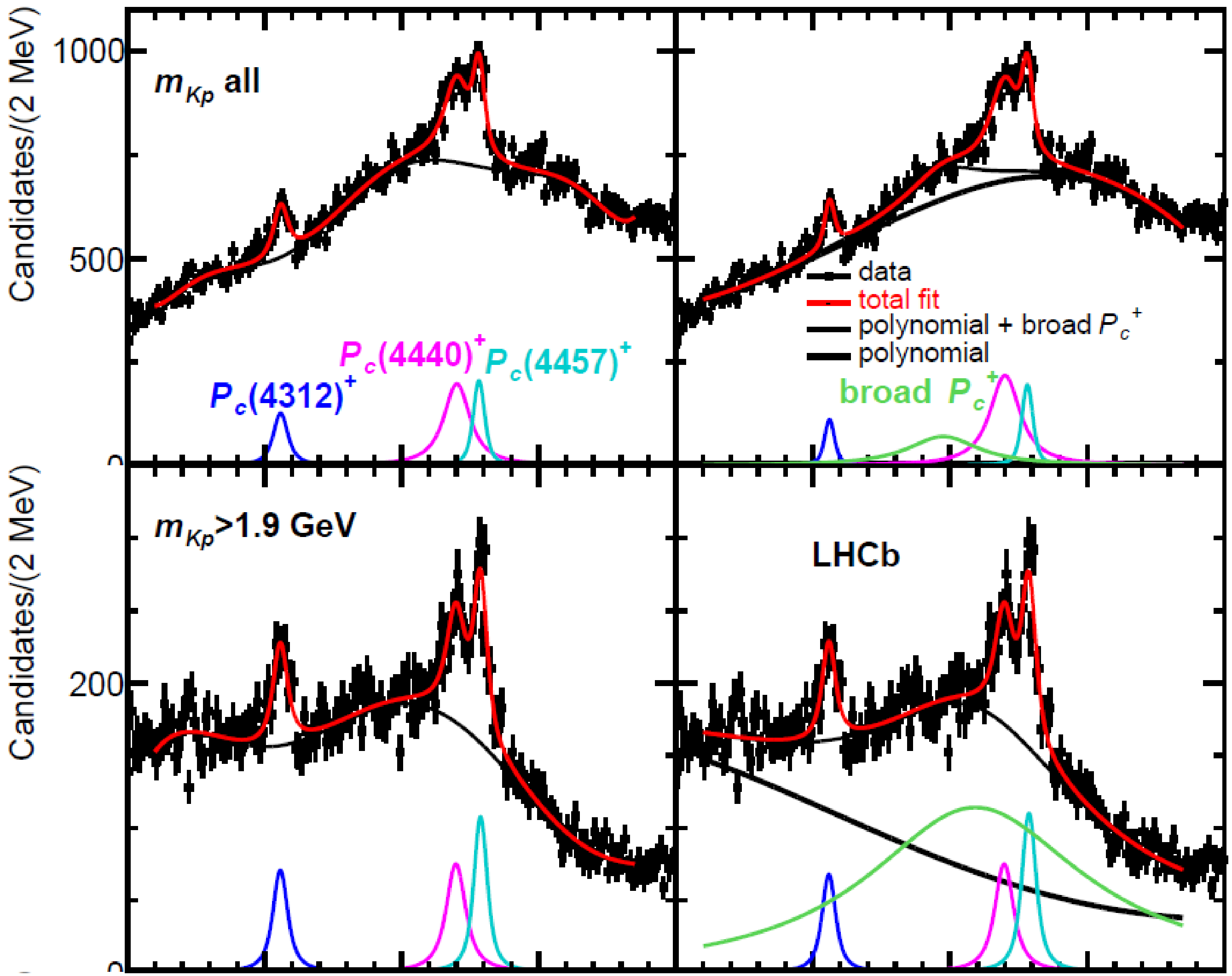
- observed in $J/\psi p$ invariant mass distribution: pentaquark $(c\bar{c}uud)$ candidates
- quantum numbers not fully determined
- Narrow pentaquark-like structures with hidden-charm had been predicted 5 years before (07.2010):

  Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV,

  J.-J. Wu, R. Molina, E. Oset, B.-S. Zou, PRL105(2010)232001

Pentaquark candidates: P_c in 2019

LHCb, PRL122(2019)222001



Production processes of hidden-charm states

- States with ordinary quantum numbers

XYZ	Production processes	Decay channels
$\chi_{c0}(3860)$	$e^+e^- \to J/\psi X$, $\gamma\gamma \to X^{\mathrm{a)}}$	$D\bar{D}$, $\gamma\gamma^{\mathrm{a)}}$
$\chi_{c1}(3872)$	$B \to KX/K\pi X, e^+e^- \to \gamma X$, $pp/p\bar{p}$ semi-inclusive, $\gamma^*\gamma$, PbPb, $\gamma^* N \to X\pi^\pm N^{\mathrm{b)}}$	$\pi^+\pi^- J/\psi, \omega J/\psi, D^{*0}\bar{D}^0, D^0\bar{D}^0\pi^0$, $\pi^0\chi_{c1}, \gamma J/\psi, \gamma\psi(2S)$
$X(3915)$	$B \to KX$, $\gamma\gamma \to X, e^+e^- \to \gamma X$	$\omega J/\psi, \gamma\gamma$
$\chi_{c2}(3930)$	$\gamma\gamma \to X$, pp semi-inclusive	$D\bar{D}, \gamma\gamma$
$X(3940)$	$e^+e^- \to J/\psi + X$	$D\bar{D}^*$
$\chi_{c1}(4140)$	$B \to KX$, $p\bar{p}$ semi-inclusive$^{\mathrm{c)}}$	$\phi J/\psi$
$X(4160)$	$e^+e^- \to J/\psi + X$	$D^*\bar{D}^*$
$\chi_{c1}(4274)$	$B \to KX$	$\phi J/\psi$
$X(4350)$	$\gamma\gamma \to X$	$\phi J/\psi, \gamma\gamma$
$\chi_{c0}(4500)$	$B \to KX$	$\phi J/\psi$
$\chi_{c0}(4700)$	$B \to KX$	$\phi J/\psi$
$\psi_2(3823)$	$B \to K\psi_2, e^+e^- \to \pi\pi\psi_2$	$\gamma\chi_{c1}$
$\psi_3(3842)$	pp semi-inclusive	$D\bar{D}$
$\psi(4230/4260)$	$e^+e^- \to Y, e^+e^- \to Y\gamma_{\mathrm{ISR}}$	$\pi\pi J/\psi, \pi\pi\psi(2S), \chi_{c0}\omega, h_c\pi\pi$, $D\bar{D}^*\pi, \gamma\chi_{c1}(3872), J/\psi K\bar{K}$
$\psi(4360)$	$e^+e^- \to Y, e^+e^- \to Y\gamma_{\mathrm{ISR}}$	$\pi\pi\psi(2S)$, $\pi\pi\psi_2(3823)^{\mathrm{d)}}$, $D_1(2420)\bar{D}^{\mathrm{d)}}$
$\psi(4390)$	$e^+e^- \to Y$	$\pi\pi h_c, \pi\pi\psi(3770)^{\mathrm{d)}}$
$\psi(4660)$	$e^+e^- \to Y\gamma_{\mathrm{ISR}}$	$\pi\pi\psi(2S), \Lambda_c\bar{\Lambda}_c, D_s^+ D_{s1}(2536)^-$

Production processes of hidden-charm states

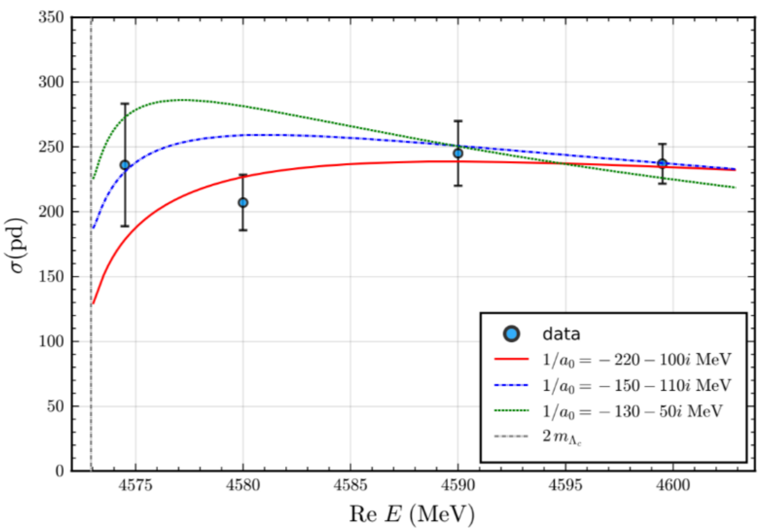
- Explicitly exotic states

XYZ	Production processes	Decay channels
$Z_c(3900)^{\pm}$	$e^+e^- \to \pi Z_c$, b-hadron semi-inclusive decays	$\pi J/\psi, D\bar{D}^*$
$X(4020)^{\pm}$	$e^+e^- \to \pi Z_c$	$\pi h_c, D^*\bar{D}^*$
$X(4050)^{\pm}$	$B \to KZ_c$	$\pi^{\pm}\chi_{c1}$
$X(4055)^{\pm}$	$e^+e^- \to \pi X$	$\pi^{\pm}\psi(2S)$
$X(4100)^{\pm}$	$B \to KZ_c$	$\pi^{\pm}\eta_c$
$Z_c(4200)^{\pm}$	$B \to KZ_c$	$\pi^{\pm}J/\psi$
$R_{c0}(4240)^{-}$	$B \to KR_{c0}$	$\pi^{-}\psi(2S)$
$X(4250)^{\pm}$	$B \to KZ_c$	$\pi^{\pm}\chi_{c1}$
$Z_c(4430)^{\pm}$	$B \to KZ_c$	$\pi^{\pm}J/\psi, \pi^{\pm}\psi(2S)$
$P_c(4312)^{+}$	$\Lambda_b \to K^- P_c$ [e)]	pJ/ψ
$P_c(4380)^{+}$	$\Lambda_b \to K^- P_c$	pJ/ψ
$P_c(4440)^{+}$	$\Lambda_b \to K^- P_c$	pJ/ψ
$P_c(4457)^{+}$	$\Lambda_b \to K^- P_c$	pJ/ψ

- ☐ b-hadron decays with $b \to c\bar{c}s$
- ☐ e^+e^- collisions
- ☐ Hadron (ion) collisions

Production processes of hidden-charm states

- In e^+e^- collisions,
  - Energy coverage limited: $\lesssim 4.9$ GeV @BESIII, thus
    - ✓ Vector heavy quarkonia; little is known above that energy (BEPCII-upgrade planned);
    - ✓ for other quantum numbers, even lower mass accessible: $e^+e^- \to X + \gamma/\text{pions}$; resonances decaying into $\psi\phi$, $\psi\omega$ can hardly be studied
    - ✓ No access to charm-anticharm baryon-pair thresholds higher than $\Lambda_c^+\overline{\Lambda}_c^-$, e.g. $\Sigma_c\bar{\Sigma}_c$

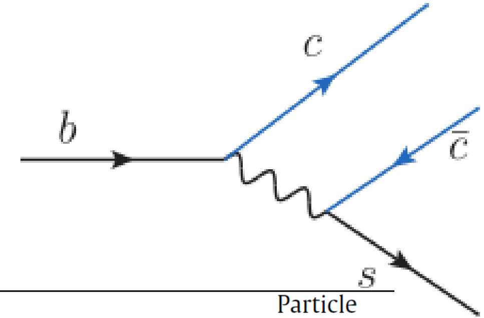


$e^+e^- \to \Lambda_c^+\Lambda_c^-$

Data taken from BESIII, PRL120(2018)132001
Fits described in
X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41(2021)65

  - $e^+e^- \to \gamma_{\text{ISR}}Y$ and two-photon processes: much lower rates

Production processes of hidden-charm states



- In weak decays $b \to [c\bar{c}]s$

Three/four-body hadronic decays: $B \to K\, X$, $\Lambda_b \to K\, P_c$

Process	Production	Decay	Particle
B and Λ_b decays	$B \to K + X$	$X \to \pi^+\pi^- J/\psi$ [4,110–115] $X \to D^{*0}\bar{D}^0$ [116–118] $X \to \gamma J/\psi$ [119–122] $X \to \gamma\psi(2S)$ [119,121]	$X(3872)$
		$X \to \omega J/\psi$ [107,123,124]	$X(3872)$ $Y(3940)$
		$X \to \gamma\chi_{c1}$ [125]	$X(3823)$
		$X \to \phi J/\psi$ [126–133]	$Y(4140)$ $Y(4274)$ $X(4500)$ $X(4700)$
	$B \to K + Z$	$Z \to \pi^\pm\chi_{c1}$ [134,135]	$Z_1(4050)$ $Z_2(4250)$
		$Z \to \pi^\pm J/\psi$ [46,136]	$Z_c(4200)$ $Z_c(4430)$
		$Z \to \pi^\pm\psi(2S)$ [30,136–140]	$Z_c(4240)$ $Z_c(4430)$
	$B \to K\pi + X$	$X \to \pi^+\pi^- J/\psi$ [141]	$X(3872)$
	$\Lambda_b \to K + P_c$	$P_c \to pJ/\psi$ [35]	$P_c(4380)$ $P_c(4450)$

Lebed, Mitchell, Swanson, PPNP93(2017)143

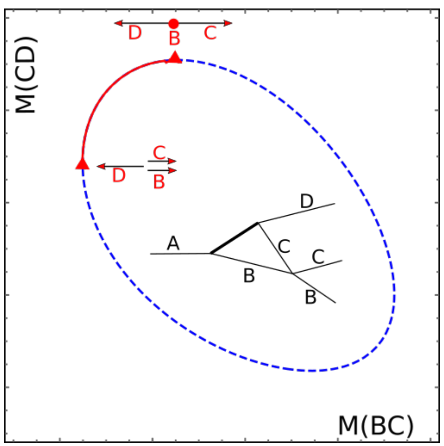
- Masses limited to

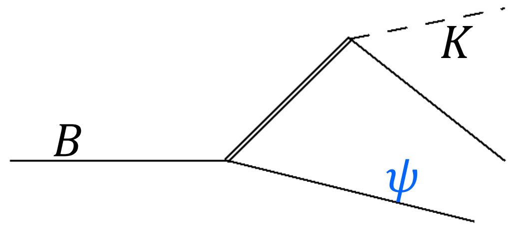
$$M_B - M_K \approx 4.8\text{ GeV} \qquad M_{\Lambda_b} - M_K \approx 5.1\text{ GeV}$$

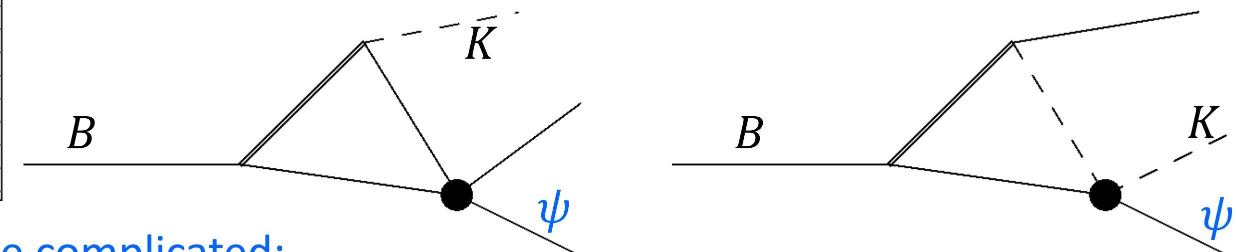
- Masses of initial states fixed

Production processes of hidden-charm states

- Difficulties for multi-hadron final states
  - ✓ Many resonances from the cross channel:
    branching fractions often unknown, interference between overlapping resonances, multi-channel unitarity, …







  - ✓ 3-body FSI is even more complicated:
    intermediate states can be different from external ones; threshold cusps; triangle singularities or more complicated Landau singularities
  - ✓ We need combined th.+exp. efforts: other production processes; better knowledge of light-flavor resonances; amplitude analysis framework considering the above subtleties

Photoproduction: charm

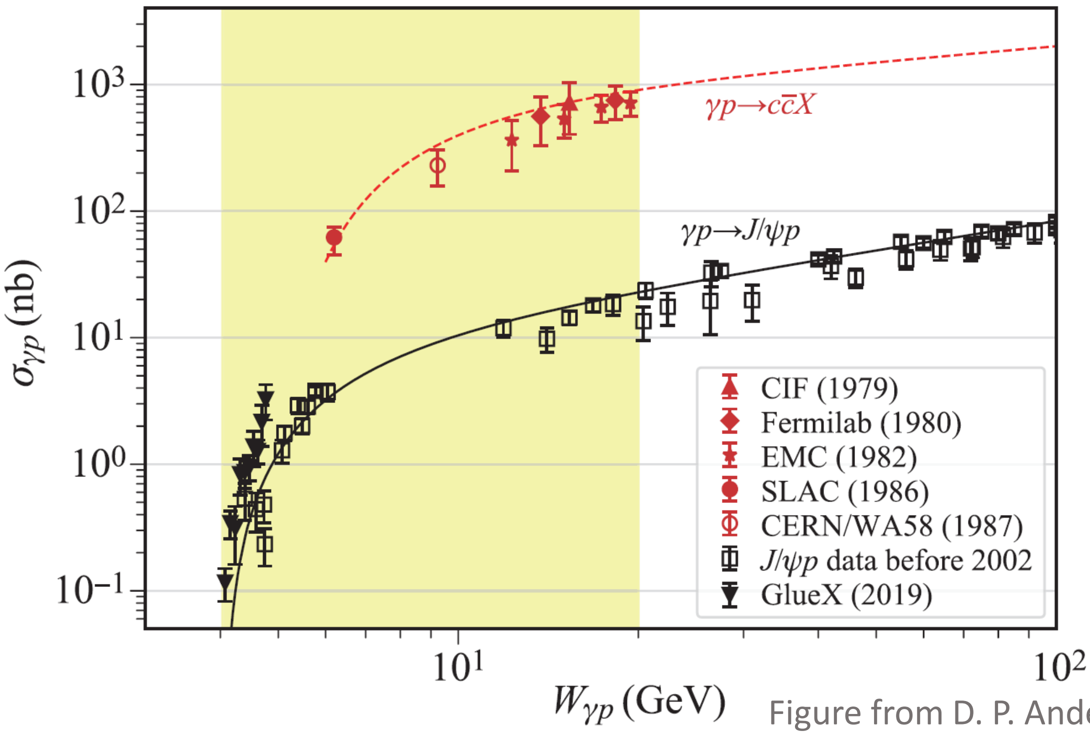


Figure from D. P. Anderle et al. Front.Phys.16(2021)64701

For W=10-20 GeV,

- Photoproduction: $\sigma(\gamma p \to J/\psi p) \sim O(10\text{ nb})$, (no resonant enhancement considered), $\sigma(\gamma p \to c\bar{c}X) \sim 50\sigma(\gamma p \to J/\psi p)$
- Leptoproduction: cross sections are roughly two orders of magnitude (α) smaller
- For an integrated luminosity of 50 fb^{-1}, no. of J/ψ is $\sim O\left(10^7 - 10^8\right)$; many more open-charm hadrons D and Λ_c

Photoproduction: bottom

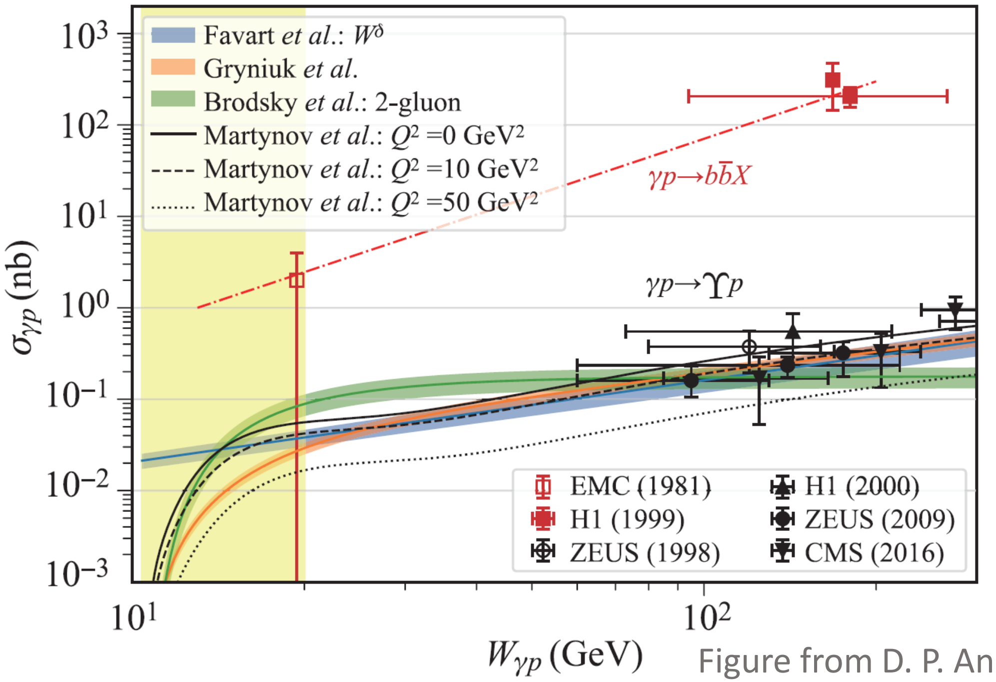


Figure from D. P. Anderle et al. Front.Phys.16(2021)64701

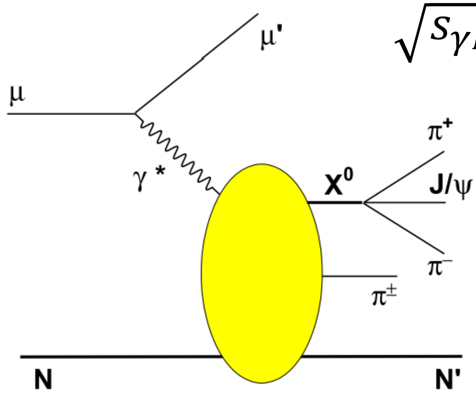
For W=15-20 GeV,

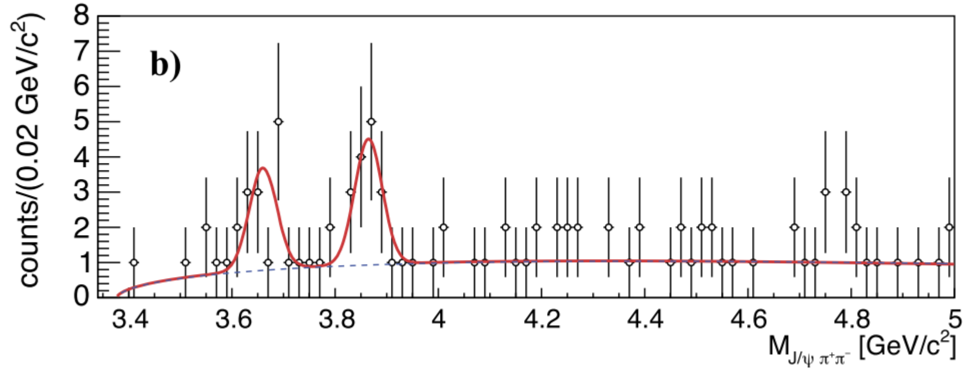
- Photoproduction: $\sigma(\gamma p \to \Upsilon p) \sim O(10\ \mathrm{pb})$ (no resonant enhancement considered), $\sigma(\gamma p \to b\bar{b}X)$ is about two orders higher
- Electroproduction: roughly two orders of magnitude (α) smaller, $\sim O(0.1\ pb)$
- For an integrated luminosity of 50 fb^{-1}, no. of Υ is $\sim O(10^4)$;

Hidden-charm exotic state observed by COMPASS

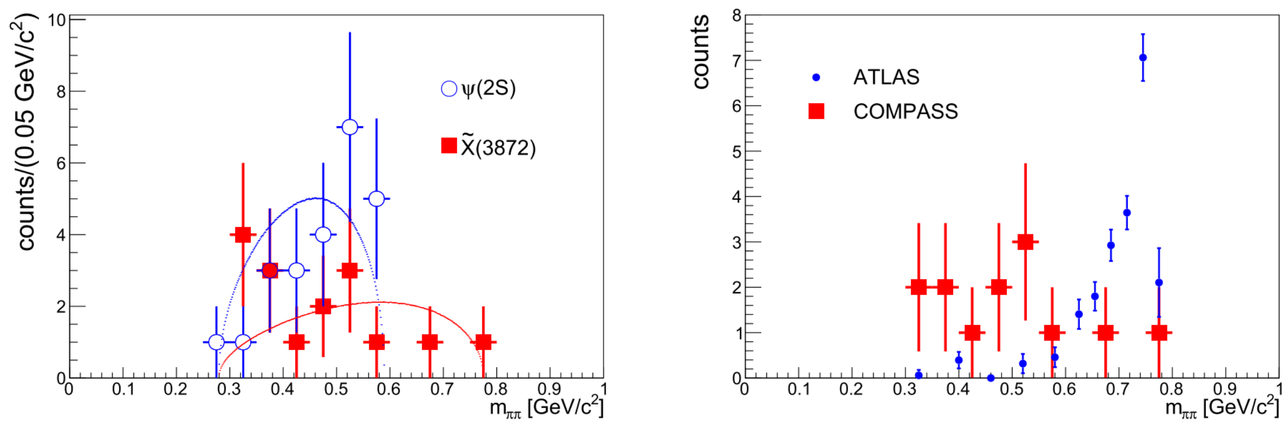
- Observation of $\tilde{X}(3872)$ in $\gamma^* N \to X^0 \pi^\pm N'$ with 4.1σ COMPASS, PLB783(2018)334

$\sqrt{s_{\gamma N}} \in [8, 18]$ GeV $\qquad M_{\tilde{X}} = 3860.4 \pm 10.0$ MeV





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



(a) (b)

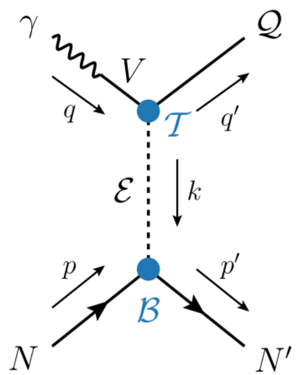
- Cross sections:

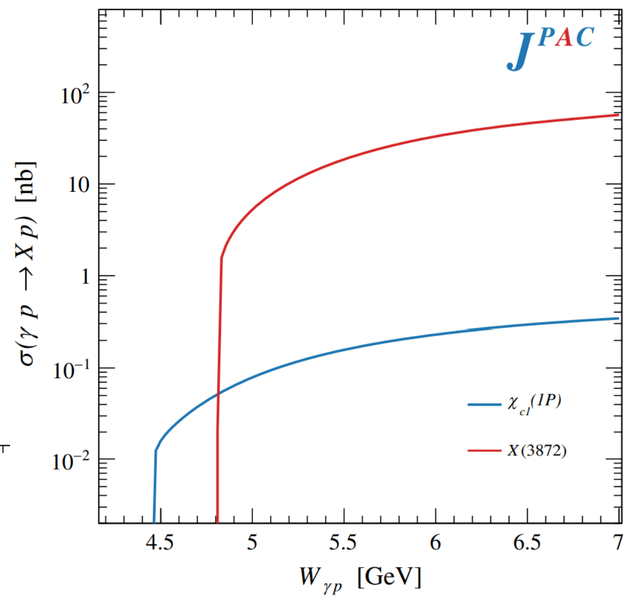
$$\sigma(\gamma N \to \tilde{X}\pi N') \times \mathcal{B}(\tilde{X} \to J/\psi\pi^+\pi^-) = 71 \pm 28 \pm 39 \text{ pb}$$

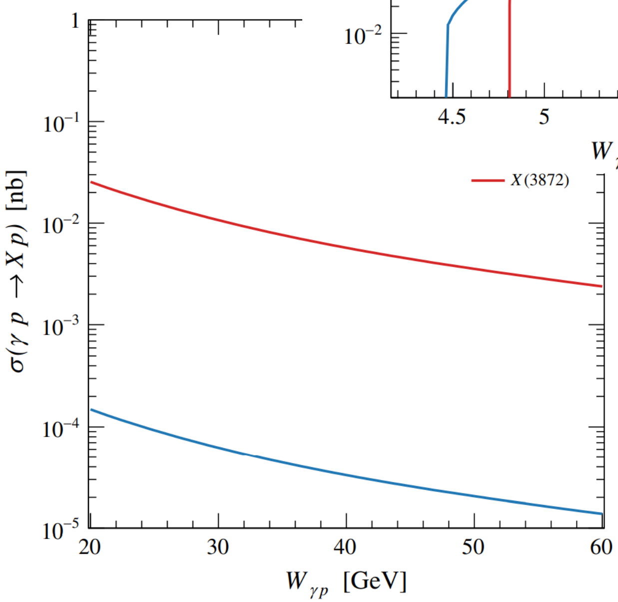
$$\sigma(\gamma N \to X(3872)N') \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 2.9 \text{ pb (CL} = 90\%)$$

Exclusive photo-production of hidden-charm states

- Estimates of exclusive photo-production of hidden-charm states normally assumes vector-meson dominance (for a list of refs., see Sec.2 in Anderle et al. Front.Phys.16(2021)64701):







JPAC, PRD102(2020)114010

➢ Estimated events for EicC

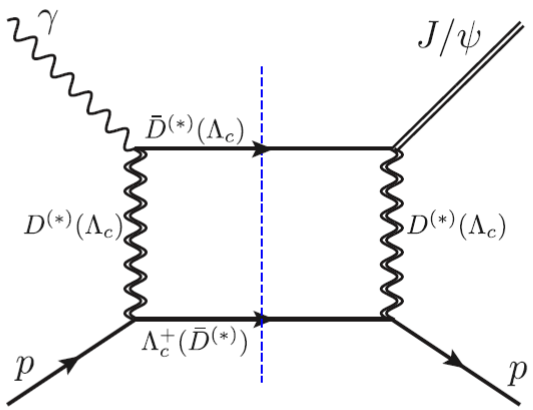
Exotic states	Production/decay processes	Detection efficiency	Expected events
$P_c(4312)$	$ep \to eP_c(4312)$ $P_c(4312) \to pJ/\psi$ $J/\psi \to l^+l^-$	∼30%	15−1450
$P_c(4440)$	$ep \to eP_c(4440)$ $P_c(4440) \to pJ/\psi$ $J/\psi \to l^+l^-$	∼30%	20−2200
$P_c(4457)$	$ep \to eP_c(4457)$ $P_c(4457) \to pJ/\psi$ $J/\psi \to l^+l^-$	∼30%	10−650
P_b(narrow)	$ep \to eP_b(\text{narrow})$ $P_b(\text{narrow}) \to p\Upsilon$ $\Upsilon \to l^+l^-$	∼30%	0−20
P_b(wide)	$ep \to eP_b(\text{wide})$ $P_b(\text{wide}) \to p\Upsilon$ $\Upsilon \to l^+l^-$	∼30%	0−200
$\chi_{c1}(3872)$	$ep \to e\chi_{c1}(3872)p$ $\chi_{c1}(3872) \to \pi^+\pi^-J/\psi$ $J/\psi \to l^+l^-$	∼50%	0−90
$Z_c(3900)^+$	$ep \to eZ_c(3900)^+n$ $Z_c^+(3900) \to \pi^+J/\psi$ $J/\psi \to l^+l^-$	∼60%	90−9300

Anderle et al. Front.Phys.16(2021)64701

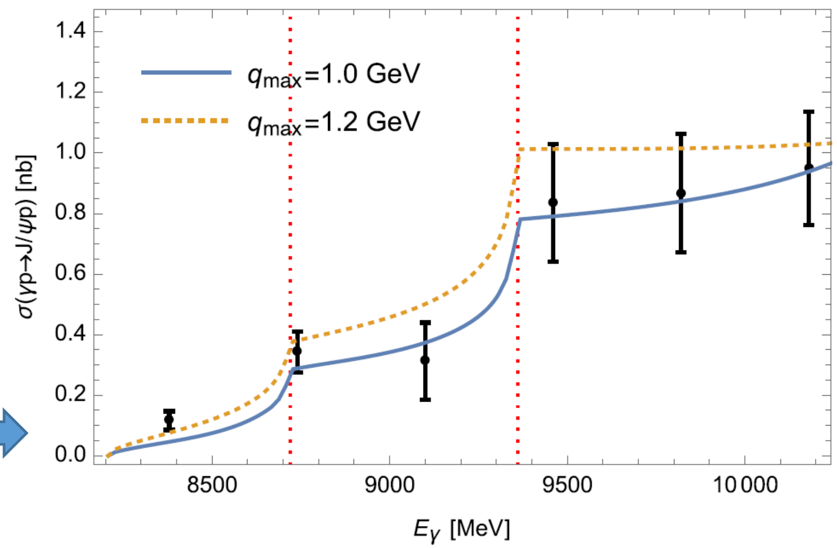
Exclusive photo-production of hidden-charm states

- However, vector-meson dominance model might not work well for J/ψ and Υ
  - Open-charm channels easier to be produced than $J/\psi p$, coupled-channel effects could be important

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



Estimated cross section w/ all couplings taken from literature

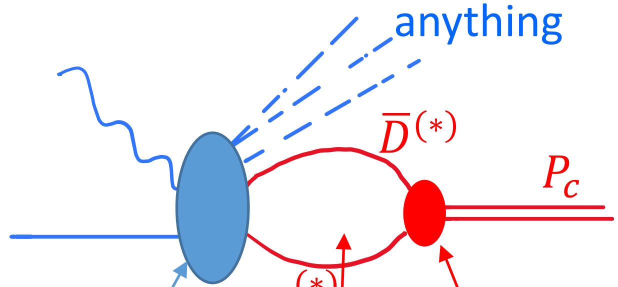


  - See also a recent critical analysis of the VMD model using DSE,

Y.-Z. Yu, S.-Y. Chen, Z.-Q. Yao, D. Binosi, Z.-F. Cui, C. D. Roberts, arXiv:2107.03488

Production of pentaquarks and XYZ in semi-inclusive processes

- Production of P_c in semi-inclusive reactions:



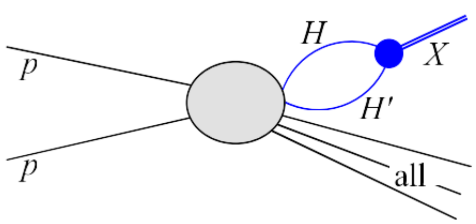
The cross section can be estimated as

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

Event generators

The method has been used to estimate the X(3872) production at hadron colliders

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

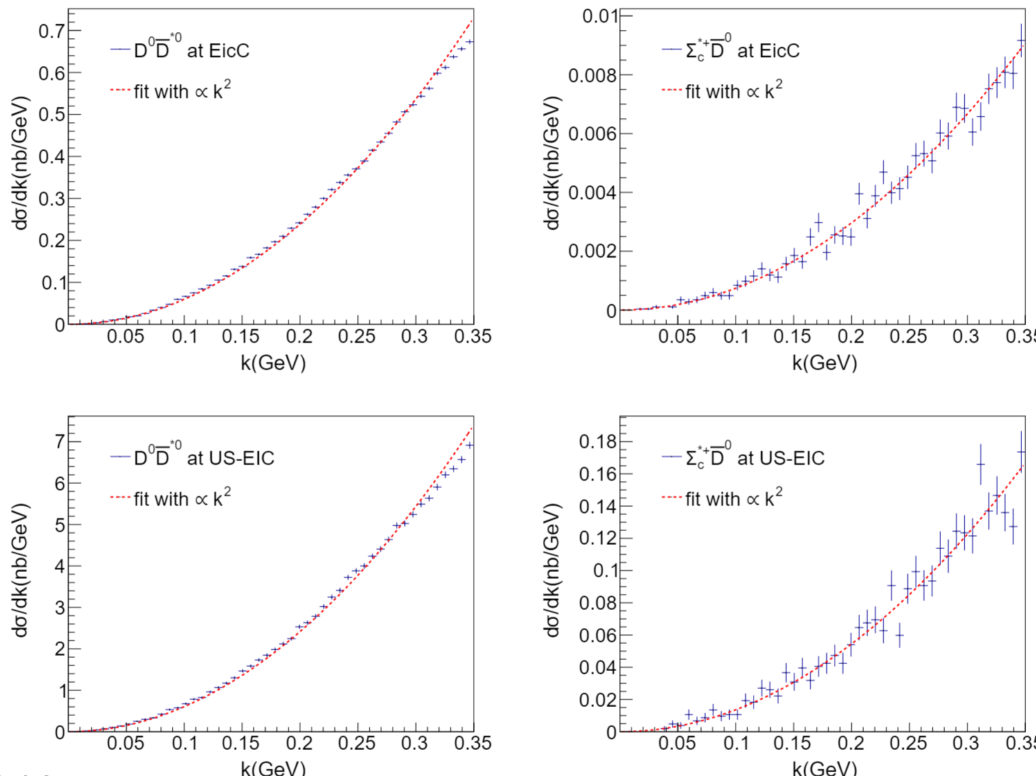


$\sigma(\mathrm{pp}/\bar{\mathrm{p}}\to\mathrm{X})$ [nb]	Exp.	Λ=0.5 GeV	Λ=1.0 GeV
Tevatron	37-115	7 (5)	29 (20)
LHC-7	13-39	13 (4)	55 (15)

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

Production of pentaquarks and XYZ in semi-inclusive processes

- Charm hadron pairs generated using Pythia



- Considered machine configurations

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

Z. Yang, FKG, arXiv:2107.xxxxx

Production of pentaquarks and XYZ in semi-inclusive processes

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

	constituent	COMPASS	EicC	US-EIC
$X(3872)$	$D\bar{D}^*$	$19(78)$	$21(89)$	$216(904)$
$Z_c(3900)^0$	$D\bar{D}^*$	$0.3 \times 10^3(1.2 \times 10^3)$	$0.4 \times 10^3(1.3 \times 10^3)$	$3.8 \times 10^3(14 \times 10^3)$
$Z_c(3900)^+$	$D^{*+}\bar{D}^0$	$0.2 \times 10^3(0.9 \times 10^3)$	$0.3 \times 10^3(1.0 \times 10^3)$	$2.7 \times 10^3(9.9 \times 10^3)$
$Z_c(4020)^0$	$D^*\bar{D}^*$	$0.1 \times 10^3(0.5 \times 10^3)$	$0.2 \times 10^3(0.6 \times 10^3)$	$1.7 \times 10^3(6.3 \times 10^3)$
Z_{cs}^-	$D^{*0}D_s^-$	$8.3(29)$	$19(69)$	$253(901)$
Z_{cs}^{*-}	$D^{*0}D_s^{*-}$	$6.2(22)$	$14(51)$	$192(679)$
$P_c(4312)$	$\Sigma_c\bar{D}$	$0.8(4.1)$	$0.8(4.1)$	$15(73)$
$P_c(4440)$	$\Sigma_c\bar{D}^*$	$0.6(4.3)$	$0.7(4.7)$	$11(79)$
$P_c(4457)$	$\Sigma_c\bar{D}^*$	$0.5(2.0)$	$0.6(2.2)$	$9.9(36)$
$P_c(4380)$	$\Sigma_c^*\bar{D}$	$1.6(8.0)$	$1.6(8.4)$	$30(155)$
$P_c(4524)$	$\Sigma_c^*\bar{D}^*$	$0.8(3.6)$	$0.8(3.9)$	$14(67)$
$P_c(4518)$	$\Sigma_c^*\bar{D}^*$	$1.2(6.6)$	$1.2(6.9)$	$22(123)$
$P_c(4498)$	$\Sigma_c^*\bar{D}^*$	$1.1(9.3)$	$1.2(9.8)$	$21(173)$

Z. Yang, FKG, arXiv:2107.xxxxx

Summary

- EIC and EicC will also contribute a lot to hadron spectroscopy
- Consider open-flavor final states (challenge: detection efficiency?)
- Supplementary to existing experiments Different production mechanisms: free of triangle singularities in B and Λ_b decays

Complementary to

Thank you for your attention!

EIC machines

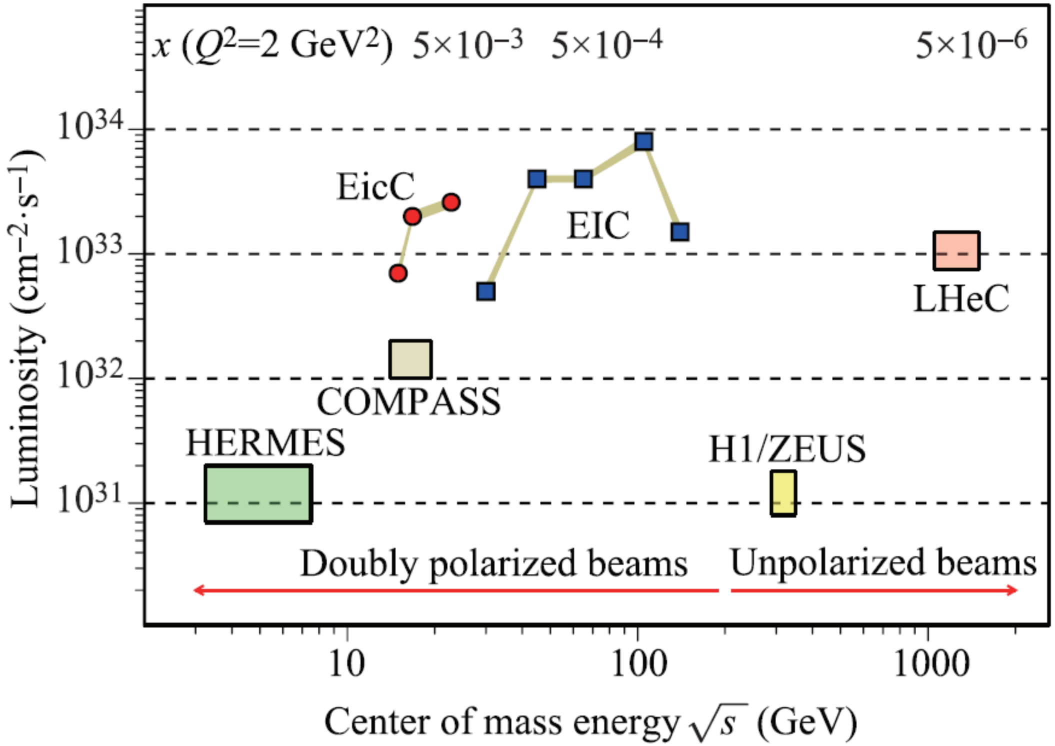


Figure taken from D. P. Anderle et al. Front.Phys.16(2021)64701