

Near-threshold exotic hadrons

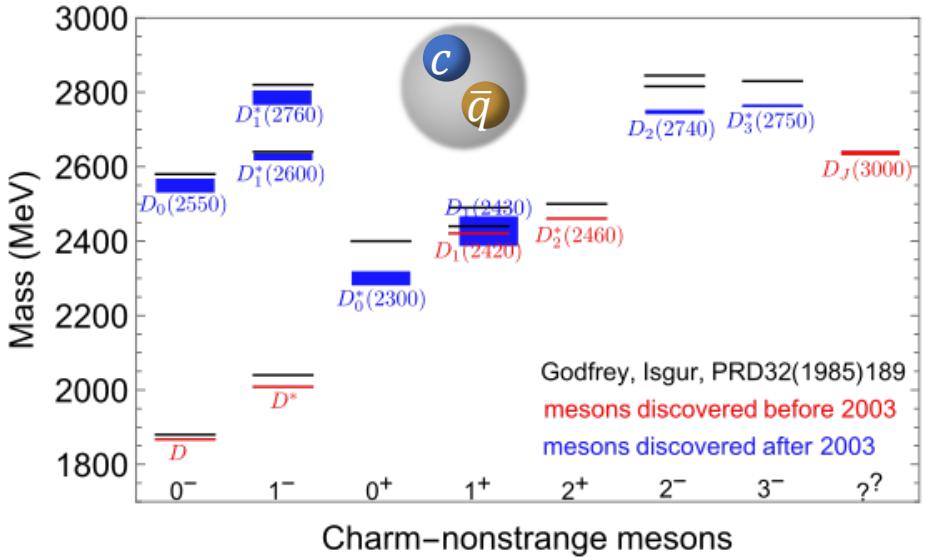
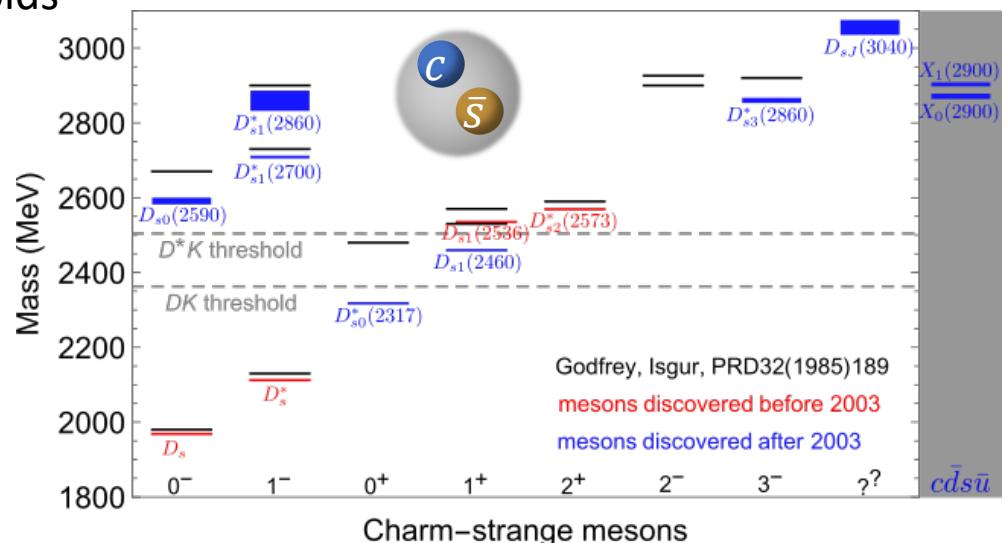
Feng-Kun Guo
Institute of Theoretical Physics, CAS



25-27 Oct. 2021

Hadron spectrum: charmonium(-like)

- Quark model provides qualitative guidance, but the physics is much richer, in particular for energies close to or above thresholds
- Abundance of new states from **peak hunting**
 - b -hadron (B, Λ_b) decays
 - e^+e^- collisions
 - Hadron collisions
 - Heavy-ion collisions
- Example: open-charm mesons

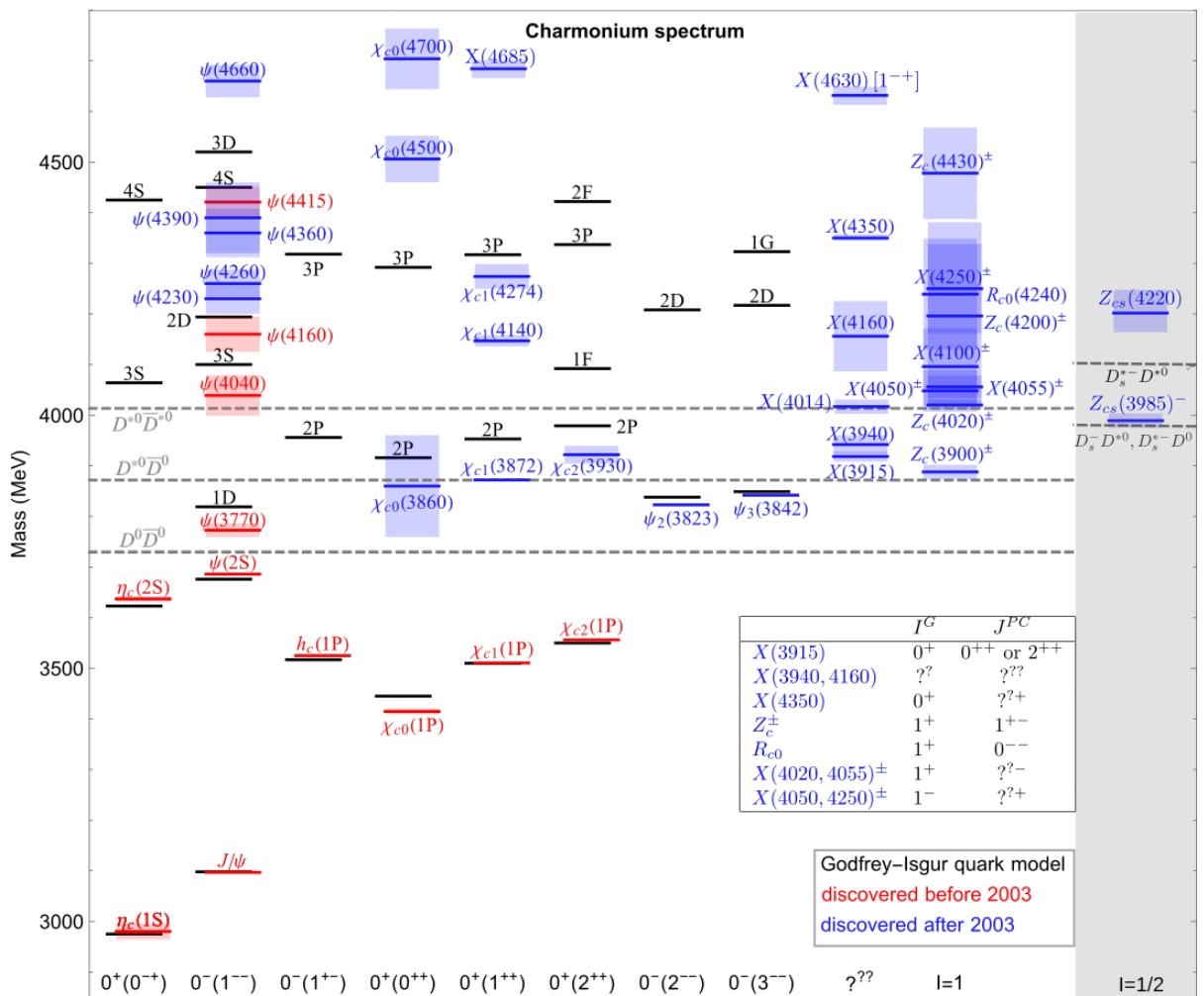


Predictions of the 2^- states taken from Godfrey, Moats, PRD93(2016)034035

Hadron spectrum: charmonium(-like)

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- Example: charmonium(-like) spectrum



Near-threshold states

- Prominent features: many are **narrow and near-threshold**; spectrum of **explicitly exotic** states is emerging

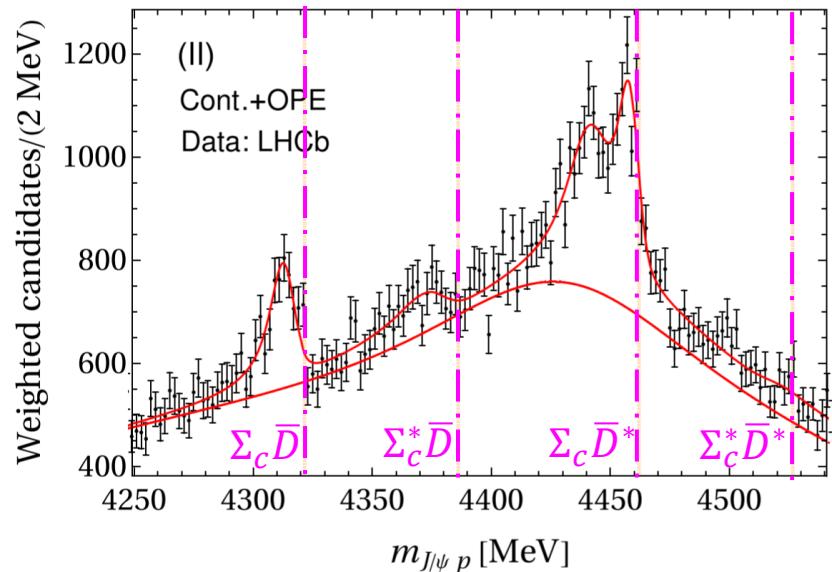
$X(3872)$ [aka $\chi_{c1}(3872)$], $Z_c(3900)^\pm$,

Belle(2003)

BESIII, Belle (2013) BESIII (2013) BESIII (2020), LHCb (2021)

$Z_c(4020)^\pm$, $Z_{cs}(3985)$, ...

P_c states: hidden-charm baryon

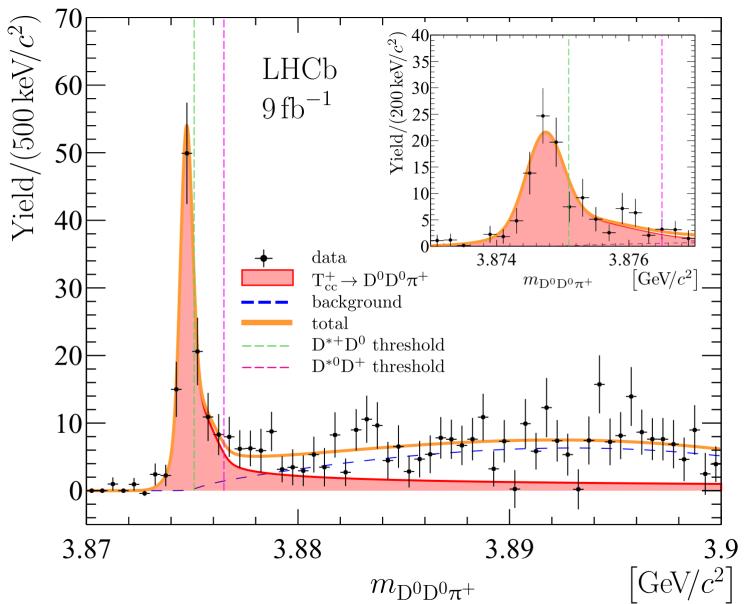


data from LHCb, PRL122 (2019) 222001;

fit from

M.-L. Du, Baru, FKG, Hanhart, Mei  ner, Oller, Q. Wang,
PRL124 (2020) 072001

T_{cc} : double-charm meson



LHCb, arXiv:2109.01038; arXiv:2109.01056

Models



hadrocharmonia



- Candidates of hadronic molecules

- Other models: compact multiquark states, hybrids, hadrocharmonia

- >10 reviews in the last 5 years:

- H.-X. Chen et al., *The hidden-charm pentaquark and tetraquark states*, Phys. Rept. 639 (2016) 1
- A. Hosaka et al., *Exotic hadrons with heavy flavors: X, Y, Z, and related states*, PTEP 2016 (2016) 062C01
- J.-M. Richard, *Exotic hadrons: review and perspectives*, Few Body Syst. 57 (2016) 1185
- R. F. Lebed, R. E. Mitchell, E. Swanson, *Heavy-quark QCD exotica*, PPNP 93 (2017) 143
- A. Esposito, A. Pilloni, A. D. Polosa, *Multiquark resonances*, Phys. Rept. 668 (2017) 1
- FKG, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, *Hadronic molecules*, RMP 90 (2018) 015004
- A. Ali, J. S. Lange, S. Stone, *Exotics: Heavy pentaquarks and tetraquarks*, PPNP 97 (2017) 123
- S. L. Olsen, T. Skwarnicki, *Nonstandard heavy mesons and baryons: Experimental evidence*, RMP 90 (2018) 015003
- Y.-R. Liu et al., *Pentaquark and tetraquark states*, PPNP107 (2019) 237
- N. Brambilla et al., *The XYZ states: experimental and theoretical status and perspectives*, Phys. Rept. 873 (2020) 154
- Y. Yamaguchi et al., *Heavy hadronic molecules with pion exchange and quark core couplings: a guide for practitioners*, JPG 47 (2020) 053001
- FKG, X.-H. Liu, S. Sakai, *Threshold cusps and triangle singularities in hadronic reactions*, PPNP 112 (2020) 103757
- G. Yang, J. Ping, J. Segovia, *Tetra- and penta-quark structures in the constituent quark model*, Symmetry 12 (2020) 1869
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- And a book:

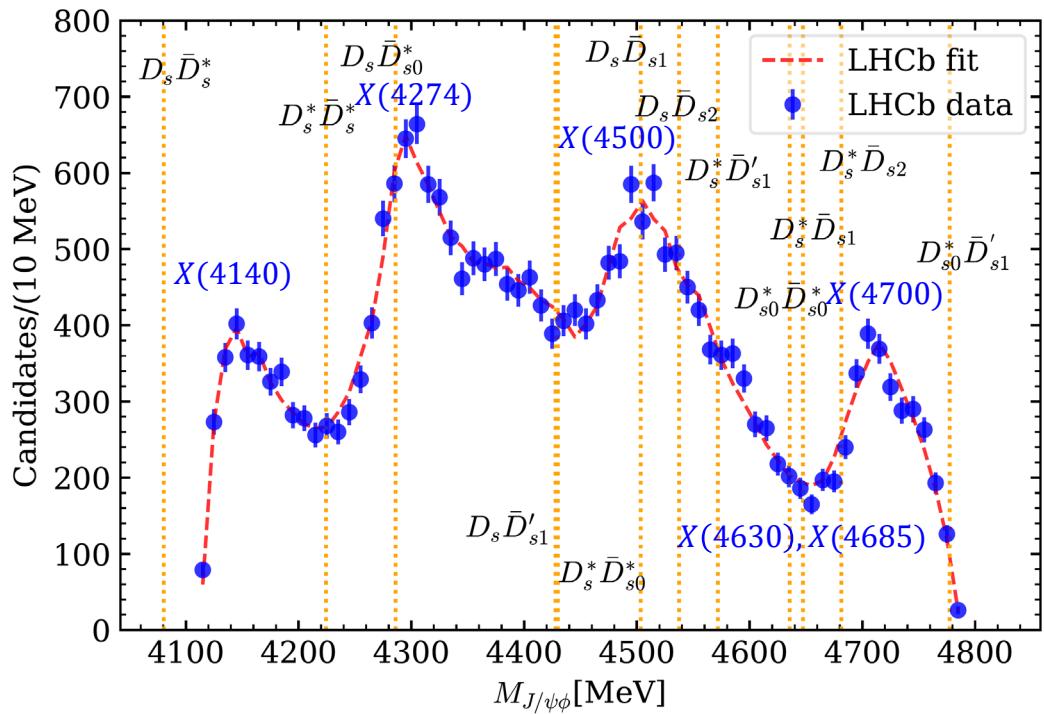
- A. Ali, L. Maiani, A. D. Polosa, *Multiquark Hadrons*, Cambridge University Press (2019)



Challenges

Challenges

- To reveal the underlying physics, we need to have **a faithful spectrum** to start with
- In most cases, resonance parameters are extracted using Breit-Wigner
 - Potentially sizeable corrections due to coupled channels and thresholds

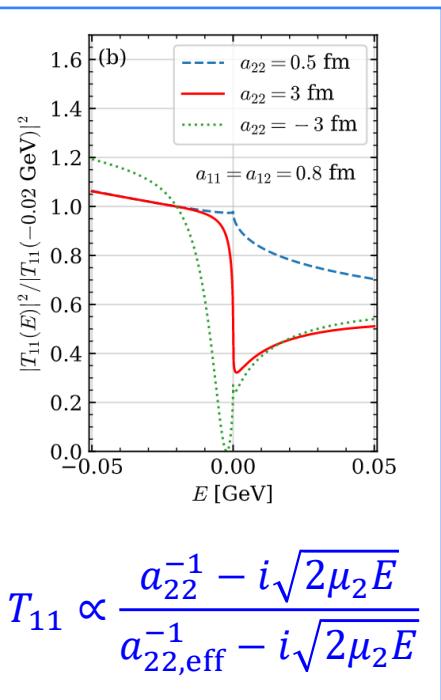
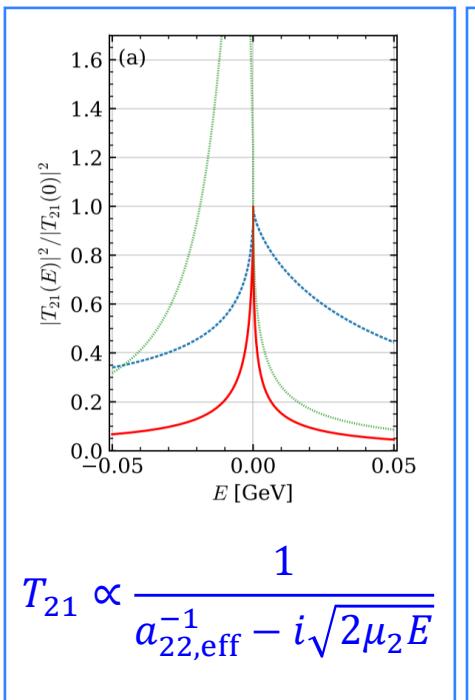


LHCb data: PRL127(2021)082001

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

Challenges

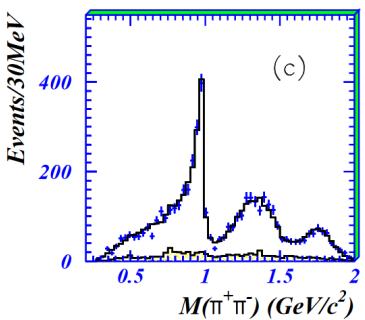
- Unitarity: the same resonance may behave completely different in different processes
- Resonance does not necessarily show up as a peak, may also be a dip



■ E.g., $f_0(980)$:

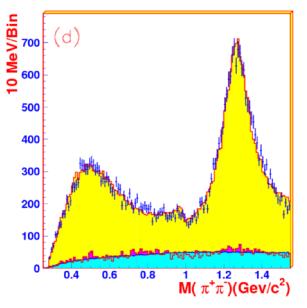
peak in
 $J/\psi \rightarrow \phi \pi^+ \pi^-$

dip in
 $J/\psi \rightarrow \omega \pi^+ \pi^-$



BES, PLB607(2005)243

$K\bar{K} \rightarrow \pi\pi$



BES, PLB598(2004)149

$\pi\pi \rightarrow \pi\pi$

Line shapes of the same poles in different processes

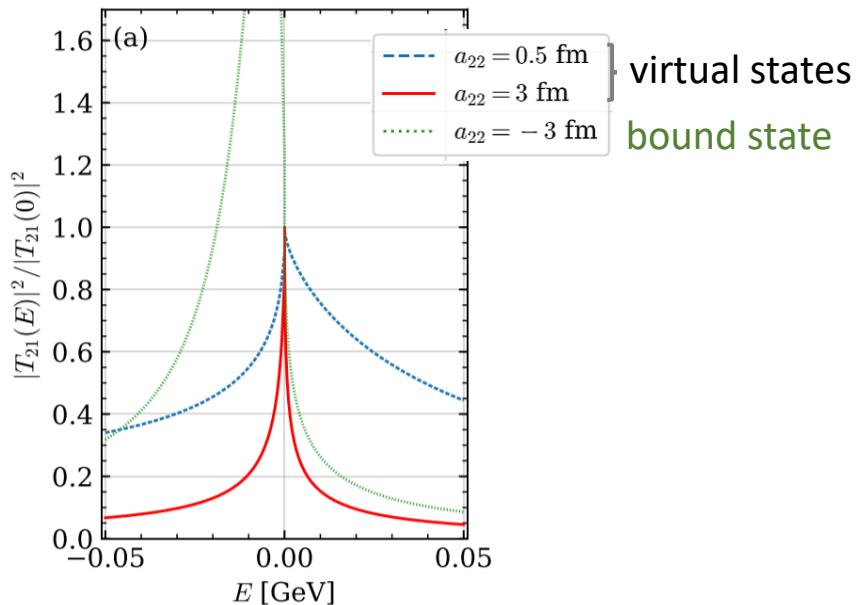
X.-K. Dong, FKG, B.-S. Zou, PRL126(2021)152001

Challenges

- Peaks exactly at threshold for S-wave attraction that is not strong enough to form a bound state:

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

- Virtual state pole



Challenges

- ❑ Unitarity: the same resonance may behave completely different in different processes;
- ❑ Resonance does not necessarily show up as a peak, may also be a dip

✓ BESIII: narrow $Z_{cs}(3985)$

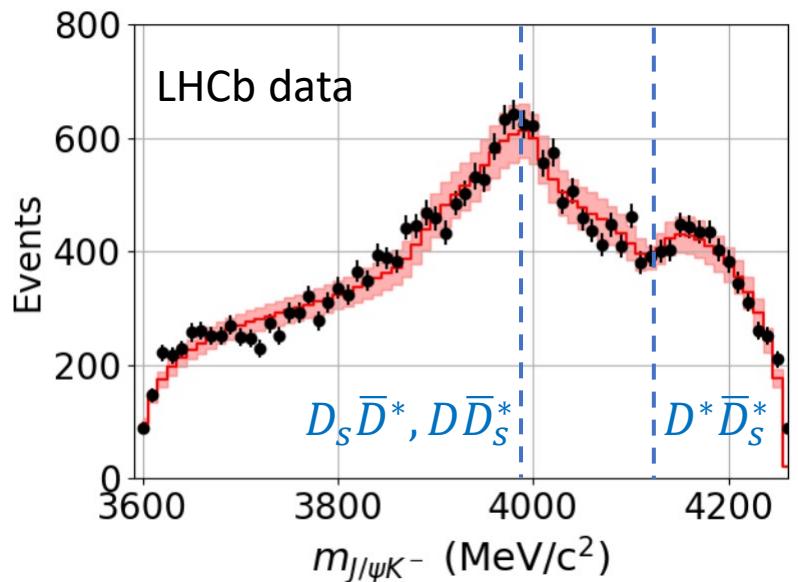
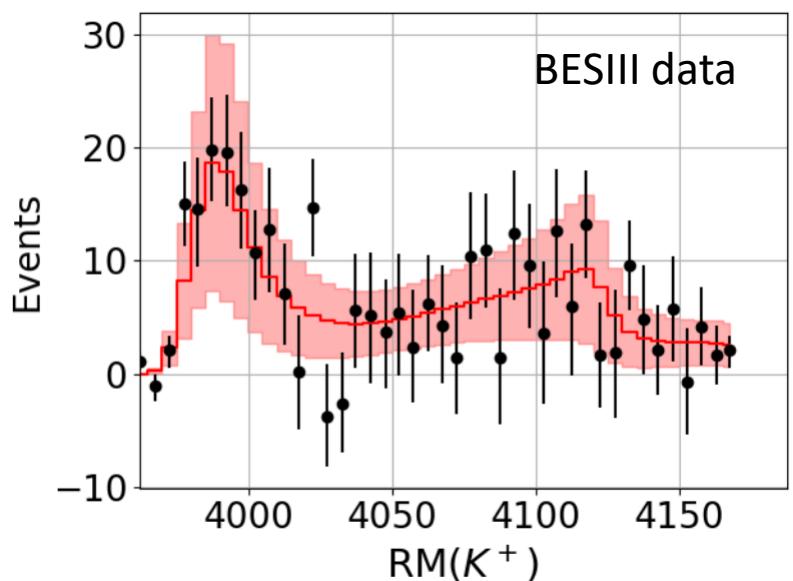
PRL126(2021)102001

✓ LHCb: broad $Z_{cs}(4000)$, and $Z_{cs}(4200)$

PRL127(2021)082001

✓ A simultaneous fit to the BESIII and LHCb Z_{cs} data: two virtual states $Z_{cs}(3990, 4110)$

Ortega, Entem, Fernandez, PLB818(2021)136382

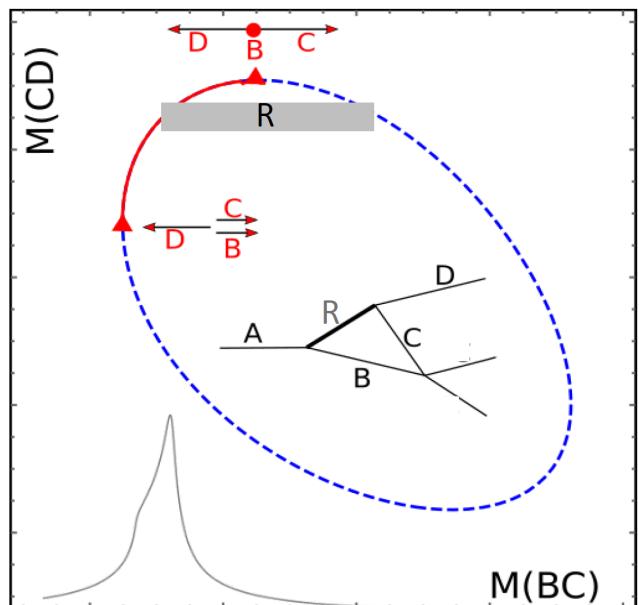


Challenges

- A peak is not necessarily due to a resonance

➤ Triangle singularities

- on shell and collinear intermediate particles
- determined by kinematic variables such as masses and energies
- sensitive to energies and processes



For a review of triangle singularities and threshold cusps,
FKG, X.-H.Liu, S. Sakai, PPNP 112 (2020) 103757

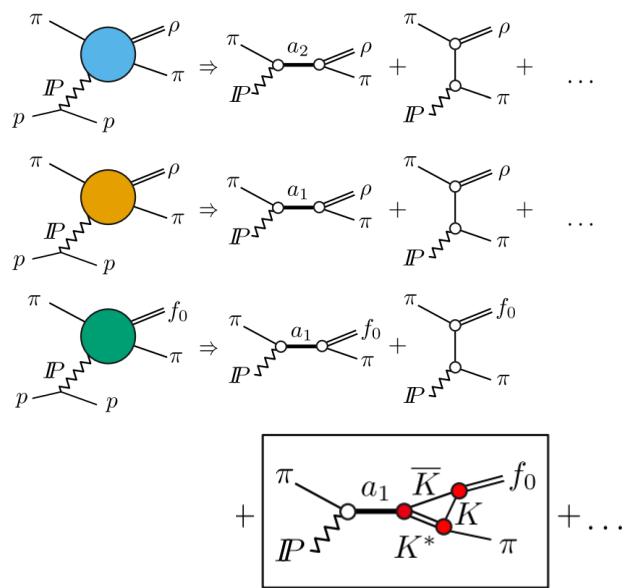
$$m_{A,TS}^2 \in \left[(m_R + m_B)^2, (m_R + m_B)^2 + \frac{m_B}{m_C} [(m_R - m_C)^2 - m_D^2] \right]$$

$$m_{BC,TS}^2 \in \left[(m_B + m_C)^2, (m_B + m_C)^2 + \frac{m_B}{m_R} [(m_R - m_C)^2 - m_D^2] \right]$$

Challenges

□ A peak is not necessarily due to a resonance

➤ Triangle singularities: E.g., $a_1(1420)$ can be well described by either a resonance or a triangle singularity (TS) effect

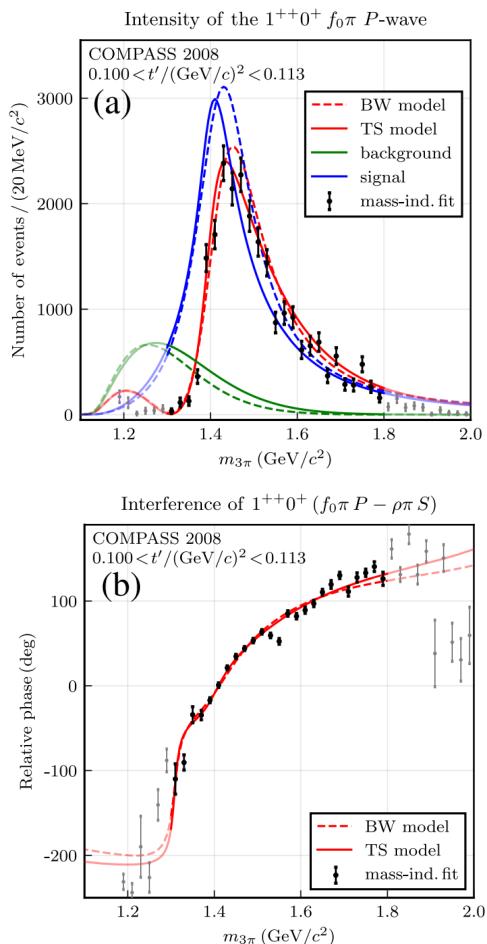


Discussions of TS for $a_1(1420)$, see also:

Q. Zhao @ Hadron2013;

M. Mikhasenko et al., PRD91(2015)094015;

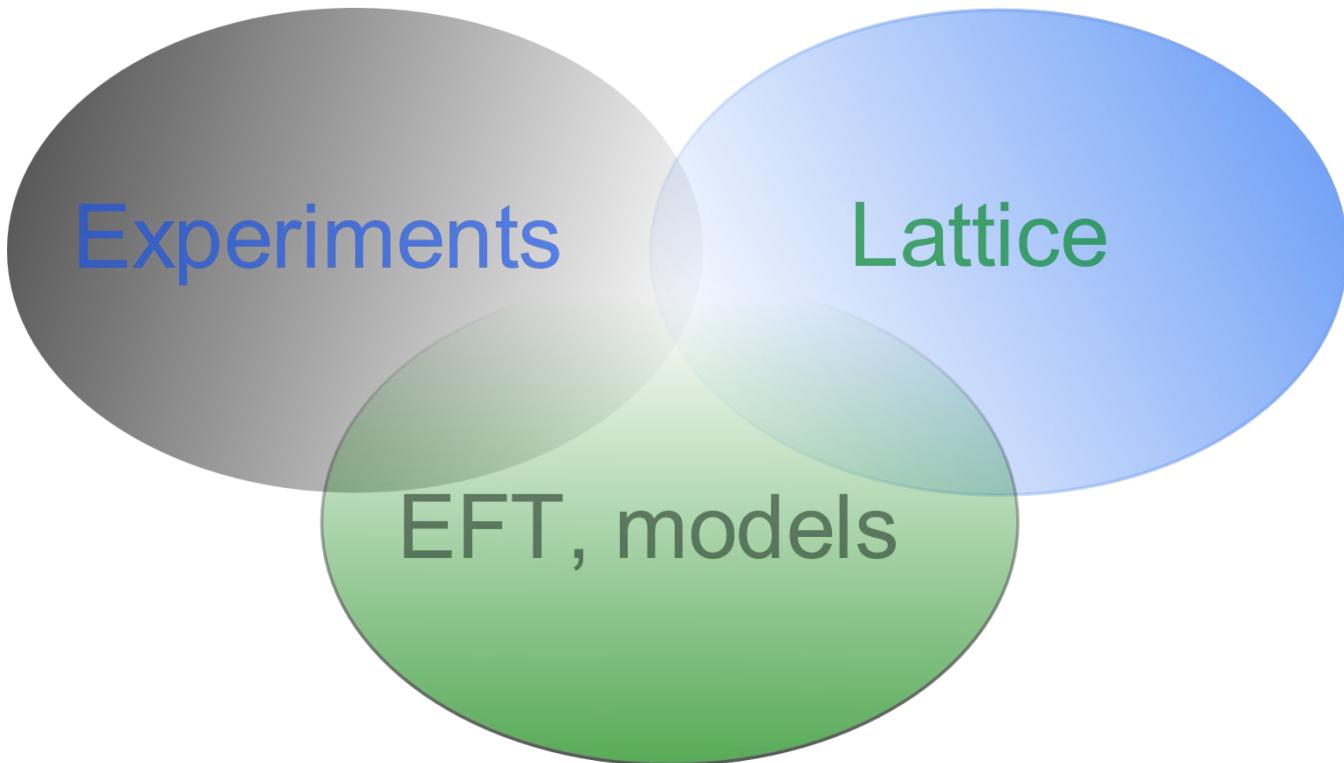
F. Aceti, L.R. Dai, E. Oset, PRD94(2016)096015



COMPASS,
PRL127(2021)082501

Exp., theory and lattice

- Precise data, complementary experiments
- Lattice QCD calculations
- Theoretical methods constrained by symmetry, unitarity and analyticity as a bridge





Near-threshold structures and molecules

Effective range expansion

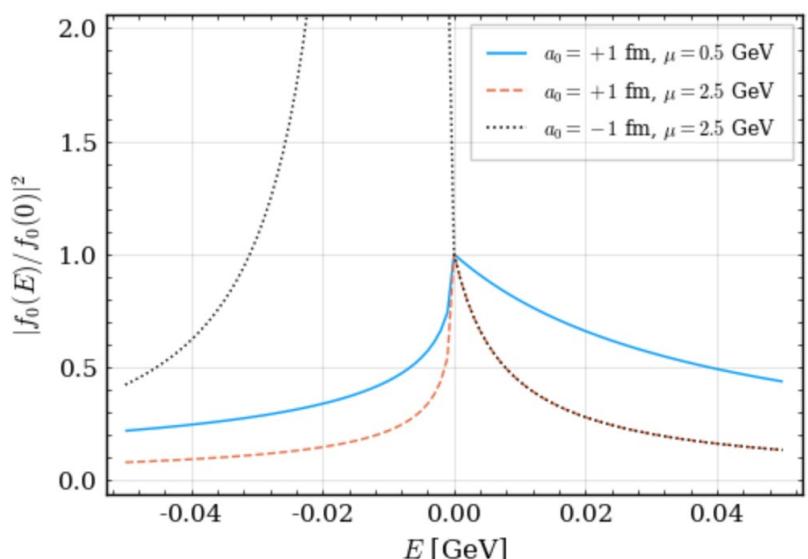
$$f_0^{-1}(k) = \frac{1}{a_0} + \frac{1}{2}r_0 k^2 - ik + \mathcal{O}\left(\frac{k^4}{\beta^4}\right)$$

a_0 : S-wave scattering length; negative for repulsion or attraction w/ a bound state
positive for attraction w/o bound state

Very close to threshold, then scattering length approximation: $f_0^{-1}(E) = \frac{1}{a_0} - i\sqrt{2\mu E}$

$$|f_0(E)|^2 = \begin{cases} \frac{1}{1/a_0^2 + 2\mu E} & \text{for } E \geq 0 \\ \frac{1}{(1/a_0 + \sqrt{-2\mu E})^2} & \text{for } E < 0 \end{cases}$$

- Cusp at threshold ($E=0$)
- Maximal at threshold for positive a_0 (attraction)
- Half-maximum width: $\frac{2}{\mu a_0^2}$;
virtual state pole at $E_{\text{virtual}} = -1/(2\mu a_0^2)$
- Strong interaction, a_0 becomes negative, pole below threshold, peak below threshold
see also, e.g., Brambilla et al. Phys. Rept. 873, 1 (2020)



Effective range expansion

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

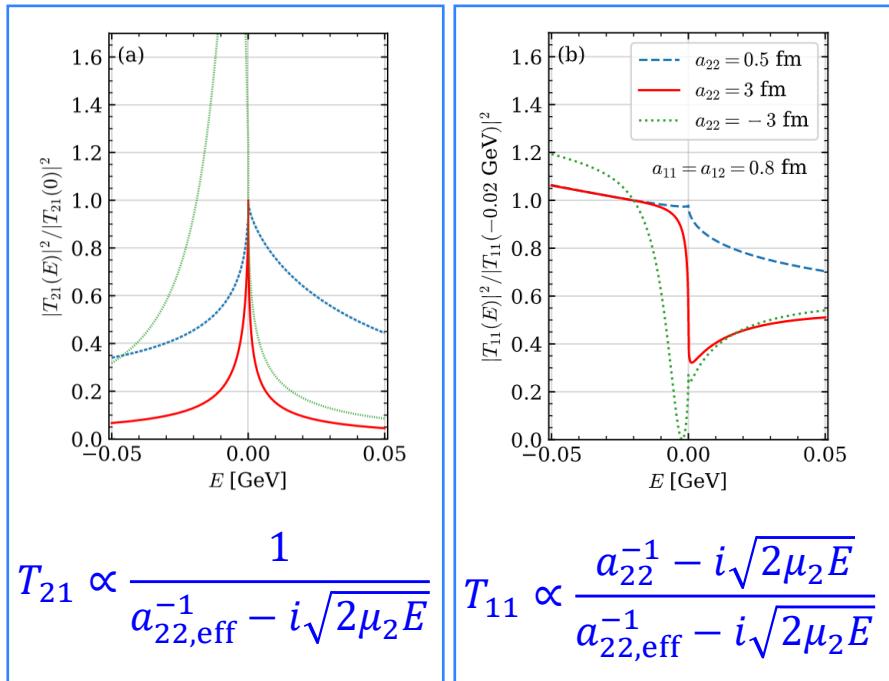
- The situation is similar for coupled channels
- Generally near-threshold structures for a pair of open-flavor hadrons with attractive interaction
- The heavier, the more pronounced structures

- Either threshold cusp or below-threshold peak
- For cusp: Half-maximum width of

$$\text{the cusp } \propto \frac{1}{\mu a_0^2}$$

- Perturbative estimate of scattering length: $a \propto m_Q$ [potential independent of m_Q]; nonperturbative for strong attraction, near-threshold pole

- Complications due to more channels



Survey of hadronic molecular spectrum

- Approximations:

- Constant contact terms (V) saturated by light-vector-meson exchange, similar to the **vector-meson dominance in the resonance saturation** of the low-energy constants in CHPT
- Single channels
- Neglecting mixing with normal charmonia

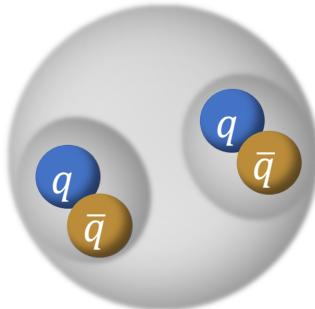
G. Ecker, J. Gasser, A. Pich, E. de Rafael, NPB321(1989)311

- The T-matrix:

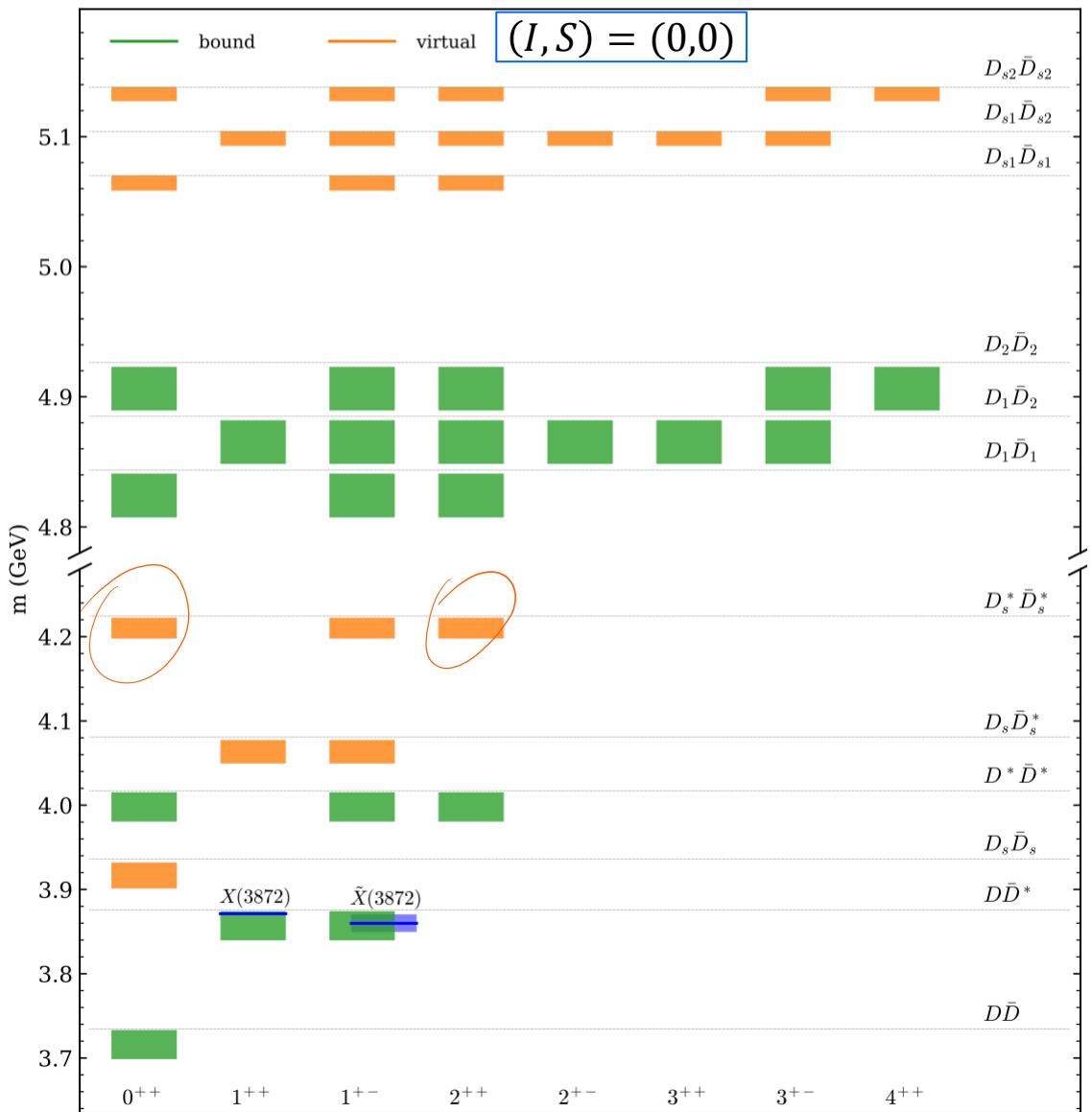
$$T = \frac{V}{1 - VG}$$

G : two-point scalar loop integral regularized using dim.reg. with a subtraction constant matched to a Gaussian regularized G at threshold, with cutoff $\Lambda \in [0.5, 1.0]$ GeV

- Hadronic molecules appear as **bound or virtual state poles** of the T matrix

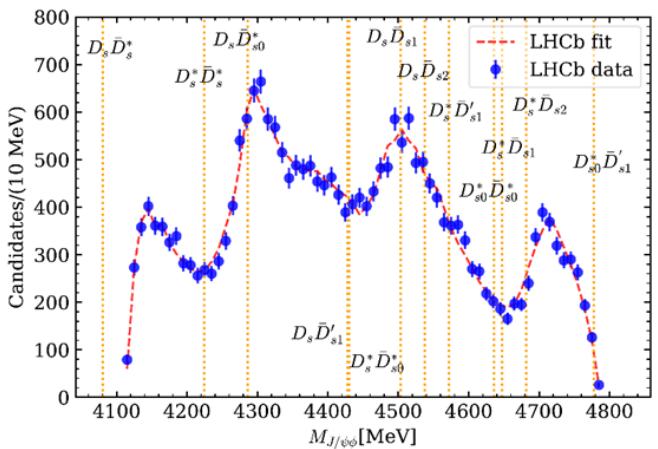


Hidden-charm



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

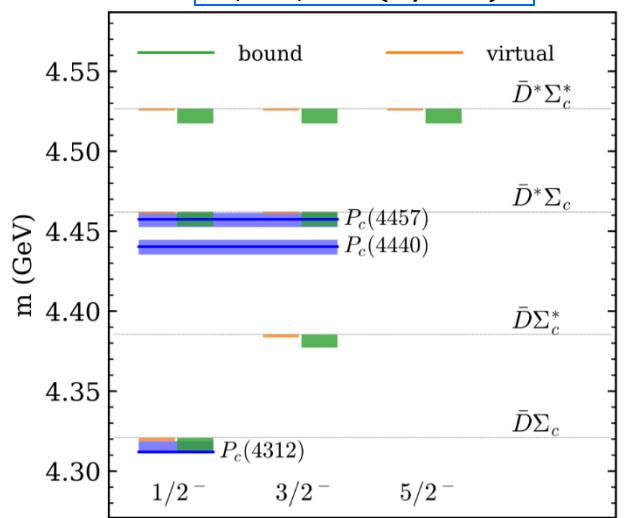
- ✓ $X(3872)$ as a $\bar{D}D^*$ bound state
- ✓ Negative-C parity partner observed by COMPASS PLB783(2018)334
- ✓ $\bar{D}D$ bound state predicted with lattice Prelovsek et al., JHEP2106,035 and other models
e.g., Wong, PRC69, 055202; Zhang et al., PRD74, 014013; Gamermann et al., PRD76, 074016; Nieves et al., PRD86, 056004; ...
- ✓ Evidence for a $D_s^*\bar{D}_s^*$ virtual state in LHCb data?



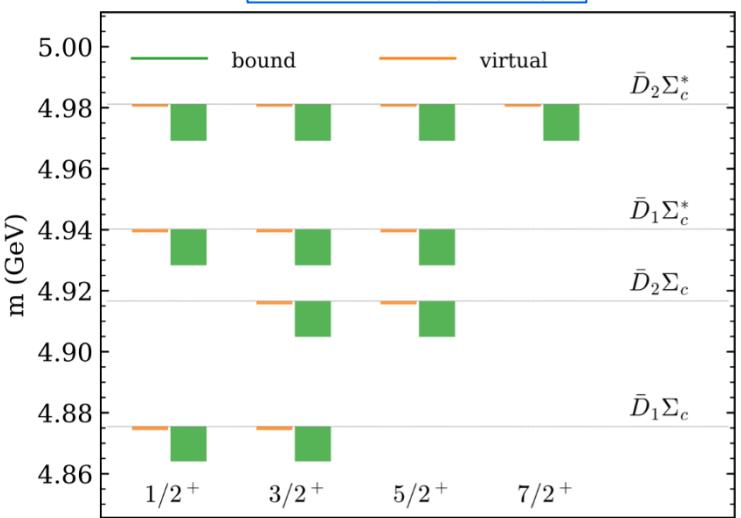
LHCb data: PRL127, 082001

Hidden-charm

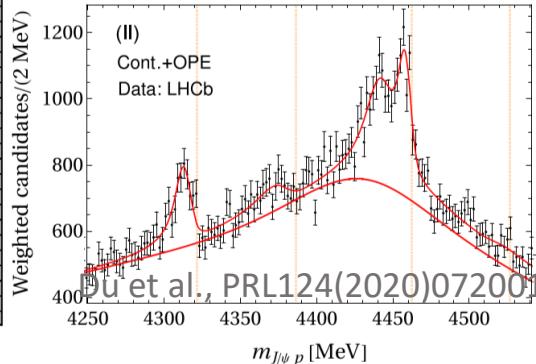
$(I, S) = (1/2, 0)$



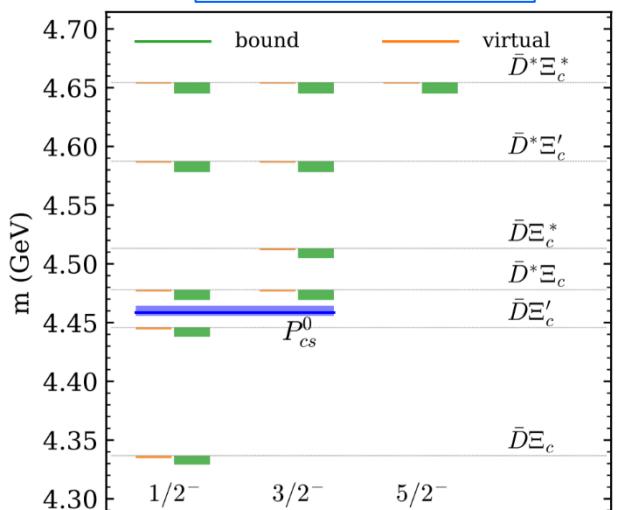
$(I, S) = (1/2, 0)$



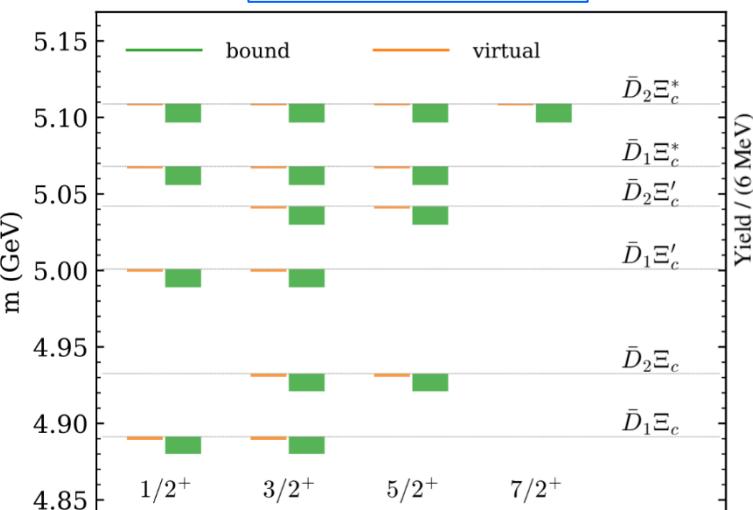
- ✓ The LHCb P_c states as $\bar{D}^{(*)}\Sigma_c$ molecules
- ✓ $\bar{D}\Sigma_c^*$ molecule: hint in the LHCb data



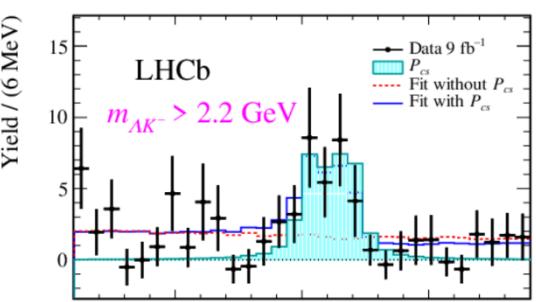
$(I, S) = (0, 1)$



$(I, S) = (0, 1)$

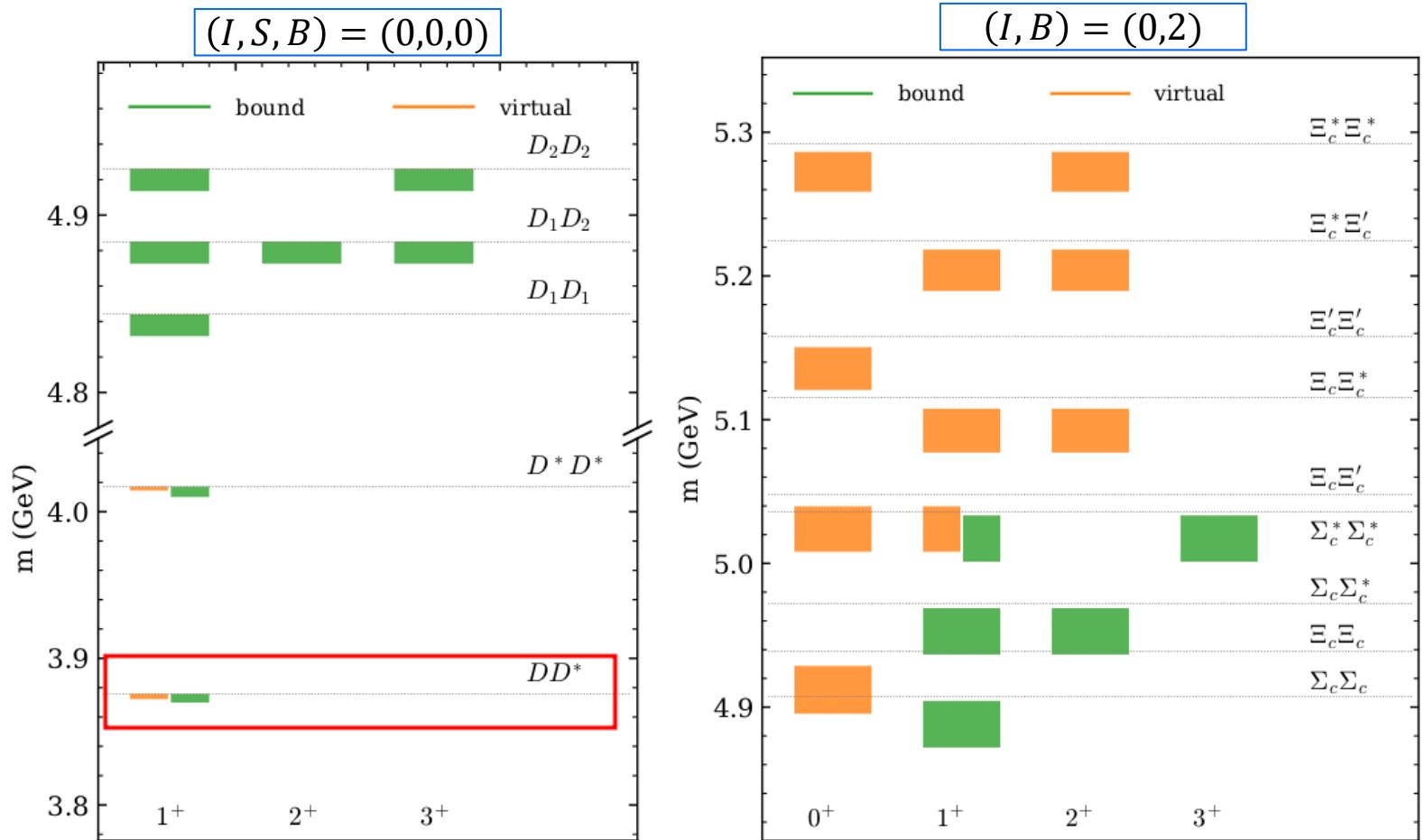


- ✓ The $P_{cs}(4459)$ could be two $\bar{D}^*\Xi_c$ molecules



- ✓ Many more molecular states in other sectors

Double-charm



- ✓ There is an **isoscalar DD^*** molecular state
- ✓ It has a spin partner **$1^+ D^*D^*$** state
- ✓ Many other similar double-charm molecular states in other sectors

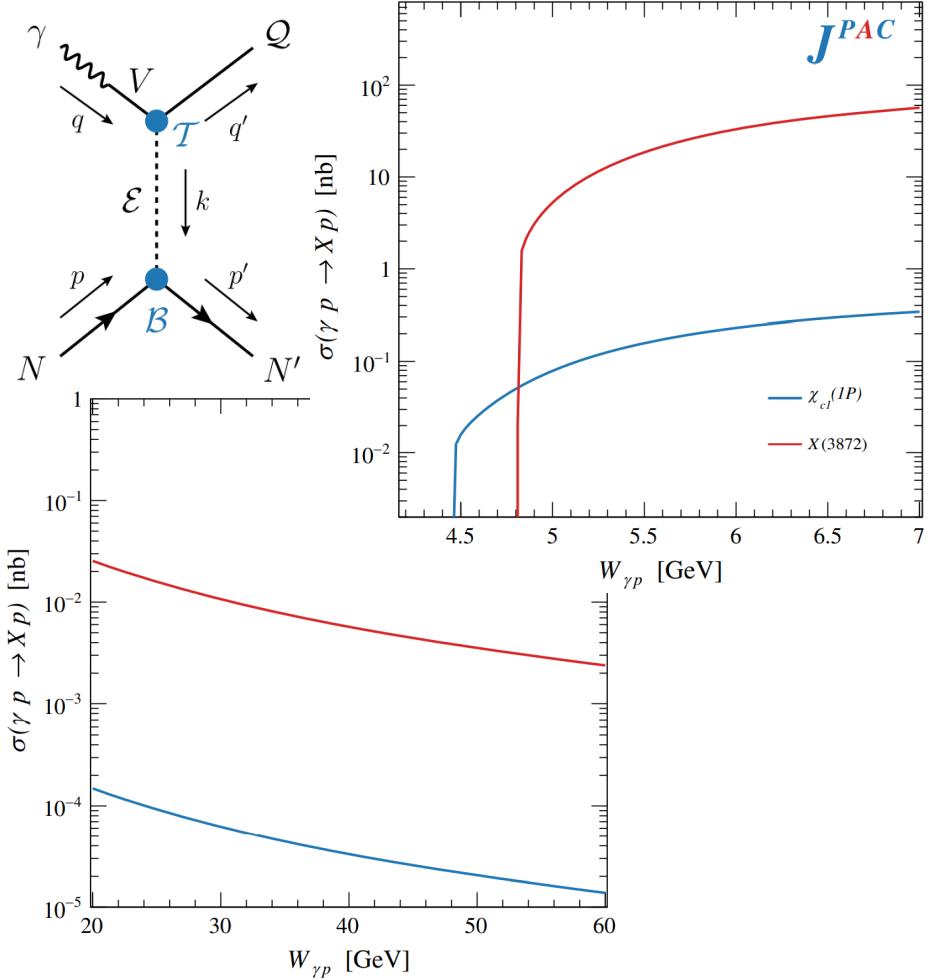
X.-K. Dong, FKG, B.-S. Zou, arXiv:2108.02673



Photoproduction of hidden-charm states

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):



➤ Estimated events for EicC

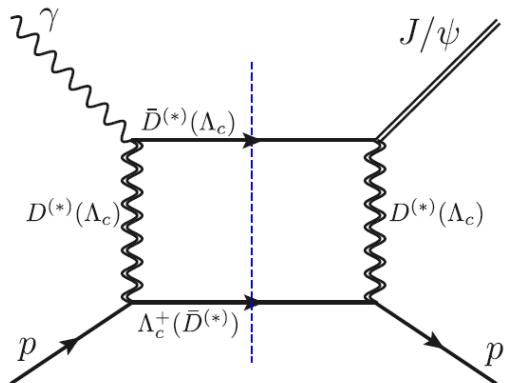
Exotic states	Production/decay processes	Detection efficiency	Expected events
$P_c(4312)$	$ep \rightarrow eP_c(4312)$ $P_c(4312) \rightarrow pJ/\psi$ $J/\psi \rightarrow l^+l^-$	~30%	15–1450
$P_c(4440)$	$ep \rightarrow eP_c(4440)$ $P_c(4440) \rightarrow pJ/\psi$ $J/\psi \rightarrow l^+l^-$	~30%	20–2200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

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

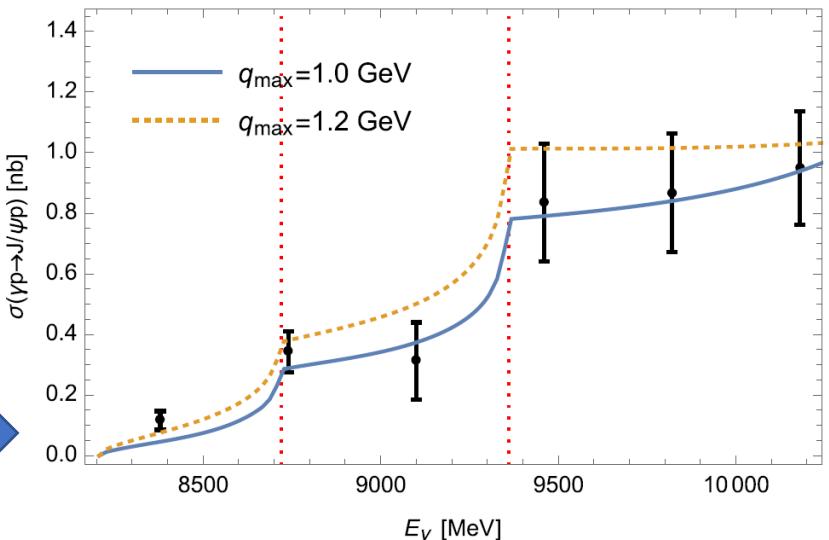
Exclusive photo-production of hidden-charm states

- 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

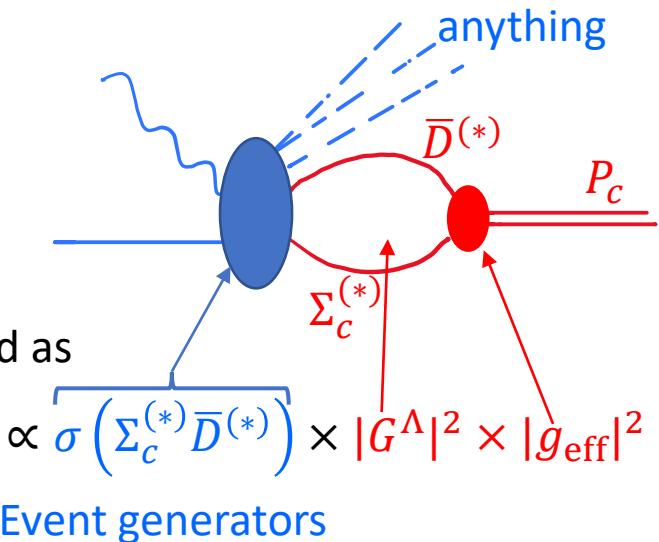


- Unique feature: **threshold cusps at the $\Lambda_c \bar{D}^{(*)}$ thresholds**; to be verified with updated GlueX data
- See also a recent critical analysis of the VMD model using DSE,

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

Production of P_c and XYZ in semi-inclusive processes

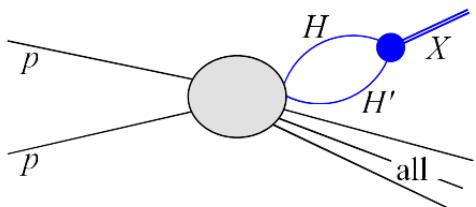
- Production of P_c in semi-inclusive reactions:



The cross section can be estimated as

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



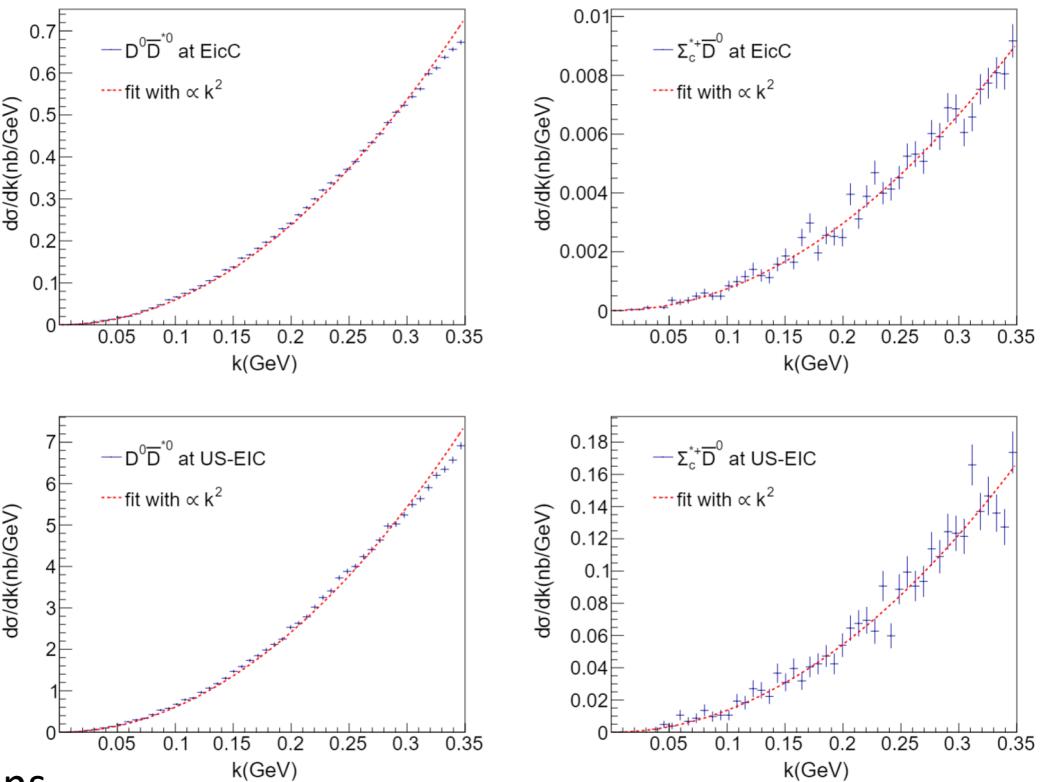
	$\sigma(pp/\bar{p} \rightarrow X) [\text{nb}]$ Exp.	$\Lambda=0.5 \text{ GeV}$	$\Lambda=1.0 \text{ GeV}$
Tevatron	37-115	7 (5)	29 (20)
LHC-7	13-39	13 (4)	55 (15)

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

Production of P_c and XYZ in semi-inclusive processes

Z. Yang, FKG, arXiv:2107.12247

- 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 ($\text{cm}^{-2}\text{s}^{-1}$)	2×10^{32}	2×10^{33}	10^{34}

Production of P_c and XYZ in semi-inclusive processes

Z. Yang, FKG, arXiv:2107.12247

- 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)

Production of P_c and XYZ in semi-inclusive processes

Z. Yang, FKG, arXiv:2107.12247

- Not in conflict with all previously reported photoproduction upper limits
- From our estimate, at GlueX $\sigma(\gamma p \rightarrow P_c) \times \mathcal{B}(P_c^+ \rightarrow J/\psi p)$ would be at most a few pb, difficult to detect
- At EicC, considering luminosity 50 fb^{-1}
 - taking $\sigma(e^- p \rightarrow X(3872) + \text{anything}) \approx 40 \text{ pb}$, then $\sim 2 \times 10^6$ events; taking $\mathcal{B}(X(3872) \rightarrow J/\psi \pi^+ \pi^-) = (3.8 \pm 1.2)\%$, $\mathcal{B}(J/\psi \rightarrow \ell^+ \ell^-) = 12\%$, then $\sim 10^4$ events
 - taking $\sigma(e^- p \rightarrow Z_c(3900)^+ + \text{anything}) \approx 400 \text{ pb}$, $\sim 2 \times 10^7$ events; assuming $\mathcal{B}(Z_c \rightarrow J/\psi \pi) \times \mathcal{B}(J/\psi \rightarrow \ell^+ \ell^-) = \mathcal{O}(1\%)$, then $\sim 2 \times 10^5$ events
 - taking $\sigma(e^- p \rightarrow P_c + \text{anything}) \approx 2 \text{ pb}$, then $\sim 10^5$ events; assuming $\mathcal{B}(P_c \rightarrow J/\psi p) \times \mathcal{B}(J/\psi \rightarrow \ell^+ \ell^-) = \mathcal{O}(0.1\%)$, then $\sim 10^2$ events
 - Open charm final states can have much larger branching fractions

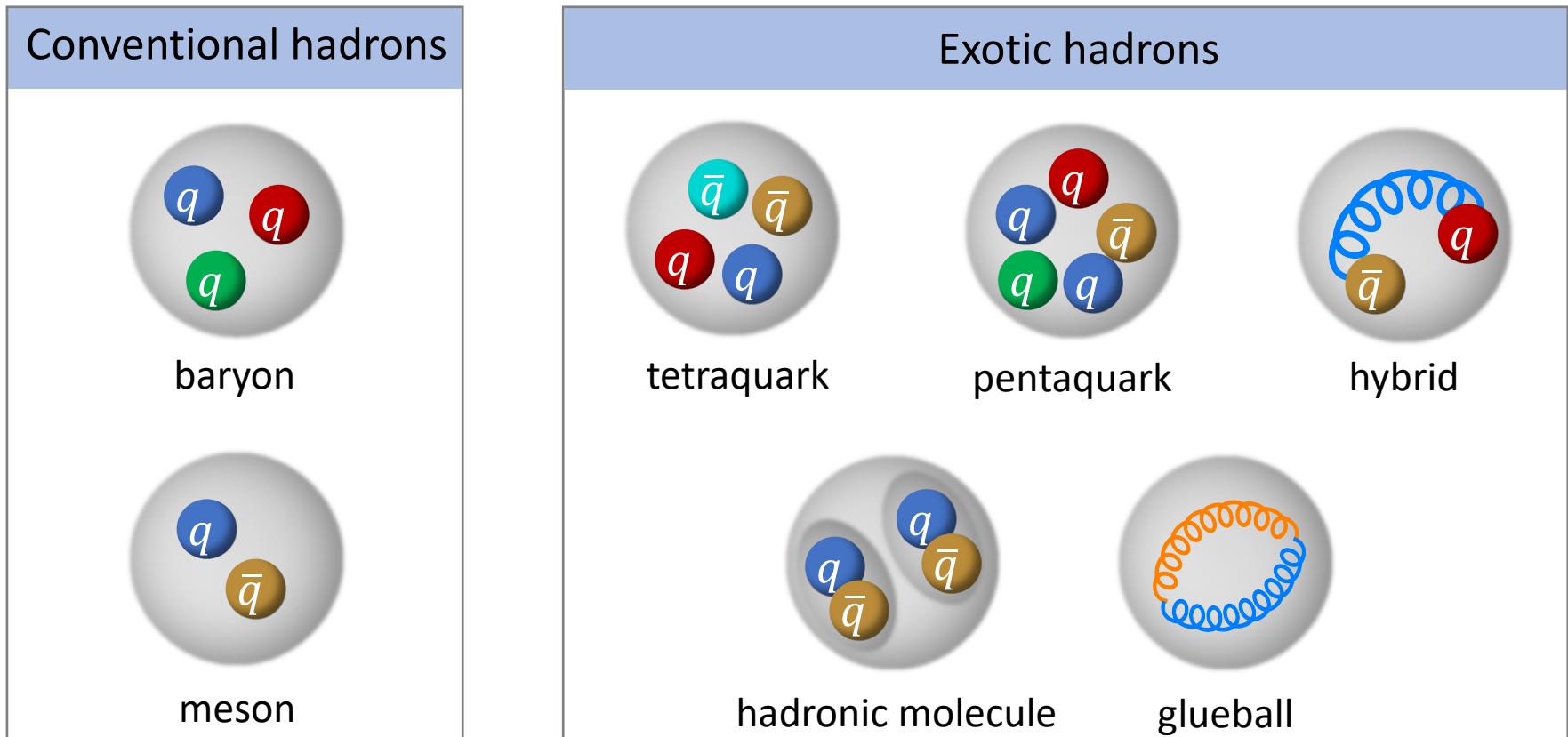
Summary and outlook

- Many new discoveries, calling for an overall understanding of the hadron spectroscopy
- Hadron spectroscopy in a controlled manner
 - Complementary experiments
 - Sophisticated analysis tools taking into theory constraints: unitarity, analyticity (including triangle singularities)
for an early analysis of light mesons, e.g., Anisovich, Bugg, Sarantsev, B.S. Zou, PRD50(1994)1972
 - Lattice formalisms for coupled channels



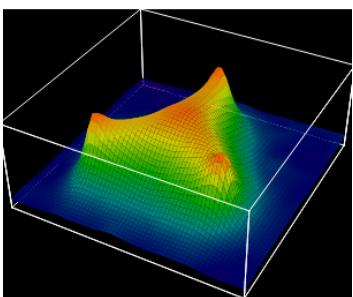
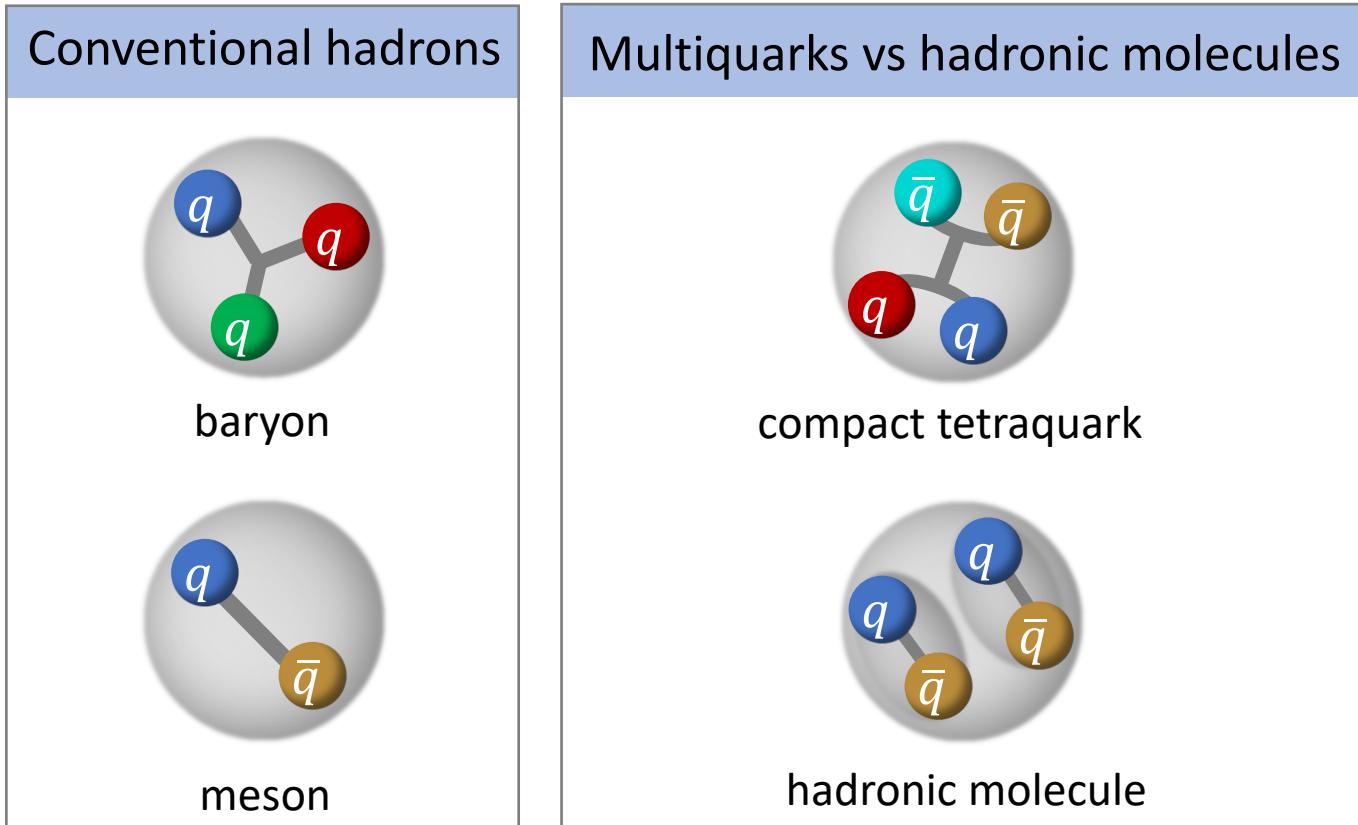
Conventional and exotic hadrons

- Hadrons are colorless; what types of color singlets should exist?
- Confinement: clue from hadron spectrum?
- Quark model: conventional and exotic hadrons



Clue to confinement mechanism?

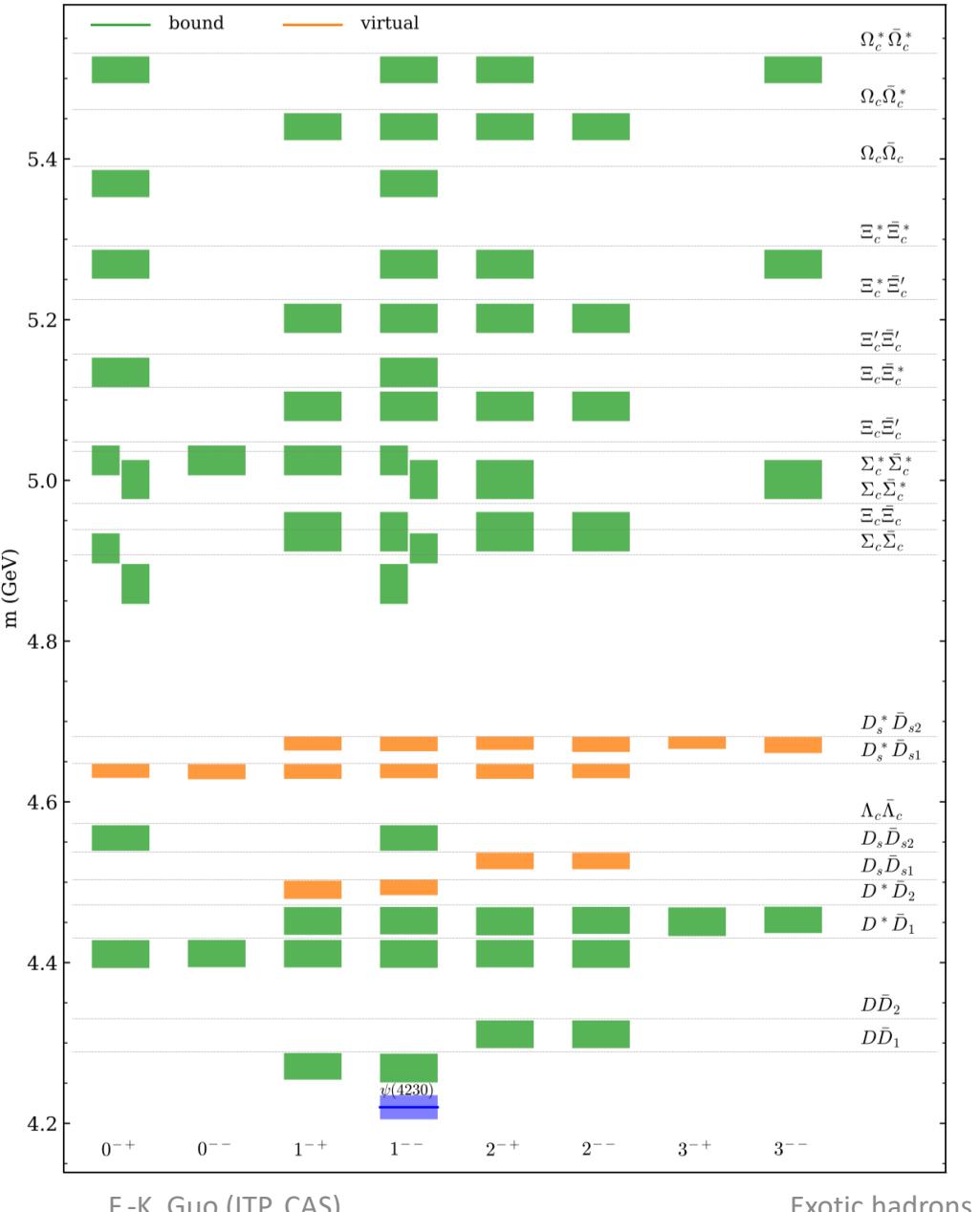
- Different flux tube configurations



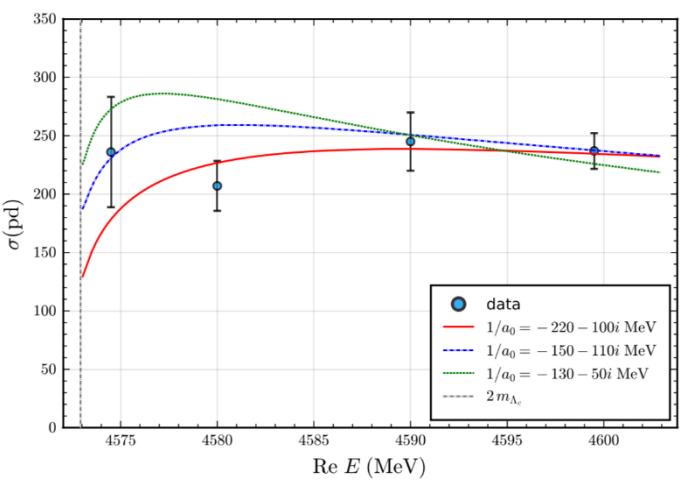
For lattice studies of flux tube picture of multiquarks, see, e.g.,
 F. Okiharu, H. Suganuma, T. T. Takahashi, PRD72(2005)014505;
 PRL94(2005)192001

An overview: H. Suganuma et al., arXiv:1103.4015

Survey of hadronic molecular spectrum



- ✓ $Y(4260)/\psi(4230)$ as a $\bar{D}D_1$ bound state
- ✓ Vector charmonia around 4.4 GeV unclear
- ✓ Evidence for 1^{--} $\Lambda_c \bar{\Lambda}_c$ bound state in BESIII data
 - Sommerfeld factor
 - Near-threshold pole
 - Different from $Y(4630/4660)$



Data taken from BESIII, PRL120(2018)132001

Hadronic molecules & tetraquarks

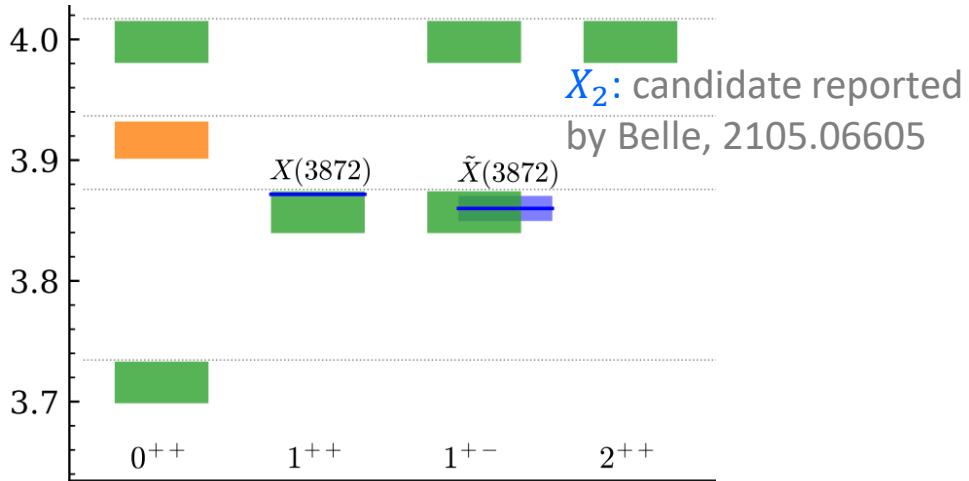
- Different models predict distinct mass spectra and decay patterns, e.g., charmonium-like

➤ $P = +$ states in a molecular model

N.A. Törnqvist, ZPC61(1994)525;
 C.-Y. Wong, PRC69(2004)055202;
 E. Swanson, JPCS9(2005)79;
 J. Nieves, M.P. Valderrama, PRD86(2012)056004;
 FKG, C. Hidalgo-Duque, J. Nieves, M.P. Valderrama,
 PRD88(2013)054007;
 V. Baru et al. PLB763(2016)20;...

Heavy-quark spin symmetry:

$$M_{X_2[D^*\bar{D}^*]} - M_{X(3872)} \approx M_{D^*} - M_D$$



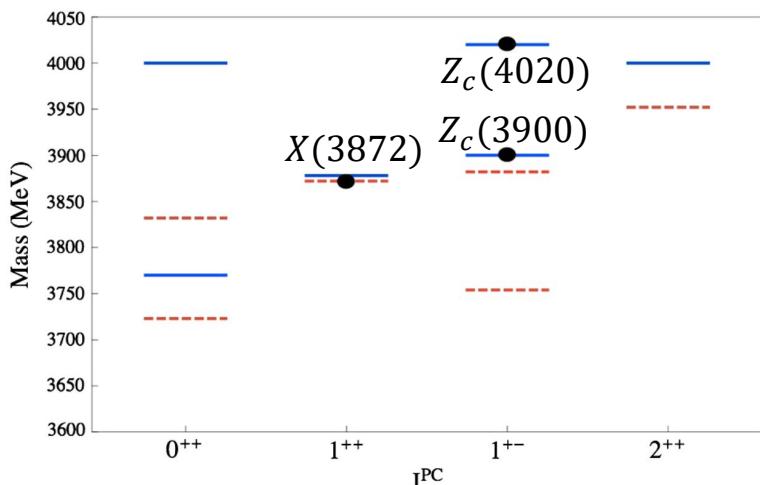
X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41(2021)65

➤ $P = +$ states in a tetraquark model

$$\mathcal{H} \approx 2\kappa_{qc}(s_q \cdot s_c + s_{\bar{q}} \cdot s_{\bar{c}})$$

Spectrum similar with molecular model
from fixing κ_{qc} using

$$M_{Z_c(4020)} - M_{Z_c(3900)} \approx M_{D^*} - M_D$$

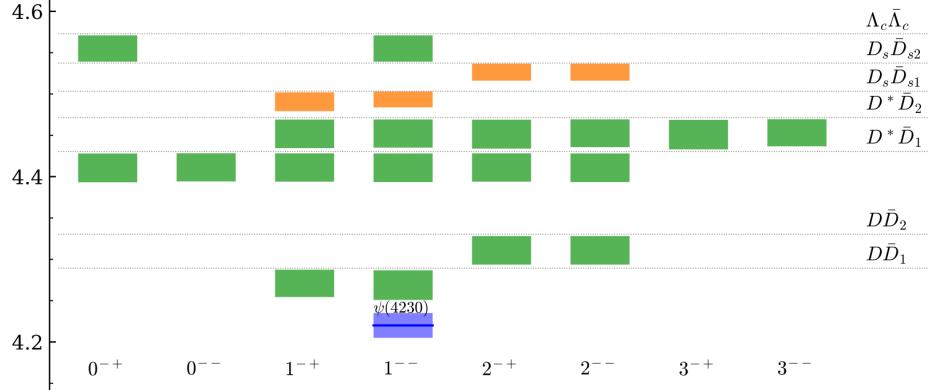


L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer,
 PRD89(2014)114010

Hadronic molecules & tetraquarks

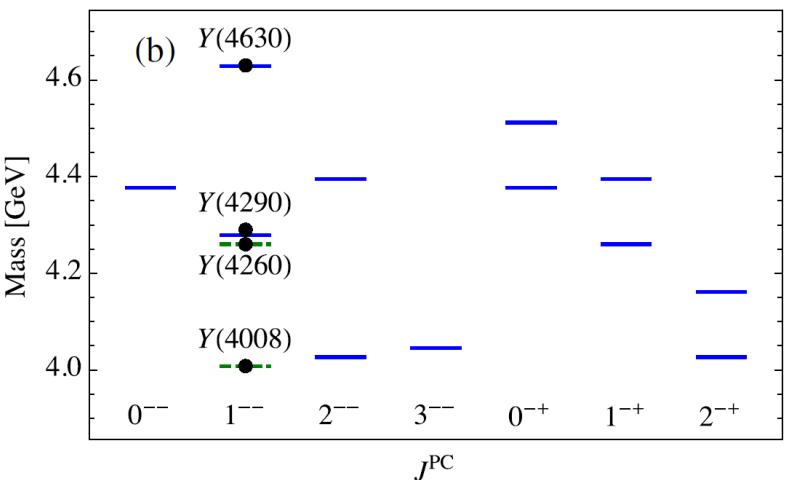
- Different models predict distinct mass spectra and decay patterns, e.g., charmonium-like

➤ $P = -$ states in a molecular model



➤ $P = -$ states in a tetraquark model

$$M = M_{00} + B_c \frac{L(L+1)}{2} + a[L(L+1) + S(S+1) - J(J+1)] + \kappa_{cq}[s(s+1) + \bar{s}(\bar{s}+1) - 3].$$



Mol. spectrum using a VMD interaction

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

M. Cleven, FKG, C. Hanhart, Q. Wang, Q. Zhao,
PRD92(2015)014005
using inputs from
L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer,
PRD89(2014)114010