Understanding the spectrum of charmonium and charmonium-like states

Qian Wang (王倩)

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The 7th International Workshop on Future Tau Charm Facilities,
Huangshan, November 23rd-27th, 2025

A short review of the vector charmonium-like state $\psi(4230)$, QW and Qiang Zhao, CPL42(2025)110201

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A short review of the vector charmonium-like state $\psi(4230)$, QW and Qiang Zhao, CPL42(2025)110201

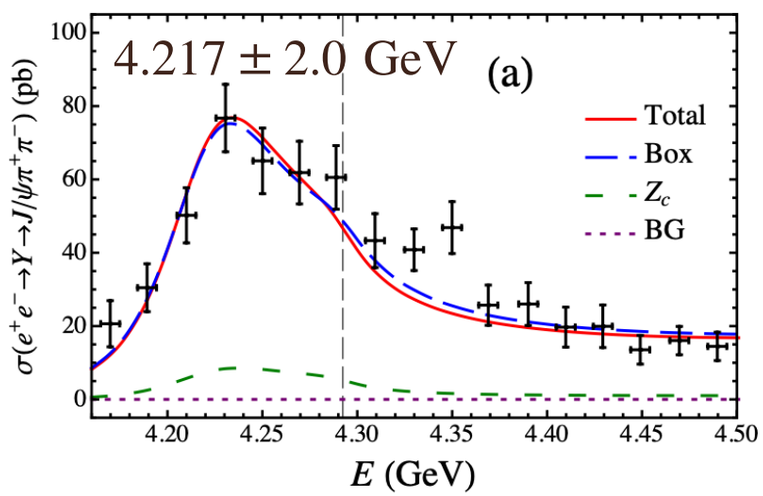
Outline

- The story of $\psi(4230)$
- Experimental evidences
- Theoretical developments
  - The compact tetraquark picture
  - The hybrid picture
  - The hadro-quarkonium picture
  - The hadronic molecular picture
- Summary and Outlook

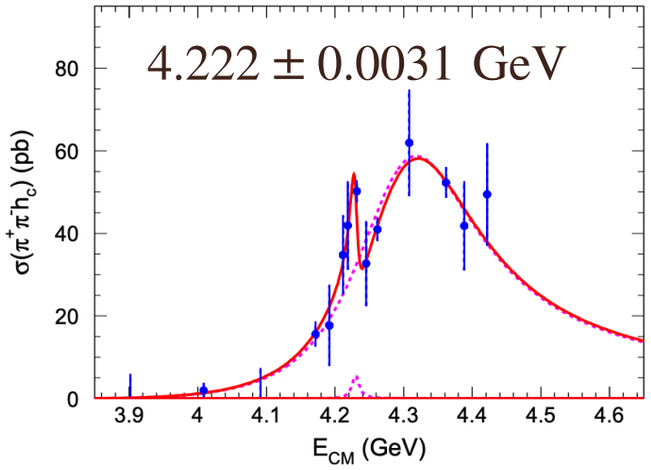
The story of the $\psi(4230)$

- The normal charmonium spectrum below threshold can be well described by Cornell potential Eichten et.al, PRL34(1975)369, Eichten et.al, PRD17(1978)3090, PRD21(1980)203
- Numerous exotic candidates are observed above threshold, e.g. $X(3872), Z_c(3900), \ldots\ldots$
- e^+e^- ann. process is the best place to study vector charmonium- or bottomonium-like state
- Vector charmonia are well described by potential quark model, e.g. $J/\psi, \psi(2S), \psi(1D), \psi(3S), \ldots$ Eichten et.al, PRD17(1978)3090, PRD21(1980)203, Godfrey et.al, PRD32(1985)189,Lakhina et.al, PRD74(2006)014012
- $Y(4260)$ was reported by BaBar collaboration in $e^+e^- \to \gamma_{\rm ISR} J/\psi\pi^+\pi^-$ process BaBar, PRL95(2005)142001
- High precision data from BESIII, especially the observation of $Z_c(3900)$ BESIII, PRL110(2013)252001

One state



Cleven et.al, PRD90(2014)074039



Two states

Yuan, CPC38(2014)043001

Experimental evidences

- Observed channels

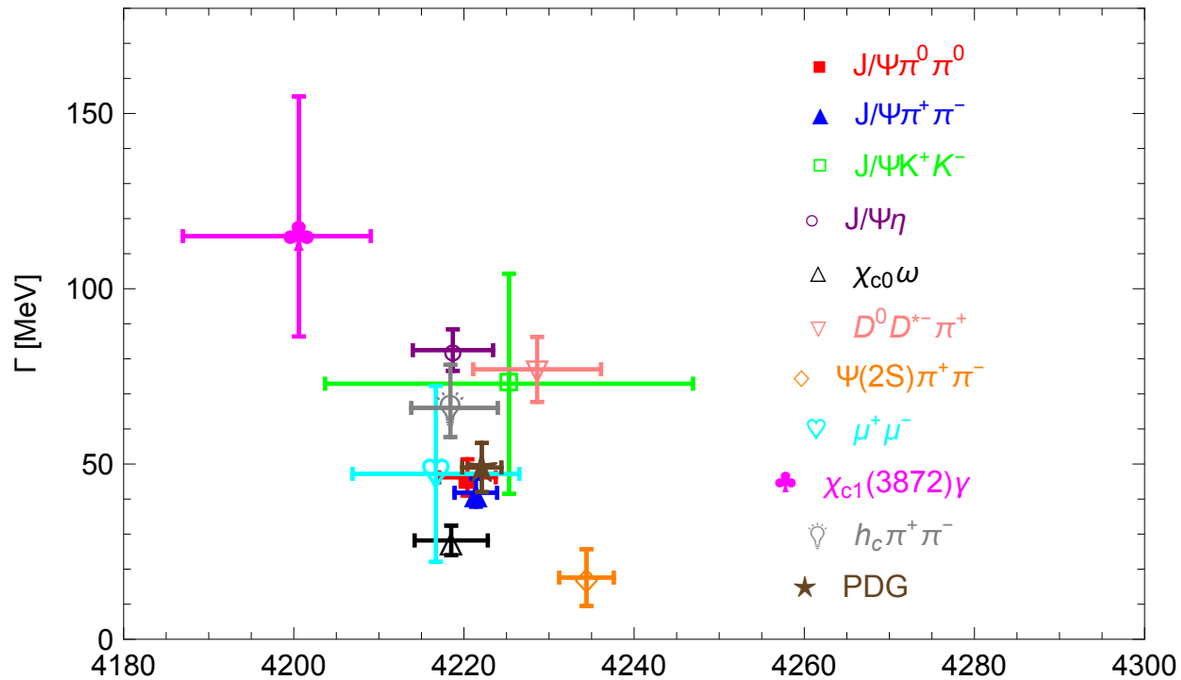
$J/\psi\pi^0\pi^0, J/\psi\pi^+\pi^-, J/\psi K^+K^-,$

$J/\psi\eta, \chi_{c0}(1P)\omega, D^0D^{*-}\pi^+,$

$\chi_{c1}(3872)\gamma, h_c(1P)\pi^+\pi^-,$

$\psi(2S)\pi^+\pi^-, \mu^+\mu^-, \Omega\bar{\Omega}$ from

BESIII collaboration



- Lineshape and mass are channel dependent
- Vague signal in two-body open charmed meson channel, i.e. $D\bar{D}, D\bar{D}^* + c.c., D^*\bar{D}^*,$ and small di-leption width, i.e. $\mathcal{O}(10^2)$ eV $\sim \mathcal{O}(1)$ keV
- The pro. in B decay $\mathscr{B}\left(B^- \to K^-\psi(4230)\right)\mathscr{B}\left(\psi(4230) \to J/\psi\pi^+\pi^-\right) = (2.0 \pm 0.7 \pm 0.2) \times 10^{-5}$

BaBar, PRL95(2005), 142001

$\mathscr{B}\left(B^+ \to \psi(4230)K^+\right) \times \mathscr{B}\left(\psi(4230) \to J/\psi\pi^+\pi^-\right) < 1.4 \times 10^{-5}$

$\mathscr{B}\left(B^0 \to \psi(4230)K^0\right) \times \mathscr{B}\left(\psi(4230) \to J/\psi\pi^+\pi^-\right) < 1.7 \times 10^{-5}$

at 90 % C.L.

Belle, PRD99(2019)071102

No signal for

$B^+ \to \psi(4230)K^+ \to J/\psi\eta K^+$

LHCb, JHEP04(2022)046

Experimental evidences

- Decay modes (open S-wave charmed meson pair)

$$\mathscr{B}\left(\psi(4230)\to D^*\bar{D}\right)/\mathscr{B}\left(\psi(4230)\to J/\psi\pi^+\pi^-\right)<34$$

$$\mathscr{B}\left(\psi(4230)\to D^*\bar{D}^*\right)/\mathscr{B}\left(\psi(4230)\to J/\psi\pi^+\pi^-\right)<40$$

at 95 % C.L.

BaBar, PRD79(2009)092001

$$\frac{\sigma\left(e^+e^-\to D^0D^{*-}\pi^+\right)}{\sigma\left(e^+e^-\to J/\psi\pi^+\pi^-\right)}\simeq 3 \qquad \frac{\sigma\left(e^+e^-\to D^0D^{*-}\pi^+\right)}{\sigma\left(e^+e^-\to J/\psi K^+K^-\right)}\simeq 50$$

BESIII, PRL122(2019)102002, CPC46(2022)111002

Do we expect $\psi(4230)$ in $D\bar{D}^*, D^*\bar{D}^*$ channel from BESIII collaboration?

- Search for heavy quark spin symmetry partners from experimental side

	1^{--}	1^{-+}	0^{--}	2^{--}	3^{--}	2^{-+}	0^{-+}
Compact tetraquark	4	2	1	2	1	2	0
Hybrid	1	1	0	0	0	1	1
Hadro-quarkonium	2	1	0	0	0	1	2
Molecule	3	3	1	3	1	3	1

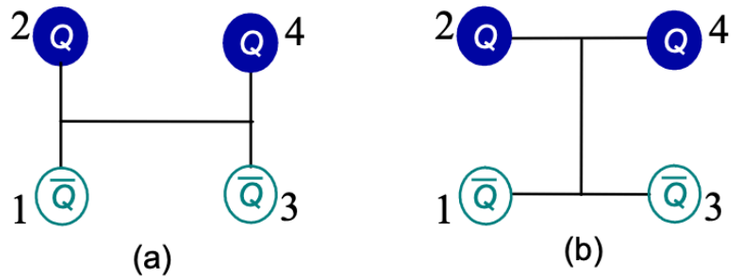
Theoretical developments

The compact tetraquark picture

- Diquark-antidiquark picture: # degrees of freedom $3^4 - 3 \to 3$
- An attempt of considering complete configurations

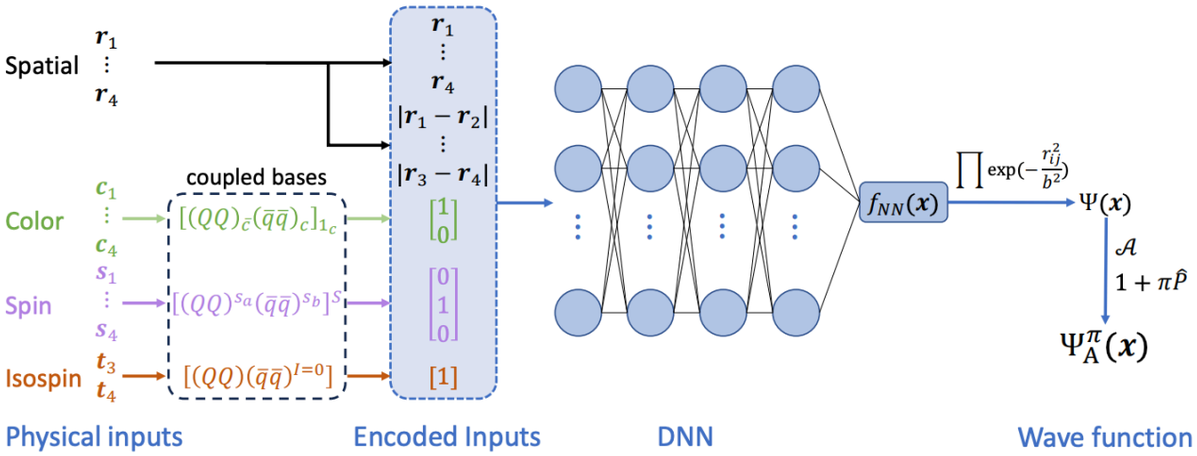
  A lattice-QCD inspired quark model

  Gang Yang, Jialun Ping, Jorge Segovia, PRD106(2022)014005

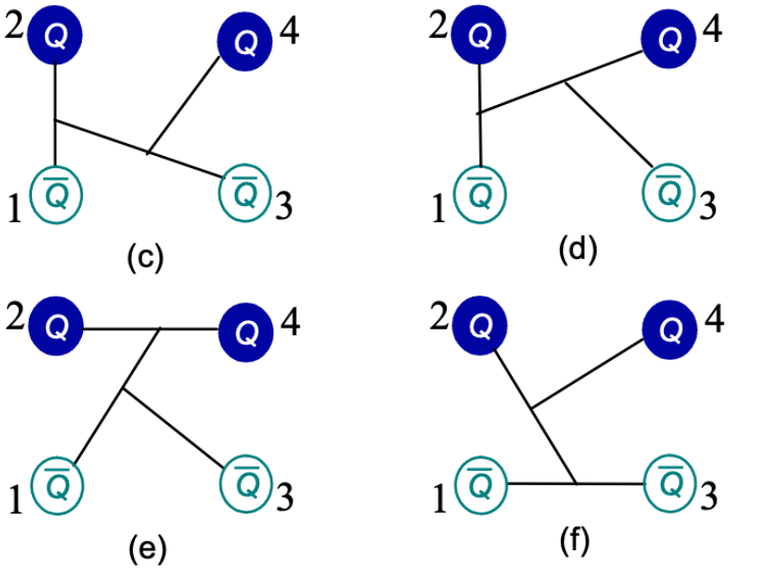


- New methods: Machine learning, Lattice EFT

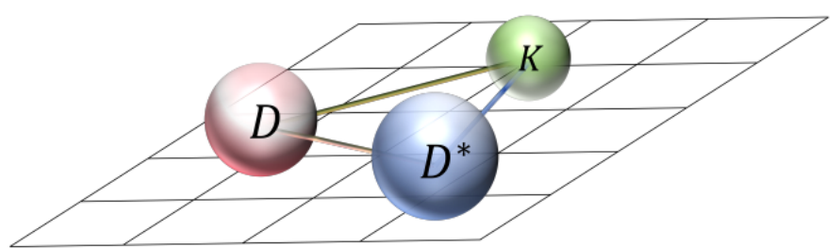
  Basic idea: Single particle wave function



Wei-Lin Wu, Lu Meng, Shi-Lin Zhu, arXiv:2506.20555[hep-ph]



Zhang, Hu, He, Liu, Shi, Lu, QW, PRD111(2025)036002



Theoretical developments

The compact tetraquark picture

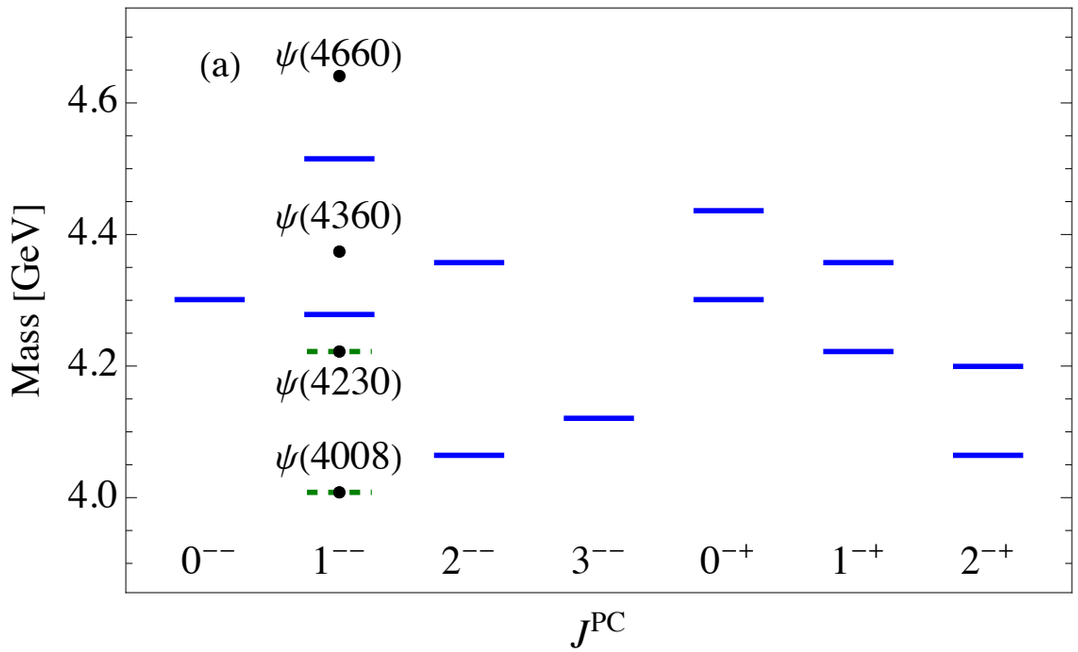
- Diquark-antidiquark picture: # degrees of freedom $3^4 - 3 \to 3$

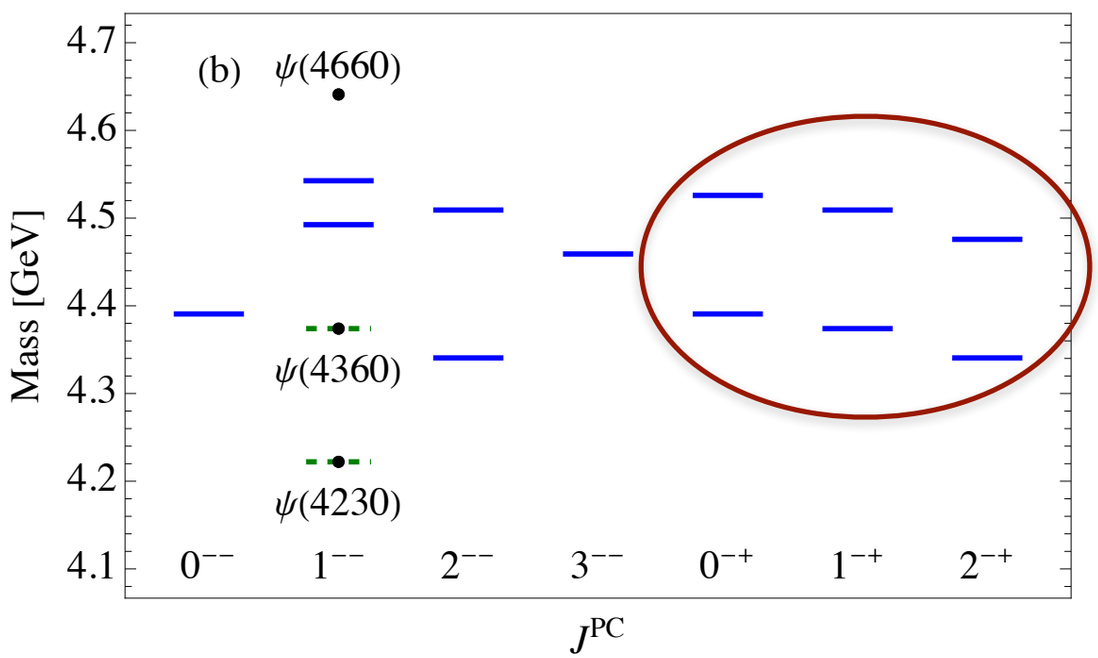
  Mass formula

  Maiani, Piccinini, Tolosa, Riquer, PRD89(2014)114010

$$M = M_{00} + B_c \frac{\boldsymbol{L}^2}{2} - 2a\boldsymbol{L}\cdot\boldsymbol{S} + 2\kappa_{cq}\left[\left(\boldsymbol{s}_q\cdot\boldsymbol{s}_c\right) + \left(\boldsymbol{s}_{\bar{q}}\cdot\boldsymbol{s}_{\bar{c}}\right)\right]$$

- The spin of $c\bar{c}$ pair is not fixed ⇒ its behavior in e^+e^- annihilation is unclear
- I=0 and I=1 spectrum is similar ⇒ the spectrum is more complicated than exp. measurement





- Four 1^{--}, two 1^{-+}, one 0^{--}

BESIII, PRD106(2022)072001

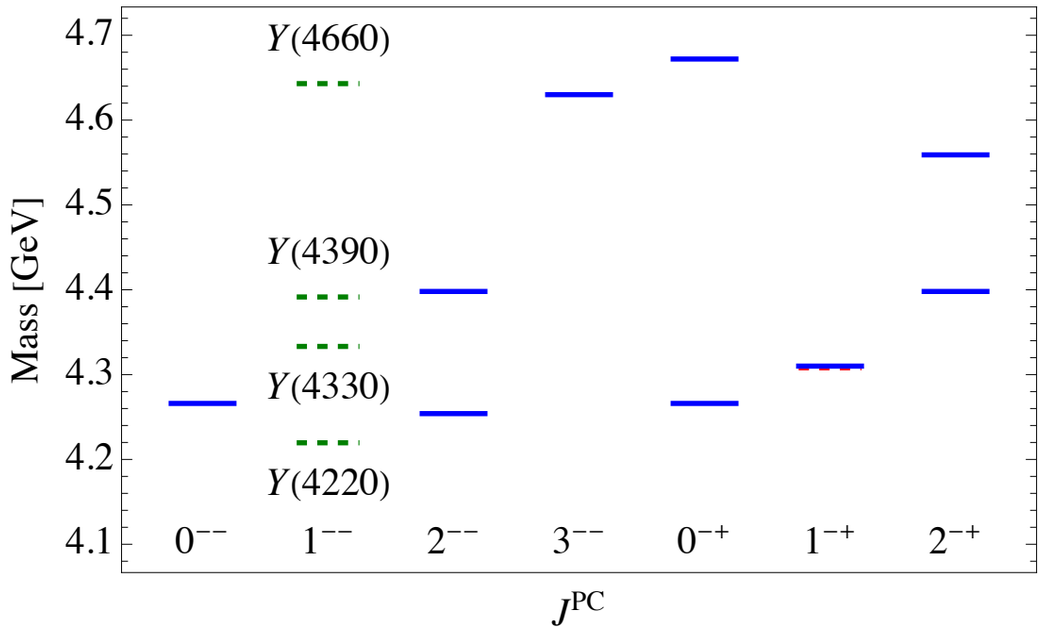
Theoretical developments

The compact tetraquark picture

- Tensor force included

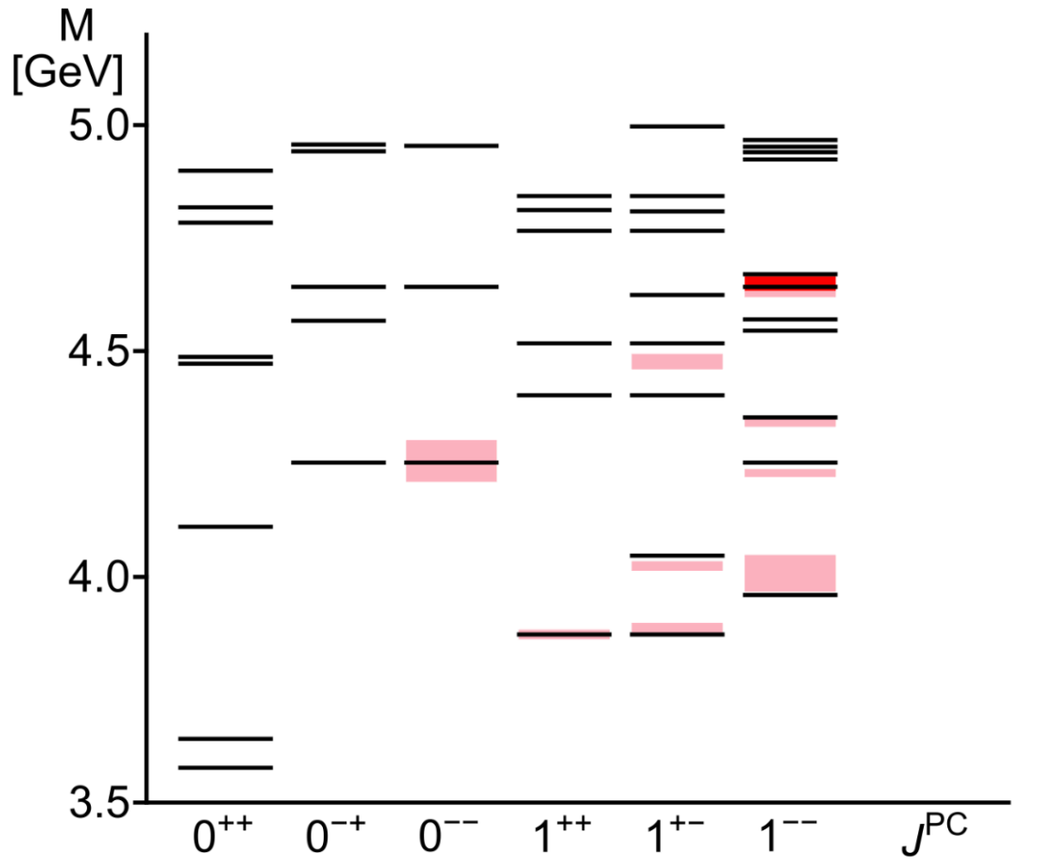
Ali et.al, EPJC78(2018)29

$$\left\langle \frac{S_{12}}{4} \right\rangle_{(L=1)} = 3a(L)\left[(\boldsymbol{L}\cdot\boldsymbol{S}_1)(\boldsymbol{L}\cdot\boldsymbol{S}_2) + (\boldsymbol{L}\cdot\boldsymbol{S}_2)(\boldsymbol{L}\cdot\boldsymbol{S}_1) - \frac{4}{3}(\boldsymbol{S}_1\cdot\boldsymbol{S}_2) \right]$$



- Numerical results based on GEM
  - Higher S states are questionable
  - Higher L states are questionable
  - Not complete configurations

- The number of states remain the same
- Two 1^{-+} states are degenerate

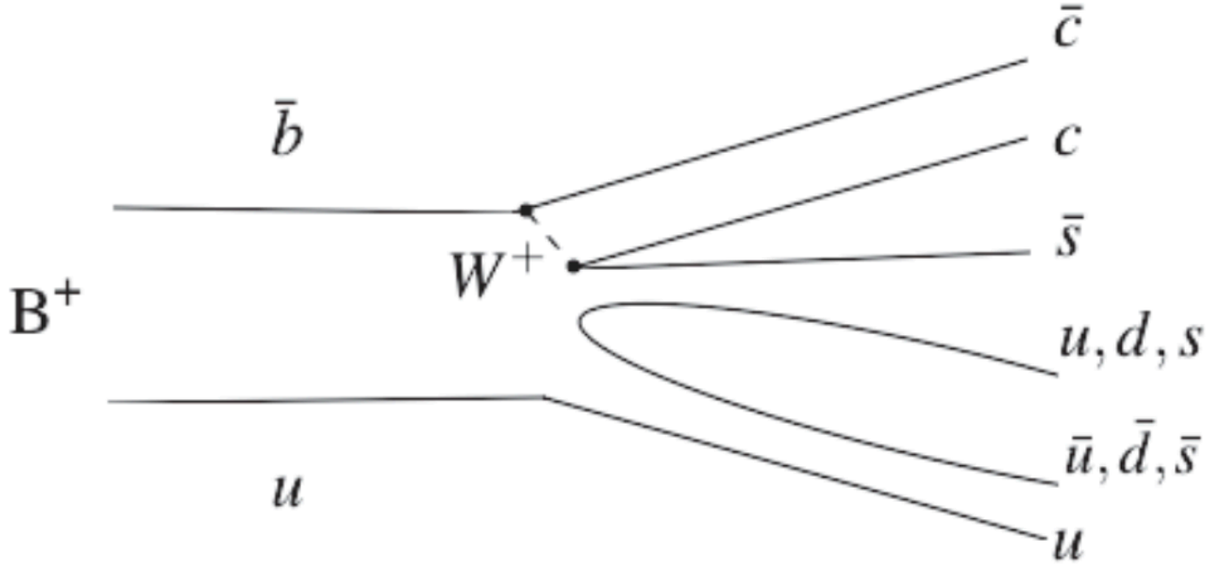


Anwar, Ferretti, Santopinto, PRD98(2018)094015

Theoretical developments

The compact tetraquark picture

- Production in B decays
- Sensitive to its internal structure



Compact tetraquark, hadronic molecule, charmonium

Bigi, Maiani, Piccinini, Polosa, Riquer, PRD72(2005)114016

$c\bar{c}(u\bar{u} + d\bar{d})/\sqrt{2}$

$b \to c(\bar{c}d)$

Doubly Cabibbo suppressed

$c\bar{c}s\bar{s}$

$b \to c(\bar{c}s)$

Single Cabibbo suppressed

Theoretical developments

The hybrid picture

- Flux tube picture

  Isgur and Paton, PRD31(1985)2910, PLB124(1983)247

  - Transverse mode: constituent gluon
  - Collinear mode: provide an effective V

$\Rightarrow$

$\Delta m \equiv m_{\text{excited}} - m_{\text{ground}}$ Ma et.al, CPC45(2021)093111

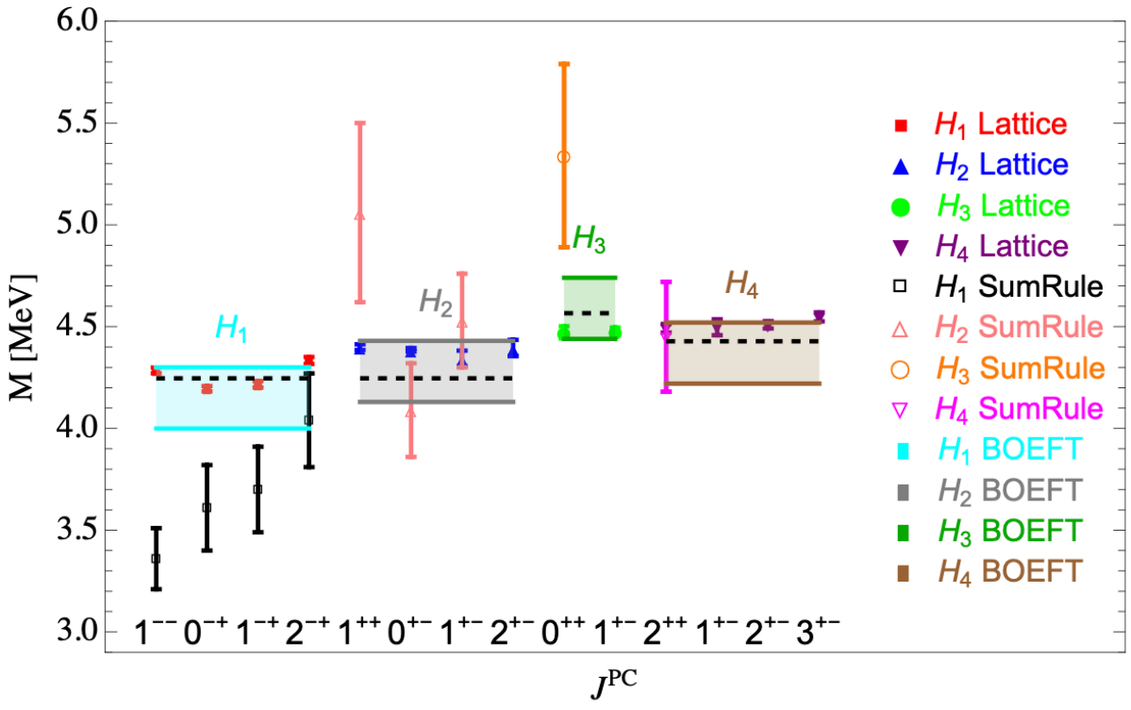
$\Delta m^{\text{transverse}} > \Delta m^{\text{collinear}}$ Braaten et.al, PRD90(2014)014044

- $\psi(4230)$ as a hybrid
  - Suppressed in dilepton pairs

    Close and Page, PLB628(2005)215
  - Absence in $e^+e^- \to D^{(*)}\bar{D}^{(*)}$ cross sections

    Isgur and Paton, PRD31(1985)2910, PLB124(1983)247

- The spectrum
  - H_1: 1^{+-} glue-lump+S-wave $Q\bar{Q}$
  - $H_2 \cup H_3 \cup H_4$: 1^{+-} glue-lump+P-wave $Q\bar{Q}$
  - QCD sum rule Chen, et.al, JHEP09(2013)019
  - Lattice calculations Liu et.al, JHEP07(2012)126
  - One 1^{--}, one 1^{-+}, zero 0^{--}



Berwein, Brambilla, Tarrus Castella, Vairo, PRD92(2015)114019

Theoretical developments

The hybrid picture

- Born-Oppenheimer (BO) approximation indicates a selection rule

$$\Gamma(\psi(4230) \to D\bar{D}) : \Gamma\left(\psi(4230) \to D^*\bar{D} + \text{ c.c. }\right) : \Gamma\left(\psi(4230) \to D^*\bar{D}^*\right) = 1 : 0 : 3$$

- The decay mode of its 1^{-+} partner

Braaten and Bruschini, PRD109(2024)094051,
Bruschini, PRD109(2024)L031501, Shi et.al, PRD109(2024)094513

$$\Gamma((0,1,2)^{-+} \to D^*\bar{D} + c\,.\,c.) : \Gamma\left((0,1,2)^{-+} \to D^*\bar{D}^*\right) = 1 : 1$$

$(0,2)^{-+} \nrightarrow D\bar{D}$ Spin-parity conservation $1^{-+} \nrightarrow D\bar{D}$ Bose statistics

- The mass ordering $0^{-+} < 1^{-+} < 1^{--} < 2^{-+}$ for $b\bar{b}g$ hybrid Drummond, et.al, PLB478(2000)151

100 MeV for $c\bar{c}g$ Liu et.al, JHEP07(2012)126

- 1^{--} $c\bar{c}g$ hybrid coupling to $s_l = \frac{3^+}{2}$ and $s_l = \frac{1^-}{2}$ charmed meson pairs is small

Close and Page, NPB443(1995)233, Page, Swanson, Szczepaniak, PRD59(1999)034016

Theoretical developments

The hadro-quarkonium picture

- Based on the experimental fact that they are observed in $(Q\bar{Q}) + 2\pi$ channel

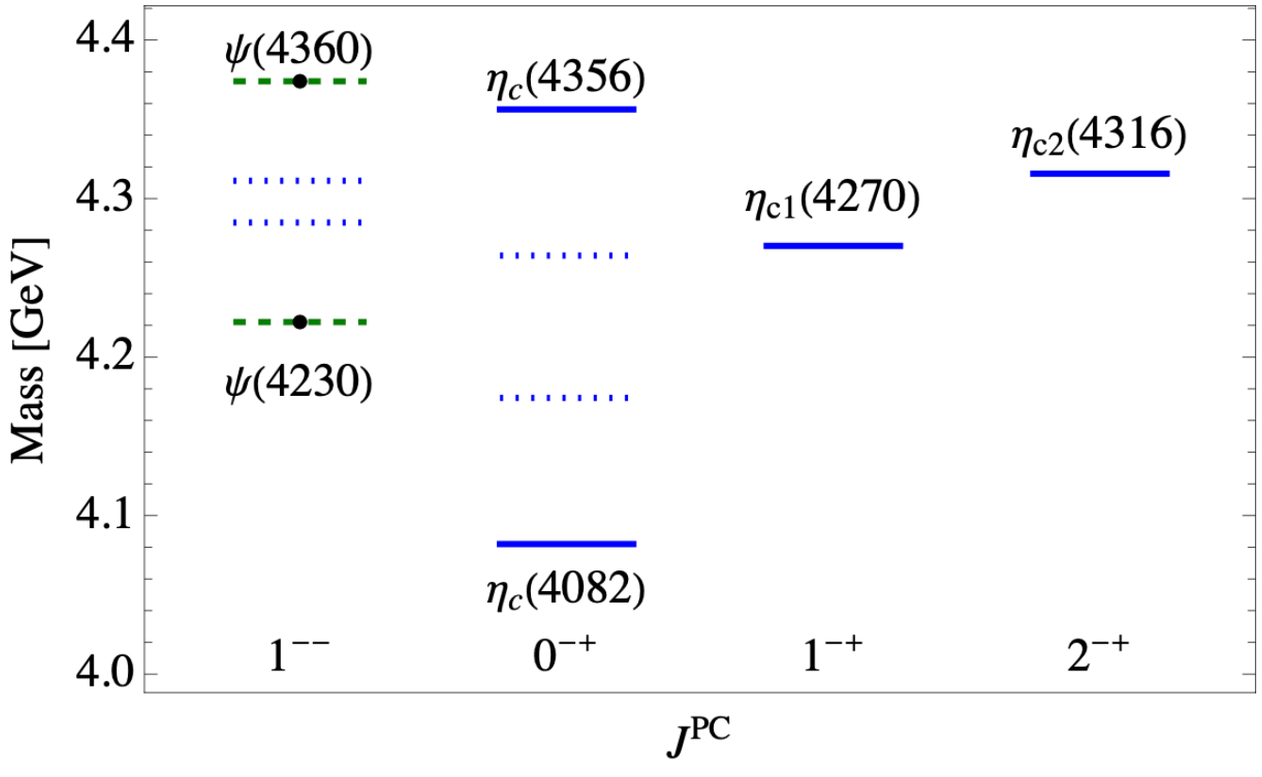
Voloshin, PPNP61(2008)455, Dubynskiy and Voloshin, PLB666(2008)344

- $\psi(4230)$ and $\psi(4360)$ as mixtures of two hadro-charmonia $(1^{--})_{c\bar{c}} \otimes (0^{++})_{q\bar{q}}$ and $(1^{+-})_{c\bar{c}} \otimes (0^{-+})_{q\bar{q}}$

Cleven et.al, PRD92(2015)014005, Li and Voloshin, MPLA29(2014)1450060

$$\begin{pmatrix} m_{\psi(4230)} & 0 \\ 0 & m_{\psi(4360)} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} m_{\psi_1} & m_{13} \\ m_{13} & m_{\psi_3} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- two 1^{--} states, one $(1,2)^{-+}$ state
- two 0^{-+} states, zero 0^{--} state



Theoretical developments

The hadro-quarkonium picture

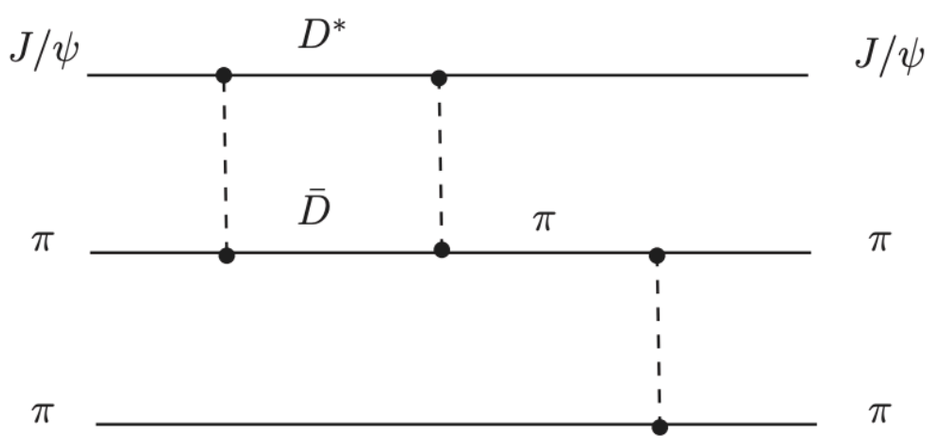
- Confirmation from various aspects

- A lattice QCD simulation ⇒ binding energy between quarkonium and light hadrons is similar to that of deuterium Alberti, et.al, PRD95(2017)074501

- Chromo-electric polarizability in the framework of the $1/N_c$ expansion Ferretti, PLB782(2018)702

- AdS/QCD Martin Contreras, Vega, PRD108(2023)126024

- Faddeev equations Martinez Torres, et.al, PRD80(2009)094012

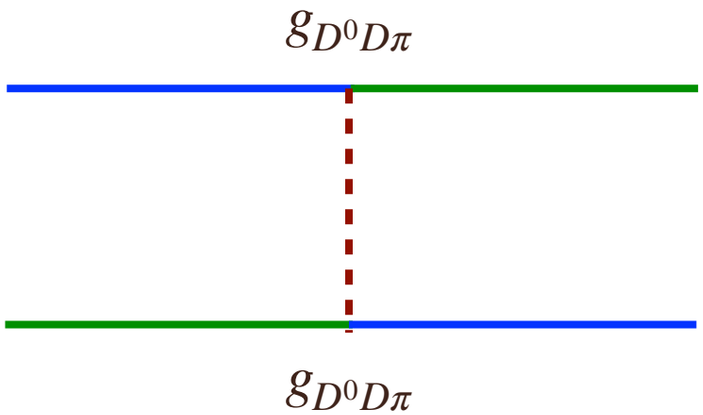


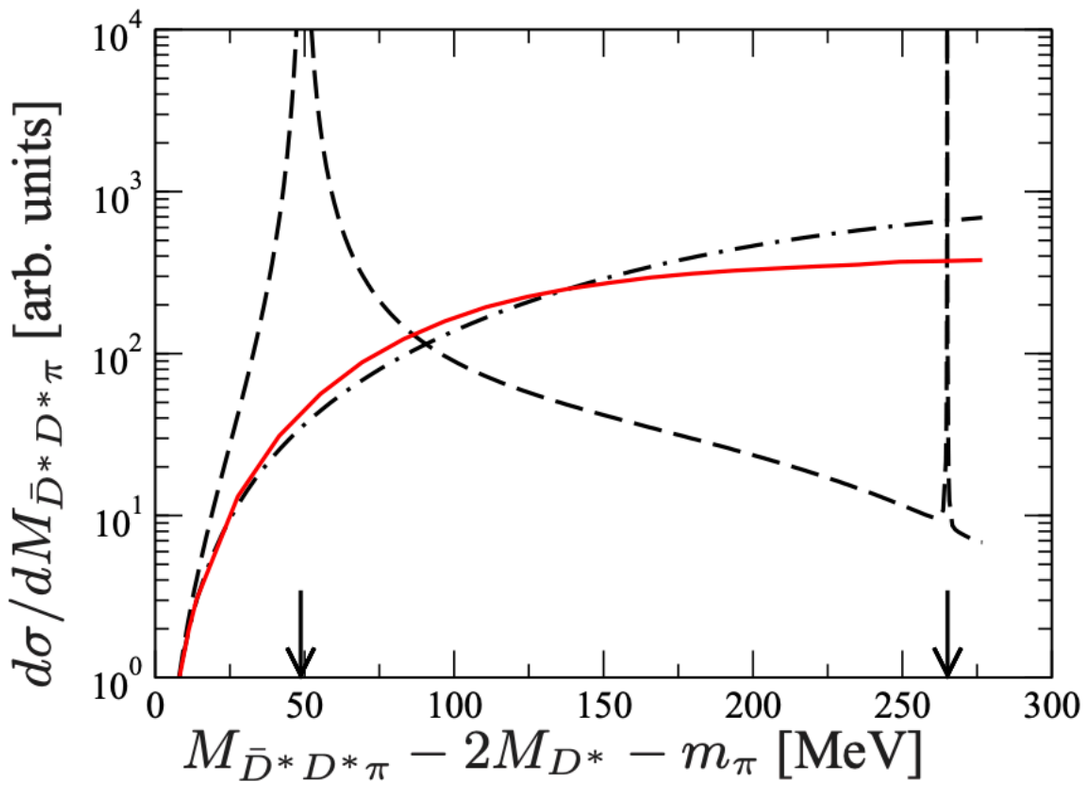
Theoretical developments

The hadronic molecular picture

- Analogous to deuteron
  - $\rho\chi_{c1}$ molecule — TWQCD, PRD73(2006)094510, Liu et.al, PRD72(2005)054023
  - $\omega\chi_{c1}$ molecule — Yuan et.al, PLB634(2006)634, Dai et.al, PRD92(2015)014020
  - $\Lambda_c\bar{\Lambda}_c$ molecule — Qiao , PLB639(2006)263
  - $D_1'\bar{D} + c.c.$ and $D_0\bar{D}^* + c.c.$ molecule — Ding, PRD79(2009)014001, Close et.al, PRD81(2010)074033, Close et.al, PRL102(2009)242003

- The large $g_{D^0D\pi}$ coupling also indicates large D^0 width — Filin et.al, PRL105(2010)019101





Filin et.al, PRL105(2010)019101

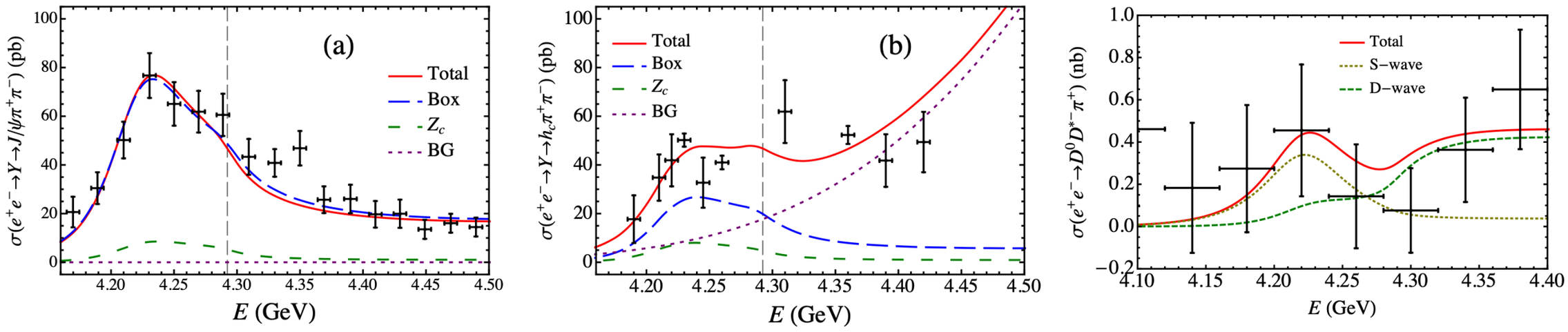
Theoretical developments

The hadronic molecular picture

QW, Hanhart, Zhao, PRL111(2013)132003

- The observation of $Z_c(3900) \Rightarrow \psi(4230)$ as an isospin singlet $D_1\bar{D} + c.c.$ molecule
- The extracted pole of $\psi(4230)$ 4217.2 ± 2.0 MeV from $e^+e^- \to J/\psi\pi\pi, h_c\pi\pi, D\bar{D}^*\pi$

Cleven, et.al, PRD90(2014)074039, QW, et.al, PRD89(2014)034001



- High-statistic data from BESIII collaboration allows for a global fitting
  - $M_{\psi(4230)} = 4227 \pm 4 - i(25^{+4}_{-1})$ MeV

    8-channel global fitting

    do not consider $D_1\bar{D}^*, D_2\bar{D}^*$ channels,

    simplified $\pi\pi - K\bar{K}$ interactions

    Detten, et.al, PRD109(2024)116002
  - $M_{\psi(4230)} = 4229.9 \pm 0.9 - i(23.2 \pm 1.3)$ MeV

    20-channel global fitting

    Phenomonly study

    simplified $\pi\pi - K\bar{K}$ interactions

    Nakamura, et.al, PRD112(2025)054027

Theoretical developments

The hadronic molecular picture

- Various studies

- Dispersive analysis of the $\psi(4230) \to J/\psi\pi^+\pi^-$ and $\psi(4230) \to J/\psi K^+K^-$ processes with $\pi\pi - K\bar{K}$ FSI, which indicates a sizable non-molecular component

  Chen et.al, PRD99(2019)074016,……

- Decay modes

  Chen et.al, EPJA52(2016)310, Liu et.al, PRD88(2013)014013, Li et.al, PRD88(2013)094008, Dong et.al, PRD89(2014)034018, Li et.al, CPC39(2015)063102,……

- Lineshapes Xue et.al, PLB779(2018)402, Wu et.al, PRD94(2016)054035, Cleven et.al, PLB766(2017)768,……

- Spectrum

  Wang, EPJC78(2018)933, Lu et.al, PRD96(2017)114022, Li et.al, arXiv:1303.4140, Peng et.al, PRD107(2023)016001, Peng et.al, PRD105(2022)034028,……

Theoretical developments

The hadronic molecular picture

- $D_1\bar{D} + c.c.$ HL decomposition $|1 \otimes 2\rangle \Rightarrow$ its coupling to photon $\dfrac{(E-2m_c)^2}{2(E+2m_c)^2}$ suppressed

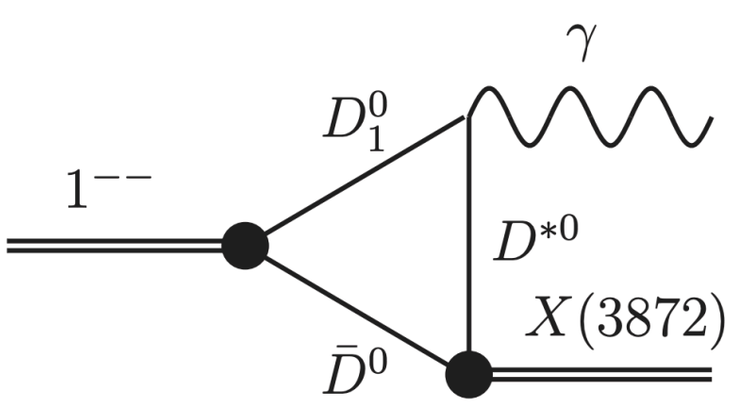
QW, et.al, PRD89(2014)034001, Qin, et.al, PRD94(2016)054035, Li, et.al, PRD88(2013)034012

- The asymmetric lineshape in the $e^+e^- \to J/\psi\pi\pi$ channel can be explained by one state + $D_1\bar{D}$

Cleven et.al, PRD90(2014)074039, Sue et.al, PLB779(2018)402, QW et.al, PRL111(2013)132003, QW et.al, PRD89(2014)034001, Wu et.al, PRD89(2014)054038, Qin et.al, PRD94(2016)054035, Chen et.al, EPJA52(2016)310, Wang, CPC41(2017)083103, Cleven et.al, PLB768(2017)52, Lu et.al, PRD96(2017)114022,Li et.al, arXiv:1303.4140, Liu et.al, PRD88(2013)014013, Li et.al, PRD88(2013)094008, Dong et.al, PRD89(2014)034018, Li et.al, CPC39(2015)063102, Chen et.al, PRD99(2019)074016, Peng et.al, PRD107(2023)016001,Peng et.al, PRD105(2022)034028

- Predict the production of $\chi_{c1}(3872)$ in the $e^+e^- \to \psi(4230) \to \gamma\chi_{c1}(3872)$

Guo et.al, PLB725(2013)127, BESIII, PRL124(2020)242001



π

$Z_c(3900)$

Theoretical developments

The hadronic molecular picture

- The spectrum

- Spectrum in vector-meson-exchanged model

  Dong, et.al, Prog. Phys. 41(2021)65

- Three 1^{--} states, three 1^{-+} states, one 0^{--}

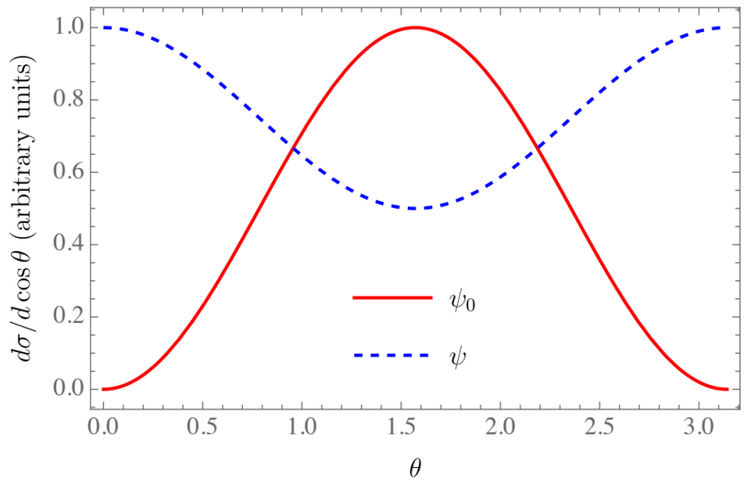
- Search for 1^{-+} exotic partners in e^+e^-

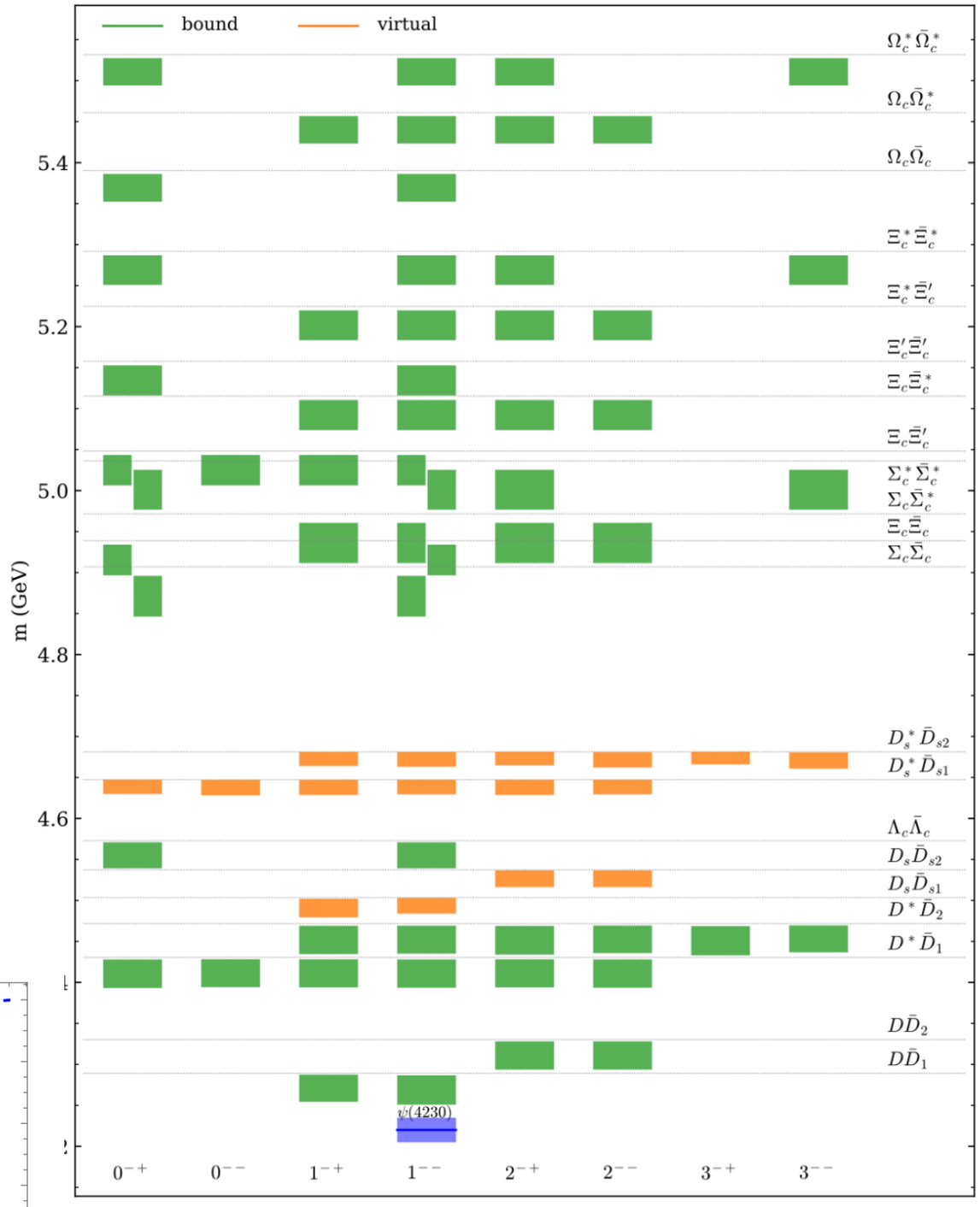
  QW, PRD89(2014)114013, Dong et.al, PRD101(2020)076003,

  Zhang et.al, PLB867(2025)139603

- A robust prediction of the mass of absolute exotic 0^{--} state, and search for it in $e^+e^- \to \eta\psi_0(4360)$

  Ji et.al, PRL129(2022)102002

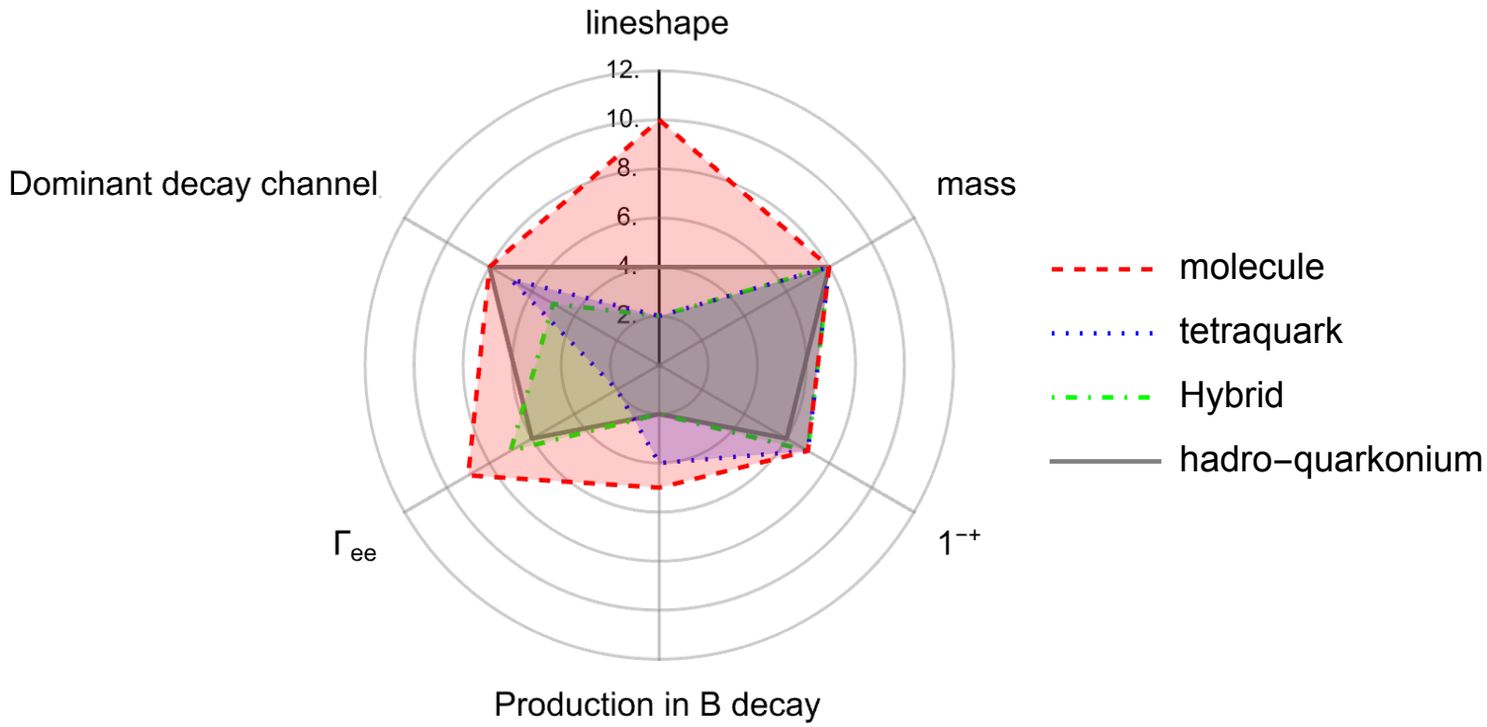




Dong, et.al, Prog. Phys. 41(2021)65

Summary and outlook

- More high precision experimental data, i.e. decay widths to exclusive channels, di-lepton decay width etc, from BESIII collaboration
- Production in other reaction, i.e. B decay and prompt production
- Further detailed analysis from theoretical side



Thank you very much for your attention!