Exotic states of fully heavy hadrons

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Long-term fruitful collaboration with my colleagues and co-authors is gratefully acknowledged!

- X. K. Dong, V. Baru, F. K. Guo, C. Hanhart, A. Nefediev,
  "Coupled-Channel Interpretation of the LHCb Double-J/ψ Spectrum and Hints of a New State Near the $J/\psi J/\psi$ Threshold,"
  Phys. Rev. Lett. **126**, 132001 (2021)
- X. K. Dong, V. Baru, F. K. Guo, C. Hanhart, A. Nefediev, B. S. Zou,
  "Is the existence of a $J/\psi J/\psi$ bound state plausible?,"
  Sci. Bull. **66**, 2462 (2021)
- X. K. Dong, F. K. Guo, A. Nefediev, J. T. Castellà,
  "Chromopolarizabilities of fully-heavy baryons,"
  Phys. Rev. D **107**, 034020 (2023)
- A. V. Nefediev,
  "$X(6200)$ as a compact tetraquark in the QCD string model",
  Eur. Phys. J. C **81** 692 (2021)

Exotic hadrons with light quarks

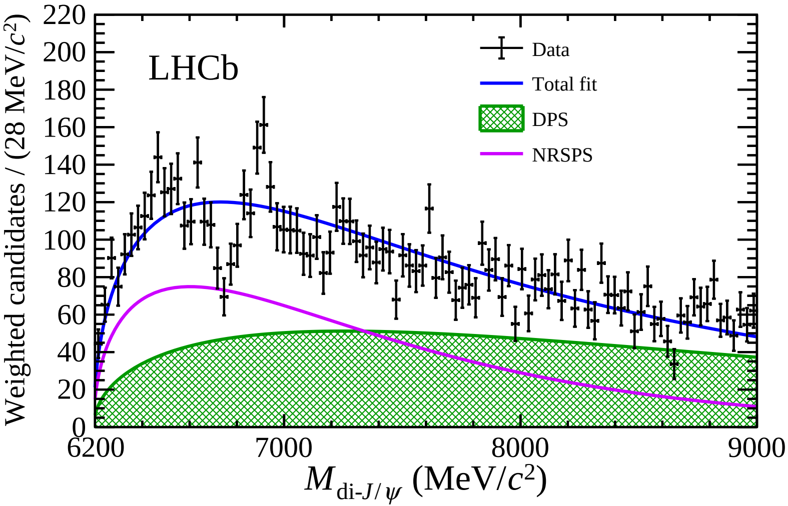
Known exotic hadrons with light quarks:

- Deuteron (bound state of proton & neutron)
- $X(3872)$ (contains large $D\bar{D}^*$ component)
- T_{cc}^+ (DD^* molecule)
- $Z_c(3900)$ and $Z_c(4020)$ ($D^{(*)}\bar{D}^*$ molecules)
- $Z_{cs}(3982)$ ($D^*\bar{D}_s/D\bar{D}_s^*$ molecule)
- $Z_b(10610)$ and $Z_b(10650)$ ($B^{(*)}\bar{B}^*$ molecules)
- ...

How about fully heavy exotic hadrons?

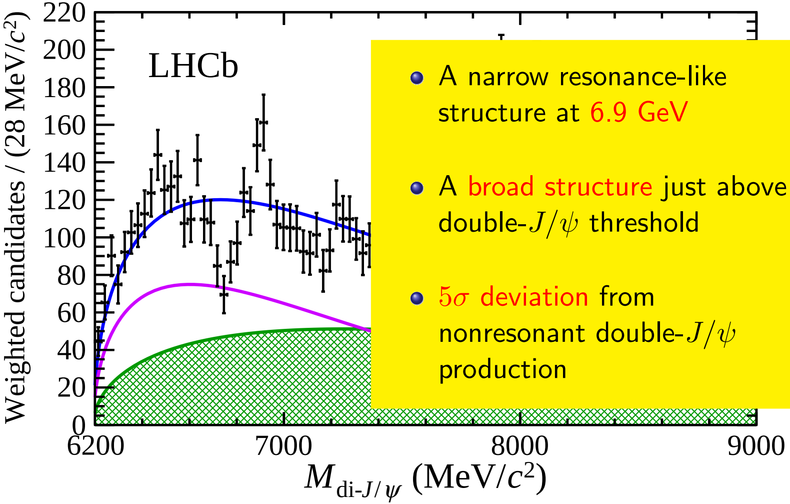
- $M_{\text{bottom}} \gtrsim 18$ GeV
  - $\Longrightarrow$ too heavy for Belle II
  - $\Longrightarrow$ too many b's for LHCb
- $M_{\text{charm}} \gtrsim 6$ GeV $\Longleftarrow$ should be feasible for LHC and KEKB

Double-J/ψ production @ LHCb (Sc.Bull. 65 (2020) 1983)



NRSPS=NonResonant Single Parton Scattering
DPS=Double Parton Scattering

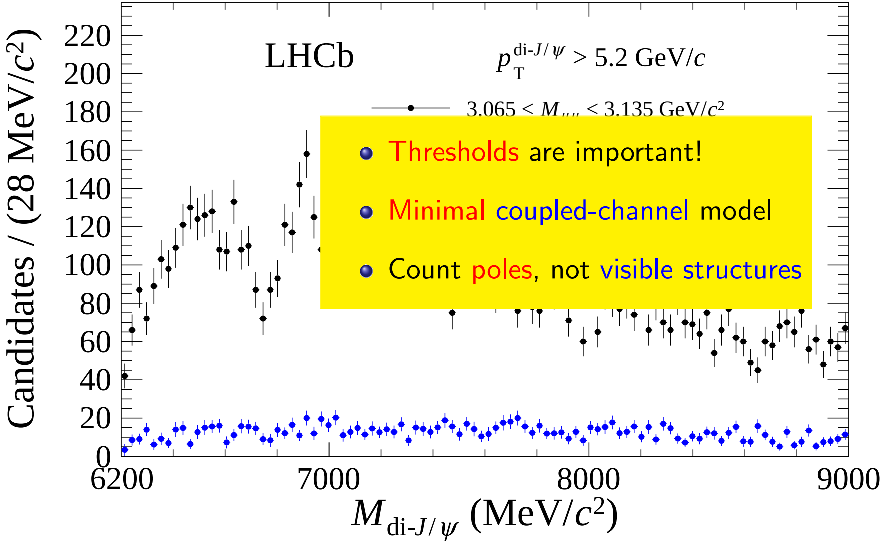
Double-J/ψ production @ LHCb (Sc.Bull. 65 (2020) 1983)



- A narrow resonance-like structure at 6.9 GeV
- A broad structure just above double-J/ψ threshold
- 5σ deviation from nonresonant double-J/ψ production

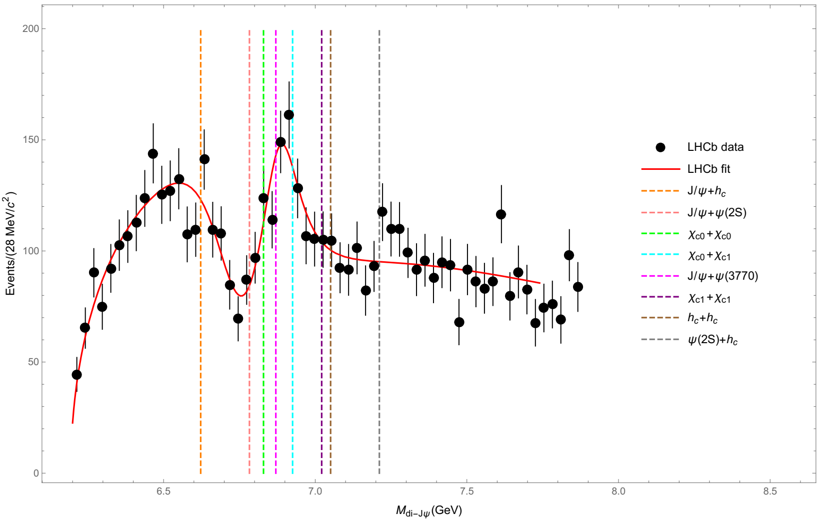
NRSPS=NonResonant Single Parton Scattering
DPS=Double Parton Scattering

Double-J/ψ production: Theoretical data analysis

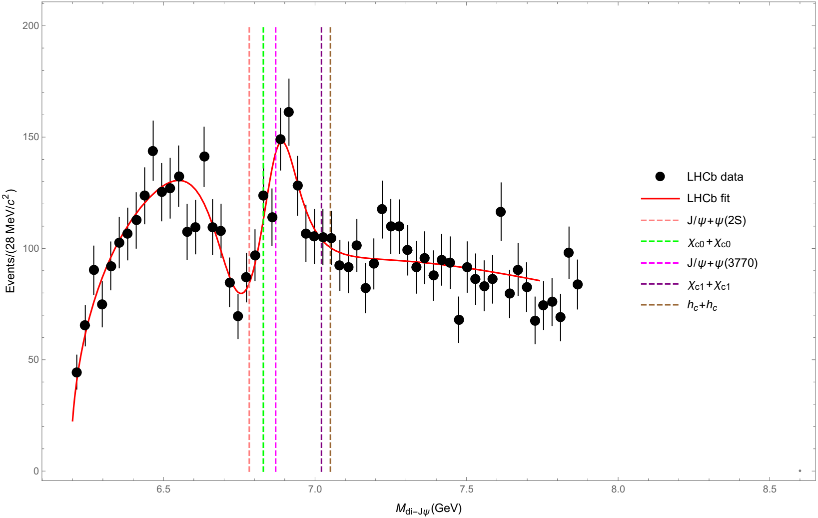


- Thresholds are important!
- Minimal coupled-channel model
- Count poles, not visible structures

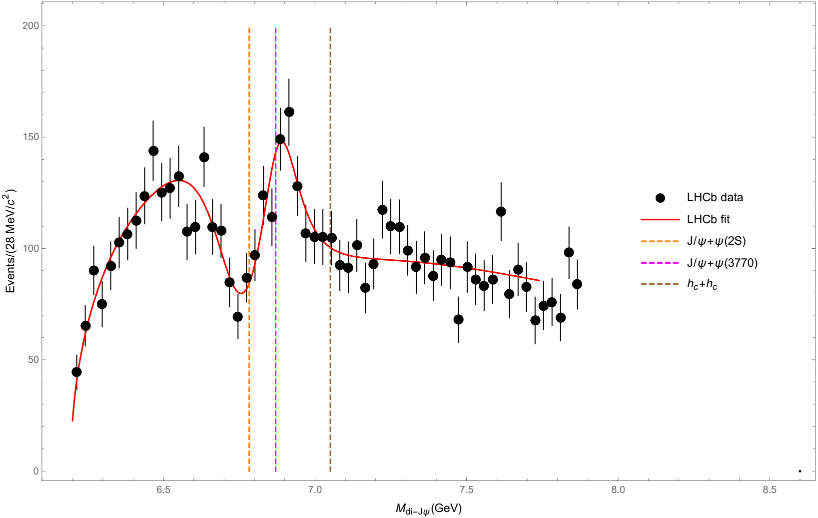
All channels



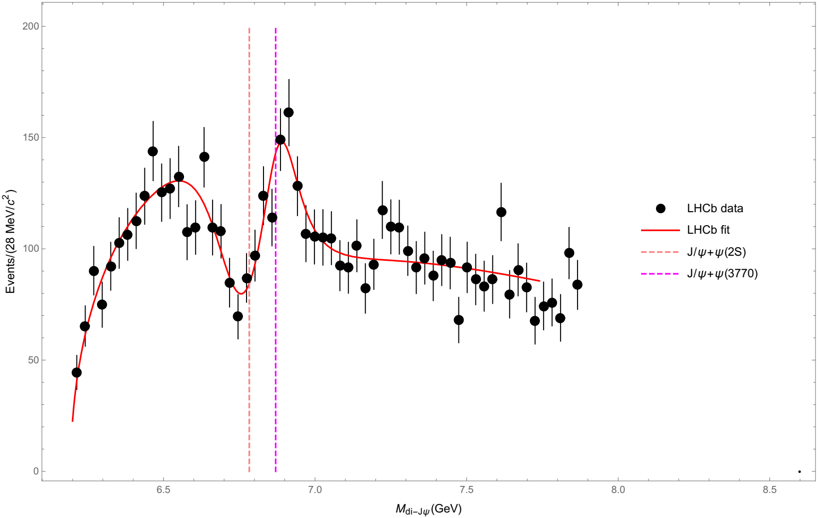
Only S-wave channels (no $J/\psi h_c$, $\psi(2S)h_c$, $\chi_{c0}\chi_{c1}$)



No heavy exchanges (no $\chi_{c0}\chi_{c0}$, $\chi_{c1}\chi_{c1}$)

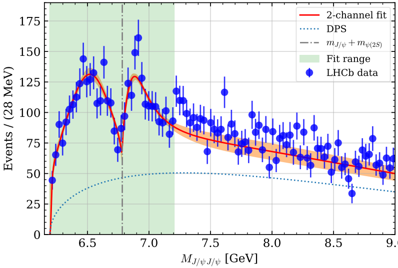


Only HQSS-allowed channels (no $h_c h_c$)

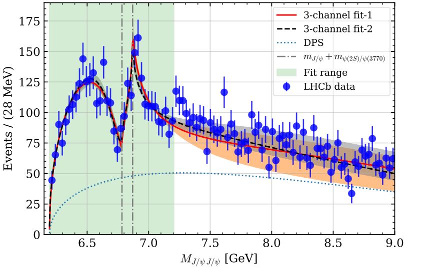


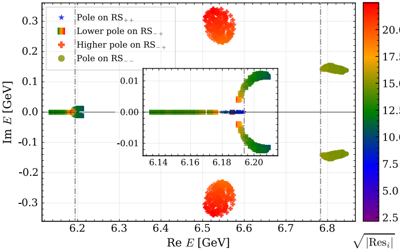
Fits & poles

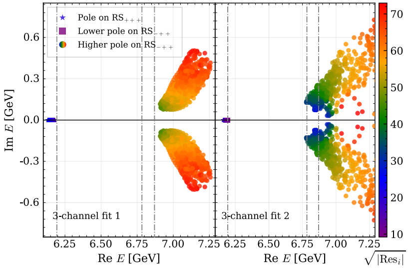
$J/\psi J/\psi$ & $J/\psi\psi(2S)$ (2+5 params)



$J/\psi J/\psi$, $J/\psi\psi(2S)$ & $J/\psi\psi(3770)$ (2+6 params)

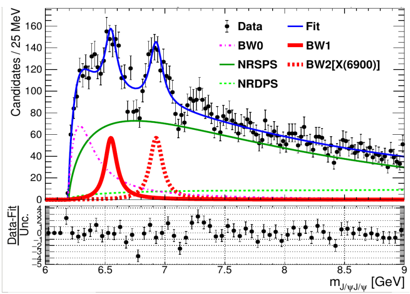


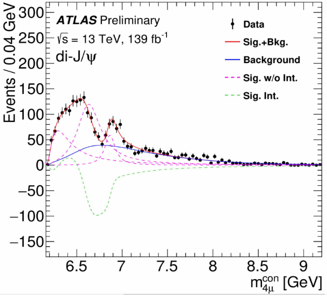




Further tests

- Analyse CMS and ATLAS data in the double-J/ψ channel





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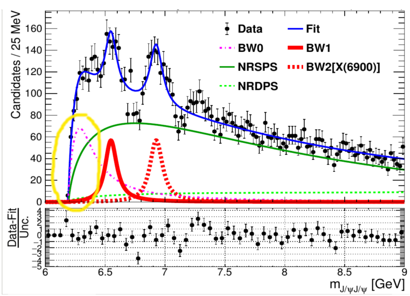

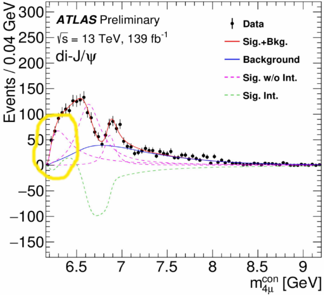

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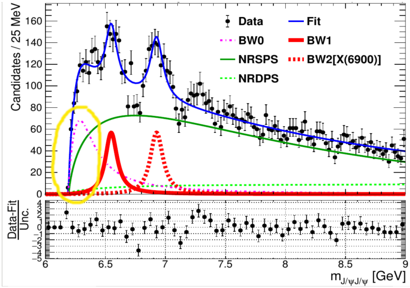
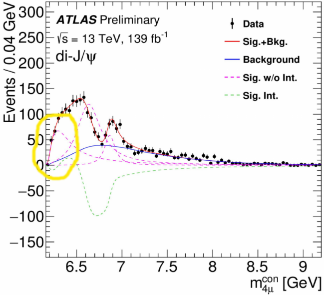


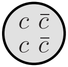


- Analyse data in the complimentary $\psi(2S)J/\psi$ channel

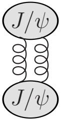
- Combined analysis of all data sets (?)

$X(6200)$ vs $X(6900)$

- Poles above the double-J/ψ threshold ($X(6900)$) are badly determined
  - Parameters of $X(6900)$ are uncertain
  - Combined analysis LHCb+CMS+ATLAS ?
- Pole $X(6200)$ near the double-J/ψ threshold is robust
- $X(6200)$ = fully charmed tetraquark
  - Compact Tetraquark



  - Hadronic Molecule



$X(6200)$ as compact $\bar{c}\bar{c}cc$ tetraquark

Progress of Theoretical Physics, Vol. 54, No. 2, August 1975

A Possible Model for New Resonances

——*Exotics and Hidden Charm*——

Yoichi IWASAKI

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Kyoto University, Kyoto

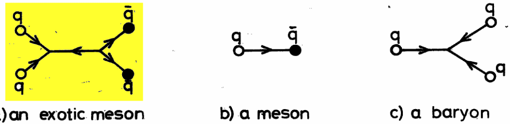


Fig. 1. An exotic state, a meson and a baryon.

We expect at least three exotic mesons with hidden charm, $c\bar{c}(p\bar{p}-n\bar{n})$ [between 3.7∼4.1 GeV], $c\bar{c}\lambda\bar{\lambda}$ [∼4.1 GeV] and $c\bar{c}c\bar{c}$ [∼6.2 GeV], to which we refer as ψ_ρ, ψ_φ and ψ_ψ, respectively. [We may refer to ψ' as ψ_ω.] We assume that the

$X(6200)$ as compact $\bar{c}\bar{c}cc$ tetraquark

[1]	[2]	[3]	[4]
6.2 GeV	6.1915 GeV	6.190 GeV	6.196 GeV

[1] Y. Iwasaki, Prog. Theor. Phys. **54** (1975), 492

[2] M. Karliner, S. Nussinov, J. L. Rosner, Phys. Rev. D **95** (2017), 034011

[3] R. Faustov, V. Galkin, E. Savchenko, Phys. Rev. D **102** (2020), 114030

[4] A. N., Eur. Phys. J. C **81**, 692 (2021)

Conclusion: Existence of a compact-state pole near the double-J/ψ threshold is supported by model calculations

$X(6200)$ as compact $\bar{c}\bar{c}cc$ tetraquark

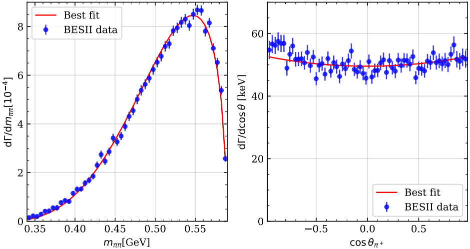
- Pros
  - Fully charmed compact tetraquark is consistent with QCD
  - Quark models predict fully charmed tetraquark with $M \approx 6.2$ GeV
- Cons
  - Czarnecki,Leng,Voloshin'2018: tetron $QQ\bar{q}\bar{q}$ is unstable for $m_q = m_Q$ *if the system is Coulombic*
  - Hughes,Eichten,Davies'2018: no lattice evidence for $\bar{b}\bar{b}bb$ bound state
- Open questions
  - Are quark model calculations reliable?
  - How stable are fully charmed compact tetraquarks?
  - Is $\bar{c}\bar{c}cc$ system Coulombic enough?
  - Does wisdom from b-sector directly apply to c-sector?

$X(6200)$ as double-J/ψ molecule

Multipole expansion for soft-gluon exchanges ($r_{\bar{Q}Q} \ll \Lambda_{\rm QCD}^{-1}$): $H_{\rm int} \approx -\frac{1}{2}\zeta_a \boldsymbol{r}\cdot\boldsymbol{E}^a$

(Gottfried'1977, Voloshin'1978, Peskin'1979, ... Voloshin&Sibirtsev'2005)

$$\beta_{\psi\psi'} = \frac{1}{9}\langle\psi'|\boldsymbol{r}\frac{1}{\hat{H}_O - M}\boldsymbol{r}|\psi\rangle \Longrightarrow \begin{cases} \mathcal{M}(\psi(2S)\to J/\psi\pi\pi) = \beta_{\psi(2S)J/\psi}\langle\pi\pi|\boldsymbol{E}^a\cdot\boldsymbol{E}^a|0\rangle \\ \boxed{V_{J/\psi J/\psi}(r) \propto \beta^2_{J/\psi J/\psi} \propto \xi^2} \quad \left(\xi = \frac{\beta_{J/\psi J/\psi}}{\beta_{\psi(2S)J/\psi}}\right) \end{cases}$$



$$\boxed{|\beta_{\psi(2S)J/\psi}| \approx 1.81\ \text{GeV}^{-3}}$$

(Dong et al.'2021)

$X(6200)$ as double-J/ψ molecule

- Simple estimate

$$\xi \sim I_{J/\psi J/\psi}/I_{\psi(2S)J/\psi} \sim 10 \qquad I_{\psi'\psi} = \langle\psi'|\, e^{-i\Delta\boldsymbol{q}_c\cdot\boldsymbol{r}/2}\, |\psi\rangle$$

(Dong et al.'2021)

- More advanced estimate

$$a_0^{\rm th}(J/\psi\pi \to J/\psi\pi) \approx 0.0036\xi \text{ fm}$$

(Dong et al.'2021)

$$|a_0^{\rm lat}(J/\psi\pi \to J/\psi\pi)| \sim 0.01 \text{ fm} \implies \xi \simeq 3$$

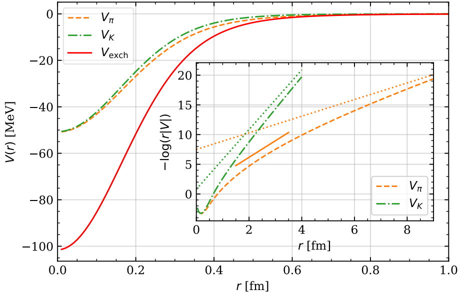
(Yokokawa et al'2006,Liu et al.'2008)

- Quark model calculation

$$\beta_{J/\psi J/\psi} = \frac{0.93}{\alpha_s^4 m_c^3} = 19^{+15}_{-14}\ \text{GeV}^{-3} \implies 3 \lesssim \xi \lesssim 19$$

(Brambilla et al.'2016,Dong et al'2023)

$X(6200)$ as double-J/ψ molecule



$$V_{\rm tot}(r,\Lambda) = V_\pi(r,\Lambda) + V_K(r,\Lambda) = V_{\rm CT}(r,\Lambda) + V_{\rm exch}(r,\Lambda)$$

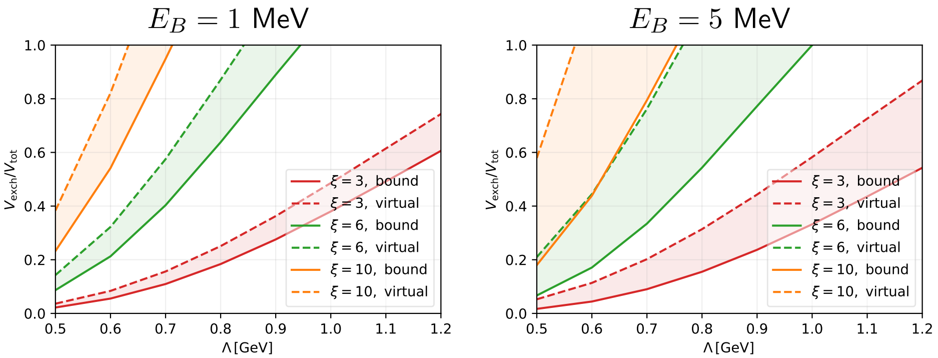
$$V_{\rm exch}(r,\Lambda) = -\frac{1}{4\pi M_{J/\psi}^2}\int \frac{d^3q}{(2\pi)^3} e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \int_{4m_\pi^2}^{\infty} d\mu^2\, \frac{{\rm Im}\mathcal{M}_{J/\psi J/\psi}(\mu^2)}{\mu^2+q^2} F\left(\frac{q^2+\mu^2}{\Lambda^2}\right)$$

Exchange of charmonia is suppressed as $\Lambda_{\rm QCD}^2/m_c^2$

$\Longrightarrow$ $V_{\rm CT}$ mainly comes from pion/kaon exchanges

$\Longrightarrow$ For natural $\Lambda \sim 1$ GeV $\boxed{V_{\rm CT} \sim V_{\rm exch}}$ $\Longrightarrow$ $V_{\rm exch}/V_{\rm tot} \gtrsim \frac{1}{2}$

$X(6200)$ as double-J/ψ molecule



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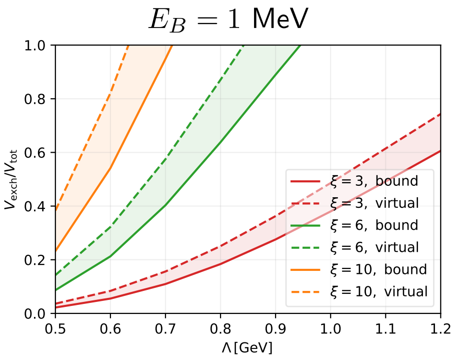

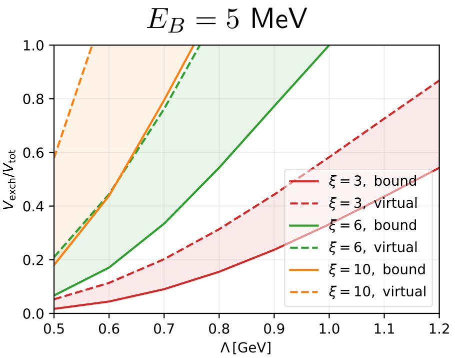

Conclusion: Existence of a molecular pole near the double-J/ψ threshold is consistent with our knowledge on hadron-hadron interactions

Di-heavy-baryon molecules?

- Quarkonium $\psi = \bar{Q}Q$

$$\beta_\psi = \frac{C_\psi}{\alpha_s^4 m_Q^3} \qquad C_\psi \approx 0.93$$

(Brambilla et al.'2016,Dong et al'2023)

- Baryon $\Omega = QQQ$

$$\beta_\Omega = \frac{C_\Omega}{\alpha_s^4 m_Q^3} \qquad C_\Omega \approx 2.4 \approx 2.6 C_\psi$$

(Dong et al'2023)

- Uncertainty from hadron being not Coulombic

$$\frac{\delta\beta}{\beta} \sim \frac{\Lambda_{\rm QCD}^2}{\alpha_s^3 m_Q^2} \sim \begin{cases} 100\% & Q = c \\ 10\% & Q = b \end{cases}$$

Di-heavy-baryon molecules?

- Quarkonium $\psi = \bar{Q}Q$

$$\beta_\psi = \frac{C_\psi}{\alpha^4 m^3} \qquad C_\psi \approx 0.93$$

Conclusion: If $X(6200)$ is a di-J/ψ molecule, then di-Ω_{ccc} and di-Ω_{bbb} molecules are also likely to exist

Supported by recent lattice results:

- $E_B(\mathrm{di}{-}\Omega_{ccc}) \simeq 5..6$ MeV (Lyu et al.'2021)
- $E_B(\mathrm{di}{-}\Omega_{bbb}) \simeq 80..100$ MeV (Mathur et at.'2022)

$$\frac{\delta\beta}{\beta} \sim \frac{\Lambda^2_{\mathrm{QCD}}}{\alpha_s^3 m_Q^2} \sim \begin{cases} 100\% & Q = c \\ 10\% & Q = b \end{cases}$$

Conclusions

- Discovery of $X(3872)$ started new era in hadronic physics of heavy quarks
- LHC studies of double-J/ψ production opened new chapter in this book
- Data collected are analysed
  - using (minimal but realistic) coupled-channel scheme
  - preserving unitarity
  - respecting (approximate but accurate) heavy quark spin symmetry
- Existence of a state at $J/\psi J/\psi$ threshold is predicted from data analysis
- Compact tetraquark assignment for $X(6200)$ is not excluded but calls for additional studies
- Conjecture of molecular nature of $X(6200)$ is consistent with our knowledge of hadron-hadron interactions
- Near-threshold state in double-J/ψ channel may imply existence of double-heavy-baryon molecules